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Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories

IPCC National Greenhouse Gas Inventories Programme

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IPCC

Robert Watson, Chair
Narasimhan Sundararaman, Secretary

IPCC NGGIP Task Force Bureau

Taka Hiraishi, co-chair
Buruhani Nyenzi, co-chair
Ian Carruthers
Marc Gillet
Dina Kruger
Carlos Lopez
Leo Meyer
Domingos Miguez
Wang Minxing
Igor Nazarov
Richard Odingo
Rajendra Pachauri
Jim Penman
Audun Rosland
John Stone

IPCC NGGIP Japan Technical Support Unit

Sal Emmanuel
Leandro Buendia
Robert Hoppaus
Jeroen Meijer
Kyoko Miwa
Kiyoto Tanabe
Kyoko Takada

PREFACE[1]

This report on *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (Good Practice Report)* is the response to the request from the United Nations Framework Convention on Climate Change (UNFCCC) for the Intergovernmental Panel on Climate Change (IPCC) to complete its work on uncertainty and prepare a report on *good practice* in inventory management.

The *Good Practice Report* provides *good practice guidance* to assist countries in producing inventories that are neither over nor underestimates so far as can be judged, and in which uncertainties are reduced as far as practicable.

To this end, it supports the development of inventories that are transparent, documented, consistent over time, complete, comparable, assessed for uncertainties, subject to quality control and quality assurance, and efficient in the use of resources.

The *Good Practice Report* treats four main topics. Firstly, Chapters 2-5 contain *good practice guidance* addressing the Energy, Industrial Processes, Agriculture, and Waste Sectors. These chapters address:

- Choice, by means of decision trees, of estimation methods suited to national circumstances;
- Advice on the most suitable emission factors and other data necessary for inventory calculations;
- Quality assurance and quality control procedures to enable cross-checks during inventory compilation;
- Information to be documented, archived and reported to facilitate review of emission estimates;
- Uncertainties at the source category level.

Secondly, Chapter 6, Quantifying Uncertainties in Practice, describes how to determine the relative contribution that each source category makes to the overall uncertainty of national inventory estimates, using a combination of empirical data and expert judgement. The chapter describes methods that will help inventory agencies report on uncertainties in a consistent manner, and provides input to national inventory research and development activities.

Thirdly, since inventory development is resource-intensive, and estimates are likely to improve in the future, Chapter 7, Methodological Choice and Recalculation, provides guidance on how to prioritise *key source categories*, and also shows how and when to recalculate previously prepared emission estimates to ensure consistent estimation of trends.

Finally, Chapter 8, Quality Assurance and Quality Control, describes *good practice* in quality assurance and quality control procedures for inventory agencies with respect to their own inventories. G*ood practice guidance* covers measurement standards, routine computational and completeness checks, and documentation and data archiving procedures. A system of independent review and auditing is also described.

Three annexes provide supporting material on basic concepts, definitions and verification.

The *Good Practice Report* does not revise or replace the *IPCC Guidelines*[2], but provides a reference that complements and is consistent with those guidelines. Consistency with the *IPCC Guidelines* is defined by three criteria:

(i) Specific source categories addressed by *good practice guidance* have the same definitions as the corresponding categories in the *IPCC Guidelines*.

(ii) *Good practice guidance* uses the same functional forms for the equations used to estimate emissions that are used in the *IPCC Guidelines*.

(iii) *Good practice guidance* allows the correction of errors or deficiencies that have been identified in the *IPCC Guidelines*.

Criterion (i) does not exclude the identification of additional source categories that may be included in the O*ther* category in the *IPCC Guidelines*. Default emission factors or model parameter values have been updated, where they can be linked to particular national circumstances, and documented.

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[1] Preface agreed by the Task Force Bureau for the IPCC National Greenhouse Gas Inventories Programme that met in Sydney on 4 March 2000.

[2] Full title: *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (*IPCC, 1996*).

Whatever the level of complexity of the inventory, *good practice guidance* provides improved understanding of how uncertainties may be managed to produce emissions estimates suitable for the purposes of the UNFCCC and for the scientific work associated with greenhouse gas inventories.

BASIC INFORMATION

Prefixes and multiplication factors

Multiplication Factor	Abbreviation	Prefix	Symbol
1 000 000 000 000 000	10^{15}	peta	P
1 000 000 000 000	10^{12}	tera	T
1 000 000 000	10^{9}	giga	G
1 000 000	10^{6}	mega	M
1 000	10^{3}	kilo	k
100	10^{2}	hecto	h
10	10^{1}	deca	da
0.1	10^{-1}	deci	d
0.01	10^{-2}	centi	c
0.001	10^{-3}	milli	m
0.000 001	10^{-6}	micro	μ

Abbreviations for chemical compounds

CH_4	Methane
N_2O	Nitrous oxide
CO_2	Carbon dioxide
CO	Carbon monoxide
NO_X	Nitrogen oxides
NMVOC	Non-methane volatile organic compound
NH_3	Ammonia
CFCs	Chlorofluorocarbons
HFCs	Hydrofluorocarbons
PFCs	Perfluorocarbons
SF_6	Sulfur hexafluoride
CCl_4	Carbon tetrachloride
C_2F_6	Hexafluoroethane
CF_4	Tetrafluoromethane

Standard equivalents

1 tonne of oil equivalent (toe)	1 x 10^{10} calories
10^3 toe	41.868 TJ
1 short ton	0.9072 tonne
1 tonne	1.1023 short tons
1 tonne	1 megagram
1 kilotonne	1 gigagram
1 megatonne	1 teragram
1 gigatonne	1 petagram
1 kilogram	2.2046 lbs
1 hectare	10^4 m^2
1 $calorie_{IT}$	4.1868 Joules
1 atmosphere	101.325 kPa

Units[1] and abbreviations

cubic metre	m^3
hectare	ha
gram	g
tonne	t
joule	J
degree Celsius	℃
calorie	cal
year	yr
capita	cap
gallon	gal
dry matter	dm

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[1] For decimal prefixes see previous page.

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1 INTRODUCTION

1.1 DEVELOPMENT OF THE PROGRAMME

At its 8th session in June 1998, the Subsidiary Body for Scientific and Technological Advice (SBSTA-8) of the United Nations Framework Convention on Climate Change (UNFCCC), *encouraged the IPCC-OECD-IEA Inventories Programme to give high priority to completing its work on uncertainty, as well as to prepare a report on good practices in inventory management and to submit a report on these issues for consideration by the SBSTA, if possible by COP5*. This report is the IPCC's (Intergovernmental Panel on Climate Change) response to the SBSTA.

To prepare for the work required, the IPCC held an Expert Meeting in Paris in October 1998. The Paris meeting treated *good practice* as a way to manage uncertainties, as these would remain associated with greenhouse gas emissions inventories for the foreseeable future. *Good practice guidance* assists countries in producing inventories that are accurate in the sense of being neither over nor underestimates so far as can be judged, and in which uncertainties are reduced as far as practicable. *Good practice guidance* further supports the development of inventories that are transparent, documented, consistent over time, complete, comparable, assessed for uncertainties, subject to quality control and assurance, efficient in the use of the resources available to inventory agencies, and in which uncertainties are gradually reduced as better information becomes available.

The Paris meeting planned a series of four sectoral Expert Meetings to define *good practice* by sector and source category. These meetings covered, respectively, (i) industrial process emissions[1] and emissions of new greenhouse gases i.e., hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6), (ii) emissions associated with energy production and consumption, (iii) agricultural emissions and (iv) emissions from waste.

The four sectoral meetings were followed by a meeting on quantifying uncertainties and cross-cutting issues in inventory management, and a concluding meeting to finalise the work. Emissions and removals associated with carbon stocks in land use, land-use change and forestry were not addressed in this phase of work because of the parallel IPCC activity to produce a Special Report on this Sector. The Paris meeting anticipated the need to define *good practice* in this area also, once the Special Report is complete and the Parties have had time to consider it. Currently, *good practice guidance* covers emissions of the direct greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), HFCs, PFCs, and SF_6. Emissions of the precursor gases carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOCs) were not covered in this phase of *good practice* but could form part of the future work programme. Emissions associated with Solvents and Other Product Use are not covered in this report as the main gases emitted in this sector fall into the class of NMVOCs.

It soon became clear that the programme initiated in Paris could not be completed by the fifth Conference of the Parties to the UNFCCC (COP5), especially given the need for the report to go through the process of government and expert review. Also, with regard to the UNFCCC, the timetable for methodological work agreed at COP4 required substantive outputs by COP6. Therefore, the timetable was extended, so that the IPCC's report on *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* could be available to the Parties at COP6 rather than COP5.

1.2 QUANTIFYING UNCERTAINTIES IN ANNUAL INVENTORIES AND TRENDS

The *IPCC Guidelines* contain some quantitative advice on uncertainties,[2] although so far relatively few countries have reported on uncertainties in a systematic way.

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[1] *Good practice guidance* complementary to the *IPCC Guidelines* has not been developed for some categories of industrial emissions that are identified at the beginning of Chapter 3, Industrial Processes.

[2] *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 1, Annex 1, *Managing Uncertainties* (IPCC, 1996).

Nevertheless, evidence considered by the Paris meeting indicated that for a developed country the overall uncertainty in emissions weighted by global warming potentials (GWPs) in a single year could be of the order of 20%, mainly due to uncertainties in non-CO_2 gases.[3]

Analysis also indicated that the uncertainty in the trend in emissions may be less than the uncertainty in the absolute value of emissions in any year. This is because a method that over or underestimates emissions from a source category in one year may similarly over or underestimate emissions in subsequent years. The preliminary evidence available to the Paris meeting suggested that, when this compensation is taken into account, the uncertainty on the trend in emissions between years could fall to a few percent for industrialised countries.[4]

Chapter 6, Quantifying Uncertainties in Practice, of this report describes methods to determine the uncertainty in each source category. These methods use a combination of empirical data and expert judgement according to availability. They estimate the relative contribution that the source category makes to the overall uncertainty of national inventory estimates, in terms of the trend as well as absolute level. These methods are consistent with the conceptual guidance on uncertainties in Annex 1, Conceptual Basis for Uncertainty Analysis. They will enable countries to report on uncertainties in a consistent manner, and provide valuable input to national inventory research and development activities. The methods are capable of allowing for relationships in uncertainties between different inventory components, and are supplemented by an extensive set of default uncertainties developed through the sector workshops.

1.3 ROLE OF GOOD PRACTICE IN MANAGING UNCERTAINTIES

To be consistent with *good practice* as defined in this report, inventories should contain *neither over nor underestimates so far as can be judged*, and the uncertainties in these estimates should be *reduced as far as practicable*.

These requirements are to ensure that emissions estimates, even if uncertain, are bona fide estimates, in the sense of not containing any biases that could have been identified and eliminated, and that uncertainties have been minimised as far as practicable given national circumstances. Estimates of this type would presumably be the best attainable, given current scientific knowledge and available resources.

Good practice aims to deliver these requirements by providing guidance on:

- Choice of estimation method within the context of the *IPCC Guidelines*;
- Quality assurance and quality control procedures to provide cross-checks during inventory compilation;
- Data and information to be documented, archived and reported to facilitate review and assessment of emission estimates;
- Quantification of uncertainties at the source category level and for the inventory as a whole, so that the resources available for research can be directed toward reducing uncertainties over time, and the improvement can be tracked.

Chapters 2 to 5 set out *good practice guidance* on the choice of estimation method at the source category level by means of decision trees of the type illustrated in Figure 1.1, Example-Decision Tree for CH_4 Emissions from Solid Waste Disposal Sites. The decision trees formalise the choice of the estimation method most suited to national circumstances. The source category guidance linked to the decision trees also provides information on the choice of emission factors and activity data, and on the associated uncertainty ranges needed to support the uncertainty estimation procedures described in Chapter 6, Quantifying Uncertainties in Practice. The most appropriate choice of estimation method (or tier) will depend on national circumstances, including the availability of resources and can be determined according to the methods set out in Chapter 7, Methodological Choice and Recalculation.

Inventory development is a resource intensive enterprise which means firstly that inventory agencies may need to prioritise among source categories and estimation methods, and secondly that data quality may improve over time. Guidance applicable to all source categories is given in Chapter 7, regarding how to identify the *key source*

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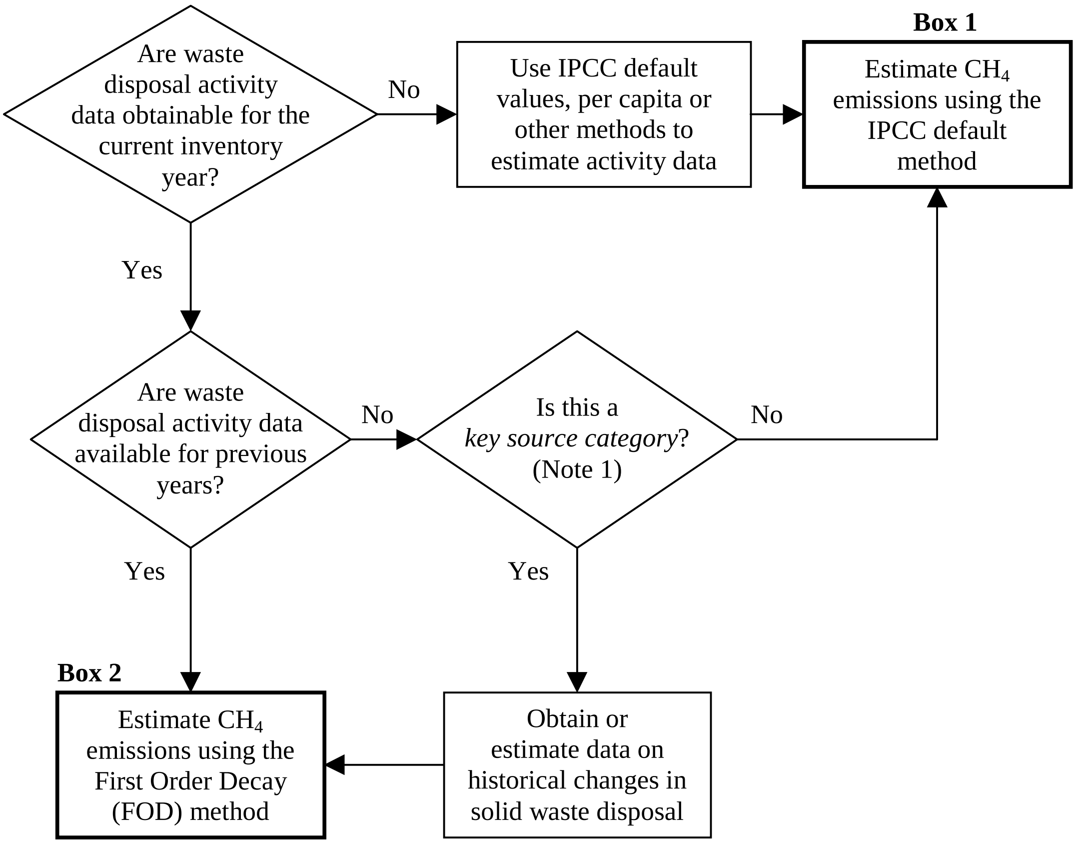
[3] Based on an analysis of the UK inventory presented to the Paris meeting (Eggleston *et al.*, 1998) and which is described in more detail in Chapter 6, Quantifying Uncertainties in Practice, Section 6.3.1, Comparison between Tiers and Choice of Method.

[4] See footnote 3

categories that should be prioritised in the inventory development process, as well as when and how to recalculate previously prepared emissions estimates to ensure consistent emission trends. A *key source category* is defined in Chapter 7, as one that has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions or the trend, or both. The outcome of the determination of the *key source category* analysis is taken into account during inventory preparation as indicated in the decision trees. Chapter 7, also addresses means to manage methodological changes and recalculations. For example, a change in a method may be due to the introduction of emissions' abatement technology, the availability of more detailed data, or the greater significance of a source category whose rapid variation over time substantially affects the trend in total emissions. Guidance is provided for splicing time series in those cases where changes in methods are consistent with *good practice*.

Good practice in quality assurance and quality control (QA/QC) procedures described in Chapter 8, Quality Assurance and Quality Control, covers measurement standards, routine computational and completeness checks, and documentation and data archiving procedures to be applied to the inventory at the compilation stage. Chapter 8, also describes a system of independent review and auditing that could be implemented by inventory agencies. QA/QC as defined here covers only actions that inventory agencies could take in respect of their own inventories. It does not include an international system of review, except insofar as the requirements for transparency would be common between an international review process and internal reviews conducted routinely by inventory agencies.

Figure 1.1 Example-Decision Tree for CH_4 Emissions from Solid Waste Disposal Sites



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Throughout this report, *good practice* refers to actions that could be undertaken by inventory agencies in producing their greenhouse gas inventories. However, the request from the SBSTA is not restricted to national actions, and in the Annexes the report reflects the broader picture, both scientifically and internationally.

Annex 1, Conceptual Basis for Uncertainty Analysis, deals with the concepts that underlie the practical advice on uncertainties provided in Chapters 2 to 8 of the main report. Annex 2, Verification, discusses international and scientific aspects of inventory verification. Annex 3, the Glossary, defines the terms of particular interest in the context of greenhouse gas inventories, and also summarises mathematical definitions of selected statistical terms for convenient reference.

1.4 POLICY RELEVANCE

The report on *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (Good Practice Report)* does not revise or replace the *IPCC Guidelines*, but provides a reference that complements and is consistent with these Guidelines. This is because the Conference of the Parties decided[5] that these *IPCC Guidelines* would be used for reporting by Parties included in Annex I to the UNFCCC. For the purposes of developing *good practice guidance*, consistency with the *IPCC Guidelines* is defined by three criteria:

(i) Specific source categories addressed by *good practice guidance* have the same definitions as the corresponding categories in the *IPCC Guidelines.*

(ii) *Good practice guidance* uses the same functional forms for the equations used to estimate emissions that are used in the *IPCC Guidelines.*

(iii) *Good practice guidance* allows correction of any errors or deficiencies[6] that have been identified in the *IPCC Guidelines*.

Criterion (i) does not exclude identification of additional source categories that may be included in the *Other* category in the *IPCC Guidelines*. Default emission factors or model parameter values have been updated where they can be linked to particular national circumstances and documented.

The main development in the negotiations since the SBSTA-8's request has been agreement on the revised reporting guidelines for Annex I Parties' greenhouse gas inventories.[7] These UNFCCC guidelines contain cross references to the IPCC's work on *good practice* concerning choice of methodology, emission factors, activity data, uncertainties, quality assessment and quality control procedures, time series consistency, accuracy and verification.

It is through *good practice guidance and uncertainty management* that a sound basis can be provided to produce more reliable estimates of the magnitude of absolute and trend uncertainties in greenhouse gas inventories than has been achieved previously. Whatever the level of complexity of the inventory, *good practice* provides improved understanding of how uncertainties may be managed to produce emissions estimates that are acceptable for the purposes of the UNFCCC, and for the scientific work associated with greenhouse gas inventories.

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[5] Decision 2/CP.3 and the document FCCC/CP/1999/7 referred to in decision 3/CP.5.

[6] For example, some of the equations in the *IPCC Guidelines* do not formally allow for emissions mitigation technologies or techniques.

[7] See Decision 3/CP.5.

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ENERGY

CO-CHAIRS, EDITORS AND EXPERTS

Co-chairs of the Expert Meeting on Emissions from Energy

Taka Hiraishi (Japan) and Buruhani Nyenzi (Tanzania)

REVIEW EDITOR

Marc Gillet (France)

AUTHORS OF GENERAL BACKGROUND PAPER

Jeroen Meijer (IEA) and Tinus Pullus (Netherlands)

Expert Group: CO_2 Emissions from Stationary Combustion

CO-CHAIRS

Tim Simmons (UK) and Milos Tichy (Czech Republic)

AUTHOR OF BACKGROUND PAPER

Tim Simmons (UK)

CONTRIBUTORS

Agus Cahyono Adi (Indonesia), Monika Chandra (USA), Sal Emmanuel (Australia), Jean-Pierre Fontelle (France), Pavel Fott (Czech Republic), Kari Gronfors (Finland), Dietmar Koch (Germany), Wilfred Kipondya (Tanzania), Sergio Lamotta (Italy), Elliott Lieberman (USA), Katarina Mareckova (IPCC/OECD), Roberto Acosta (UNFCCC secretariat), Newton Paciornik (Brazil), Tinus Pulles (Netherlands), Erik Rassmussen (Denmark), Sara Ribacke (Sweden), Bojan Rode (Slovenia), Arthur Rypinski (USA), Karen Treanton (IEA), and Stephane Willems (OECD)

Expert Group: Non-CO_2 Emissions from Stationary Combustion

CO-CHAIRS

Samir Amous (Tunisia) and Astrid Olsson (Sweden)

AUTHOR OF BACKGROUND PAPER

Samir Amous (Tunisia)

CONTRIBUTORS

Ijaz Hossain (Bangladesh), Dario Gomez (Argentina), Markvart Miroslav (Czech Republic), Jeroen Meijer (IEA), Michiro Oi (Japan), Uma Rajarathnam (India), Sami Tuhkanen (Finland), and Jim Zhang (USA)

Expert Group: Mobile Combustion: Road Transport

CO-CHAIRS

Michael Walsh (USA) and Samir Mowafy (Egypt)

AUTHOR OF BACKGROUND PAPER

Simon Eggleston (UK)

CONTRIBUTORS

Javier Hanna (Bolivia), Frank Neitzert (Canada), Anke Herold (Germany), Taka Hiraishi (Japan), Buruhani Nyenzi (Tanzania), Nejib Osman (Tunisia), Simon Eggleston (UK), David Greene (UK), Cindy Jacobs (USA), and Jean Brennan (USA)

Expert Group: Mobile Combustion: Water-borne Navigation

CHAIR

Wiley Barbour (USA)

AUTHORS OF BACKGROUND PAPER

Wiley Barbour, Michael Gillenwater, Paul Jun

CONTRIBUTORS

Leonnie Dobbie (Switzerland), Robert Falk (UK), Michael Gillenwater (USA), Robert Hoppaus (IPCC/OECD), Roberto Acosta (UNFCCC secretariat), Gilian Reynolds (UK), and Kristin Rypdal (Norway)

Expert Group: Mobile Combustion: Aviation

CHAIR

Kristin Rypdal (Norway)

AUTHOR OF BACKGROUND PAPER

Kristin Rypdal (Norway)

CONTRIBUTORS

Wiley Barbour (USA), Leonie Dobbie (IATA), Robert Falk (UK), Michael Gillenwater (USA), and Robert Hoppaus (IPCC/OECD)

Expert Group: Fugitive Emissions from Coal Mining and Handling

CO-CHAIRS

David Williams (Australia) and Oleg Tailakov (Russia)

AUTHORS OF BACKGROUND PAPER

William Irving (USA) and Oleg Tailakov (Russia)

CONTRIBUTORS

William Irving (USA) and Huang Shenchu (China)

Expert Group: Fugitive Emissions from Oil and Natural Gas Activities

CO-CHAIRS

David Picard (Canada) and Jose Domingos Miguez (Brazil)

AUTHOR OF BACKGROUND PAPER

David Picard (Canada)

CONTRIBUTORS

Marc Darras (France), Eilev Gjerald (Norway), Dina Kruger (USA), Robert Lott (USA), Katarina Mareckova (IPCC/OECD), Marc Phillips (USA), and Jan Spakman (Netherlands)

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2.1 CO_2 EMISSIONS FROM STATIONARY COMBUSTION

2.1.1 Methodological issues

Carbon dioxide (CO_2) emissions from stationary combustion result from the release of the carbon in fuel during combustion. CO_2 emissions depend on the carbon content of the fuel. During the combustion process, most carbon is emitted as CO_2 immediately. However, some carbon is released as carbon monoxide (CO), methane (CH_4) or non-methane volatile organic compounds (NMVOCs), all of which oxidise to CO_2 in the atmosphere within a period of a few days to about 12 years. The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines)* account for all the released carbon as CO_2 emissions. The other carbon-containing gases are also estimated and reported separately. The reasons for this intentional double counting are explained in the Overview of the *IPCC Guidelines.* Unoxidised carbon, in the form of particulate matter, soot or ash, is excluded from greenhouse gas emissions totals.

2.1.1.1 CHOICE OF METHOD

There are three methods provided in the *IPCC Guidelines,* Chapter 1, Energy: two Tier 1 approaches (the ‘Reference Approach’ and the ‘Sectoral Approach’) and the Tier 2/Tier 3 approach (a detailed technology-based method, also called ‘bottom-up’ approach).

The Reference Approach estimates CO_2 emissions from fuel combustion in several steps:

- Estimation of fossil fuel flow into the country (apparent consumption);
- Conversion to carbon units;
- Subtraction of the amount of carbon contained in long-lived materials manufactured from fuel carbon;
- Multiplication by an oxidation factor to discount the small amount of carbon that is not oxidised;
- Conversion to CO_2 and summation across all fuels.

For the Tier 1 Sectoral Approach, total CO_2 is summed across all fuels (excluding biomass) and all sectors. For Tiers 2 and 3, the Detailed Technology-Based Approach, total CO_2 is summed across all fuels and sectors, plus combustion technologies (e.g. stationary and mobile sources). Both approaches provide more disaggregated emission estimates, but also require more data.

The choice of method is country-specific and is determined by the level of detail of the activity data available as illustrated in Figure 2.1, Decision Tree for Selecting the Method for Estimation of CO_2 Emissions from Stationary Combustion. The ‘bottom-up’ approach is generally the most accurate for those countries whose energy consumption data are reasonably complete.[1] Consequently, inventory agencies should make every effort to use this method if data are available.

Although continuous monitoring is generally recommended because of its high accuracy, it cannot be justified for CO_2 alone because of its comparatively high costs and because it does not improve accuracy for CO_2. It could, however, be undertaken when monitors are installed for measurements of other pollutants such as SO_2 or NO_x where CO_2 is monitored as the diluent gas in the monitoring system.[2]

The Reference Approach provides only aggregate estimates of emissions by fuel type distinguishing between primary and secondary fuels, whereas the Sectoral Approach allocates these emissions by source category. The

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[1] If the gap between apparent consumption and reported consumption is small, then energy consumption data are probably reasonably complete.

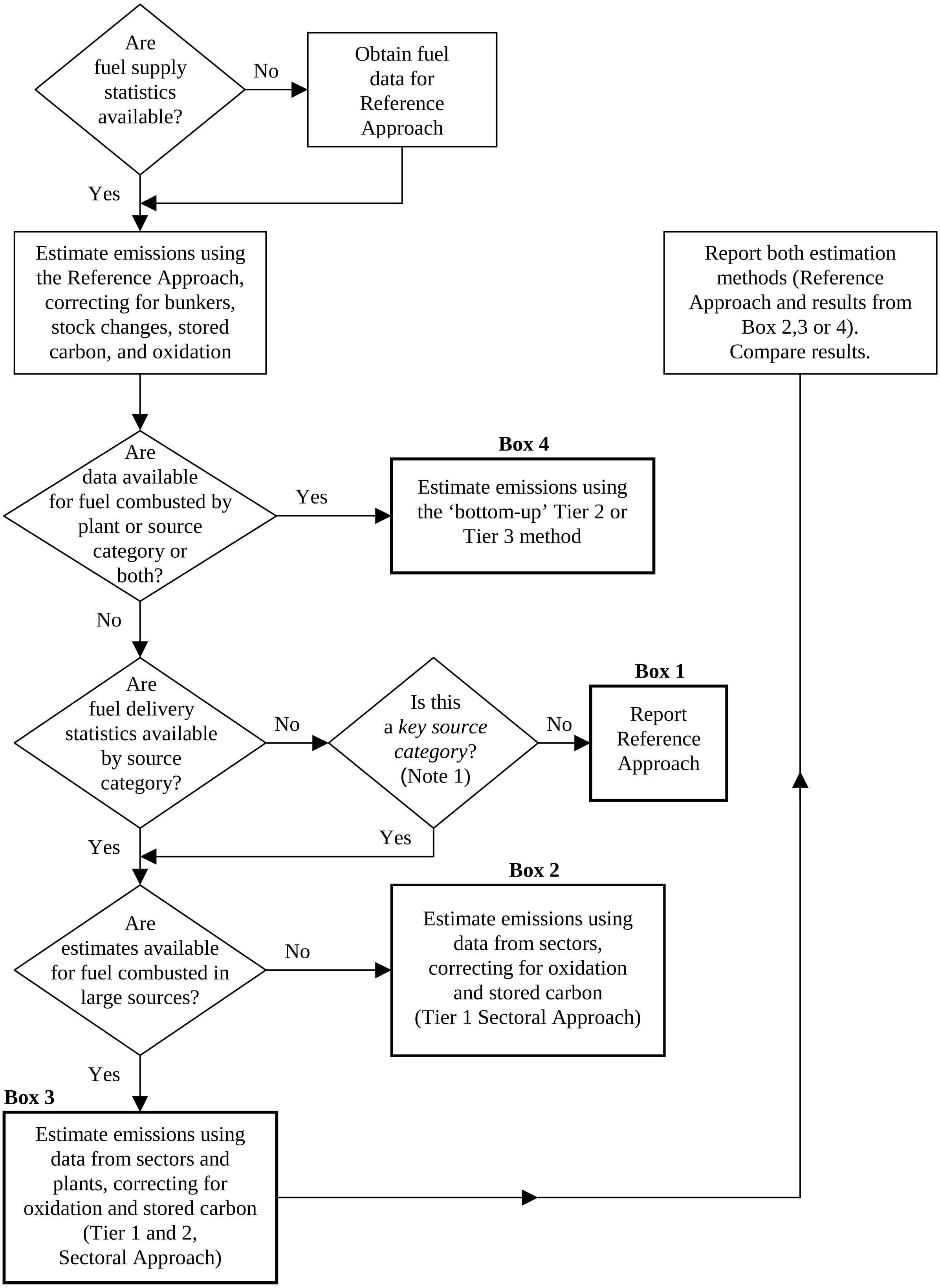
[2] If continuous emissions monitoring were used for certain industrial sources it would be difficult to differentiate emissions related to fuel combustion from emissions related to processing (e.g. cement kilns).

aggregate nature of the Reference Approach estimates means that stationary combustion emissions cannot be distinguished from mobile combustion emissions. Likewise, the Sectoral Approach is not always able to differentiate between different emission source categories within an economic activity (e.g. between use of gas or oil for heating or for off-road and other mobile machinery in the construction industry).

Estimates of emissions based on the Reference Approach will not be exactly the same as estimates based on the Sectoral Approach. The two approaches measure emissions at differing points and use slightly different definitions. However, the differences between the two approaches should not be significant.

For some countries, however, there may be large and systematic differences between estimates developed using the two approaches. This will normally indicate a systematic under or overcounting of energy consumption by one method or the other. If this occurs, it is *good practice* to consult with national statistical authorities and seek their advice on which method is the most complete and accurate indication of total consumption for each fuel, and use it.

Figure 2.1 Decision Tree for Selecting the Method for Estimation of CO_2 Emissions from Stationary Combustion



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

2.1.1.2 CHOICE OF EMISSION FACTORS AND CALORIFIC VALUES

CO_2 emission factors (EF) for fossil fuel combustion depend upon the carbon content of the fuel. The carbon content of a fuel is an inherent chemical property (i.e. fraction or mass of carbon atoms relative to total number of atoms or mass) and does not depend upon the combustion process or conditions. The energy content (i.e. calorific value or heating value) of fuels is also an inherent chemical property. However, calorific values vary more widely between and within fuel types, as they are dependent upon the composition of chemical bonds in the fuel. Net calorific values (NCVs) measure the quantity of heat liberated by the complete combustion of a unit volume or mass of a fuel, assuming that the water resulting from combustion remains as a vapour, and the heat of the vapour is not recovered. Gross calorific values, in contrast, are estimated assuming that this water vapour is completely condensed and the heat is recovered. Default data in the *IPCC Guidelines* are based on NCVs.

Emission factors for CO_2 from fossil fuel combustion are expressed on a per unit energy basis because the carbon content of fuels is generally less variable when expressed on a per unit energy basis than when expressed on a per unit mass basis. Therefore, NCVs are used to convert fuel consumption data on a per unit mass or volume basis to data on a per unit energy basis.

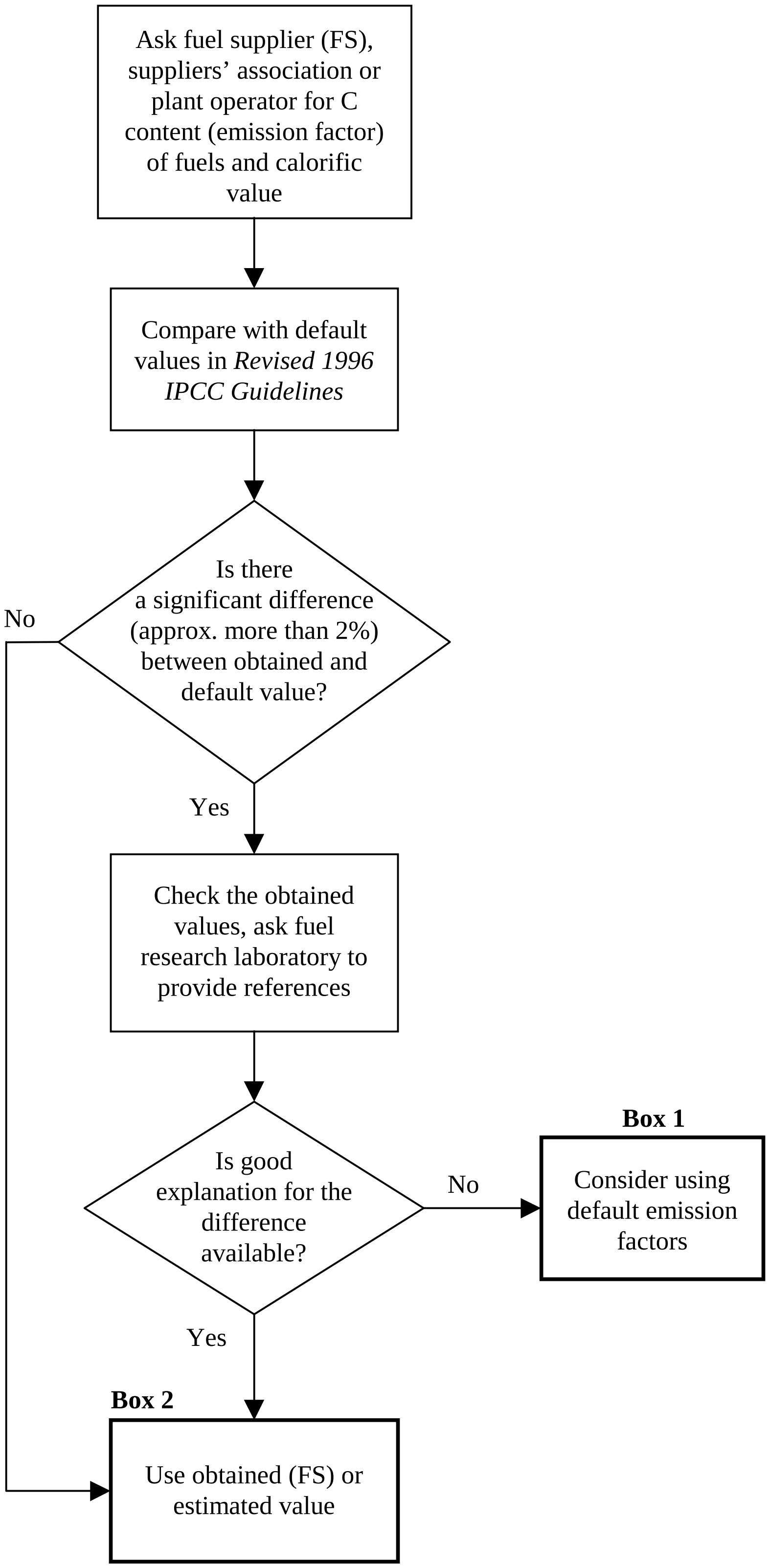
Carbon content values can be thought of as potential emissions, or the maximum amount of carbon that could potentially be released to the atmosphere if all carbon in the fuels were converted to CO_2. As combustion processes are not 100% efficient, though, some of the carbon contained in fuels is not emitted to the atmosphere. Rather, it remains behind as soot, particulate matter and ash. Therefore, an oxidation factor is used to account for the fraction of the potential carbon emissions remaining after combustion.

For traded fuels in common circulation, it is *good practice* to obtain the carbon content of the fuel and net calorific values from fuel suppliers, and use local values wherever possible. If these data are not available, default values can be used. Figure 2.2, Decision Tree for Selecting Calorific Values and Carbon Emission Factors illustrates the choice of emission factors.

It may be more difficult to obtain the carbon content and NCV for non-traded fuels, such as municipal solid waste (MSW) and for fuels that are not sold by heat content, such as crude oil. If necessary, default values are available. Values for MSW may be obtained by contacting operators of waste combustion plants for heat raising. The suggested default values for the NCV of municipal solid waste range from 9.5 to 10.5 GJ/t (based on information from Sweden and Denmark). The default carbon content of waste is given in Chapter 6, Waste of the *IPCC Guidelines*. For crude oil, information is available relating the carbon content to the density and the sulfur content of the crude oil (see Table 2.2, Typical API Gravities and Sulfur Contents for Various Crude Oil Streams and Table 2.3, Average API Gravity and Sulfur Content of Imported Crude Oil for Selected Countries Listed in Annex II of the UN Framework Convention on Climate Change). Information on NCVs for coal types in non-OECD countries is listed in Table 2.4, 1990 country-specific net calorific values. Default net calorific values for most other fuels are available in the Reference Manual of the *IPCC Guidelines* (Table 1-3, Net Calorific Values for Other Fuels).

Generally, default oxidation factors for gases and oils are known accurately. For coal, oxidation factors are dependent on the combustion conditions and can vary by several percent. It is *good practice* to discuss the factors with local users of coal and coal products. However, default factors are also provided in the *IPCC Guidelines*.

Figure 2.2 Decision Tree for Selecting Calorific Values and Carbon Emission Factors



2.1.1.3 CHOICE OF ACTIVITY DATA

Activity data for all tiers are the amount and type of fuel combusted. These data will often be available from national energy statistics agencies which collect them directly from the enterprises that consume the fuels or from individuals responsible for the combustion equipment. These data are also available from suppliers of fuels who record the quantities delivered and the identity of their customers usually as an economic activity code, or from a combination of these sources. Direct collection of fuel consumption data may occur through periodic surveys of a sample of enterprises, or, in the case of large combustion plants, through enterprise reports made to the national energy statistics agency or under emission control regulations. Fuel deliveries are well identified for gas, where metering is in place, and also for solid and liquid fuels, both of which are distributed to the household and the small commercial consumers market.

It is *good practice* to use fuel combustion statistics rather than delivery statistics where they are available.[3] Agencies collecting emission data from companies under an environmental reporting regulation could request fuel combustion data in this context. Fuel combustion data, however, are very seldom complete, since it is not practicable to measure the fuel consumption or emissions of every residential or commercial source. Hence, national inventories using this approach will generally contain a mixture of combustion data for larger sources and delivery data for other sources. The inventory agency must take care to avoid both double counting and omission of emissions when combining data from multiple sources.

Where confidentiality is an issue, direct discussion with the company affected often allows the data to be used. In cases where such permission is not given, aggregation of the fuel consumption or emissions with those from other companies is usually sufficient to conceal the identity of the company without understating emissions.

It is necessary to estimate the amount of carbon stored in products for the Reference Approach, and if no detailed calculation in the Industrial Processes sector is performed. It is *good practice* to obtain stored carbon factors by contacting the petrochemical industry that uses the feedstock. A list of fuels/products that accounts for the majority of carbon stored is given in the *IPCC Guidelines* together with default stored carbon factors. It should be used unless more detailed country-specific information is available. Where data are available for other fuels/ products, the estimation of stored carbon is strongly encouraged.[4] The default factor for stored carbon in lubricants may be overestimated because waste lubricants are often burned for energy. It is *good practice* to contact those responsible for recovering used oils in order to discover the extent to which used oils are burned in the country.

When using the Reference Approach, fuel supply statistics[5] should be used and there may be a choice of source for import and export data. Official customs figures or industry figures may be used. The compilers of national energy data will have made this choice based on their assessment of data quality when preparing national fuel balances. The choice may differ from fuel to fuel. Thus, it is *good practice* to consult with the national energy statistics agency when choosing between energy supply and delivery statistics in order to establish whether the criteria the agency has used in selecting the basis for import and export statistics of each fuel are appropriate for inventory use.

When activity data are not quantities of fuel combusted but instead deliveries to enterprises or main sub-categories, there is a risk of double counting emissions from the Industrial Processes, Solvents or Waste Sectors. Identifying double counting is not always easy. Fuels delivered and used in certain processes may give rise to by-products used as fuels elsewhere in the plant or sold for fuel use to third parties (e.g. blast furnace gas, derived from coke and other carbon inputs to blast furnaces). It is *good practice* to coordinate estimates between the stationary CO_2 source category and relevant industrial categories to avoid double counting or omissions. Appendix 2.1A.1 lists the categories and subcategories where fossil fuel carbon is reported, and between which double counting of fossil fuel carbon could, in principle, occur.

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[3] Quantities of solid and liquid fuels delivered to enterprises will, in general, differ from quantities combusted by the amounts put into or taken from stocks held by the enterprise. Stock figures shown in national fuel balances may not include stocks held by final consumers, or may include only stocks held by a particular source category (for example electricity producers). Delivery figures may also include quantities used for mobile sources or as feedstock.

[4] The Frauenhofer Institute in Germany is currently undertaking an examination of carbon flows through petrochemical industries in a number of countries. It is hoped that this work will result in better estimates of the fraction of petrochemical feedstock stored within the products manufactured. The study will be completed by mid-2000.

[5] These are national production of primary fuels, and imports, exports and stock changes of all fuels. Oils used for international bunkers are treated like exports and excluded from supply.

For some source categories (e.g. combustion in the Agriculture Sector), there may be some difficulty in separating fuel used in stationary equipment from fuel used in mobile machinery. Given the different emission factors for non-CO_2 gases of these two sources, *good practice* is to derive energy use of each of these sources by using indirect data (e.g. number of pumps, average consumption, needs for water pumping). Expert judgement and information available from other countries may also be relevant.

2.1.1.4 COMPLETENESS

A complete estimate of emissions from fuel combustion must include emissions from all fuels and all source categories identified within the *IPCC Guidelines*. A reliable and accurate bottom-up CO_2 emissions estimate is important because it increases confidence in the underlying activity data. These, in turn, are important underpinnings for the calculation of CH_4 and N_2O emissions from stationary sources.

All fuels delivered by fuel producers must be accounted for, so that sampling errors do not arise. Mis-classification of enterprises and the use of distributors to supply small commercial customers and households increase the chance of systematic errors in the allocation of fuel delivery statistics. Where sample survey data that provide figures for fuel consumption by specific economic sectors exist, the figures may be compared with the corresponding delivery data. Any systematic difference should be identified and the adjustment to the allocation of delivery data may then be made accordingly.

Systematic under-reporting of solid and liquid fuels may also occur if final consumers import fuels directly. Direct imports will be included in customs data and therefore in fuel supply statistics, but not in the statistics of fuel deliveries provided by national suppliers. If direct importing by consumers is significant, then the statistical difference between supplies and deliveries will reveal the magnitude. Once again, a comparison with consumption survey results will reveal which main source categories are involved with direct importing.

Experience has shown that the following activities may be poorly covered in existing inventories and their presence should be specifically checked:

- Change in producer stocks of fossil fuels;
- Combustion of waste for energy purposes. Waste incineration should be reported in the Waste source category, combustion of waste for energy purposes should be reported in the Energy source category;
- Energy industries' own fuel combustion;
- Conversion of petrochemical feedstocks into petrochemical products (carbon storage);
- Fuel combustion for international aviation and marine transport (needed for the Reference Approach). Sections 2.4.1.3 and 2.5.1.3 of this chapter provide more guidance on this subject.

The reporting of emissions from coke use in blast furnaces requires attention. Crude (or pig) iron is typically produced by the reduction of iron oxides ores in a blast furnace, using the carbon in coke (sometimes other reducing agents) as both the fuel and reducing agent. Since the primary purpose of coke oxidation is to produce pig iron, the emissions should be considered as coming from an industrial process if a detailed calculation of industrial emissions is being undertaken. It is important not to double-count the carbon from the consumption of coke or other fuels. So, if these emissions have been included in the Industrial Processes sector, they should not be included in the Energy sector. However, there are countries where industrial emissions are not addressed in detail. In these instances, the emissions should be included in the Energy sector. In any case, the amount of carbon that is stored in the final product should be subtracted from the effective emissions.

2.1.1.5 DEVELOPING A CONSISTENT TIME SERIES

It is *good practice* to prepare inventories using the method selected in Figure 2.1, Decision Tree for Selecting the Method for Estimation of CO_2 Emissions from Stationary Combustion for all years in the time series. Where this is difficult due to a change of methods or data over time, estimates for missing data in the time series should be prepared based on backward extrapolation of present data. When changing from a Reference Approach to a higher tier approach, inventory agencies should establish a clear relationship between the approaches and apply this to previous years if data are lacking. Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques, provides guidance on various approaches that can be used in this case.

2.1.1.6 UNCERTAINTY ASSESSMENT

ACTIVITY DATA

The information in this section can be used in conjunction with the methods outlined in Chapter 6, Quantifying Uncertainties in Practice, to assess overall uncertainties in the national inventory. Chapter 6 explains how to use empirical data and expert judgement to obtain country-specific uncertainty.

The accuracy in determining emission estimates using the Sectoral Approach is almost entirely determined by the availability of the delivery or combustion statistics for the main source categories. The main uncertainty arises from:

- The adequacy of the statistical coverage of all source categories;
- The adequacy of the coverage of all fuels (both traded and non-traded).

Statistics of fuel combusted at large sources obtained from direct measurement or obligatory reporting are likely to be within 3% of the central estimate.[6] For the energy intensive industries, combustion data are likely to be more accurate. It is *good practice* to estimate the uncertainties in fuel consumption for the main sub-categories in consultation with the sample survey designers because the uncertainties depend on the quality of the survey design and size of sample used.

In addition to any systematic bias in the activity data as a result of incomplete coverage of consumption of fuels, the activity data will be subject to random errors in the data collection that will vary from year to year. Countries with good data collection systems, including data quality control, may be expected to keep the random error in total recorded energy use to about 2-3% of the annual figure. This range reflects the implicit confidence limits on total energy demand seen in models using historical energy data and relating energy demand to economic factors. Percentage errors for individual energy use activities can be much larger.

Overall uncertainty in activity data is a combination of both systematic and random errors. Most developed countries prepare balances of fuel supply and deliveries and this provides a check on systematic errors. In these circumstances, overall systematic errors are likely to be small. Experts believe that uncertainty resulting from the two errors is probably in the range of ±5%. For countries with less well-developed energy data systems, this could be considerably larger, probably about ±10%. Informal activities may increase the uncertainty up to as much as 50% in some sectors for some countries. See Table 2.6, Level of Uncertainty Associated with Stationary Combustion Activity Data, for more detailed uncertainty estimates.

EMISSION FACTORS

The uncertainty associated with EFs and NCVs results from two main elements, viz. the accuracy with which the values are measured, and the variability in the source of supply of the fuel and quality of the sampling of available supplies. There are few mechanisms for systematic errors in the measurement of these properties. Consequently, the errors can be considered mainly random. For traded fuels, the uncertainty is likely to be less than 5%. For non-traded fuels, the uncertainty will be higher and will result mostly from variability in the fuel composition.

Default uncertainty ranges are not available for stored carbon factors or coal oxidation factors. It is evident, however, that consultation with consumers using the fuels as raw materials or for their non-fuel characteristics is essential for accurate estimations of stored carbon. Similarly, large coal users can provide information on the completeness of combustion in the types of equipment they are using.

2.1.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Section 8.10.1 of Chapter 8, Quality Assurance and Quality Control.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

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[6] The percentages cited in this section represent an informal polling of assembled experts aiming to approximate the 95% confidence interval around the central estimate.

Some examples of specific documentation and reporting which are relevant to this source category are provided below:

- The sources of the energy data used and observations on the completeness of the data set;
- The sources of the calorific values and the date they were last revised;
- The sources of emission factors and oxidation factors, the date of the last revision and any verification of the accuracy. If a carbon storage correction has been made, documentation should include the sources of the factor and how the figures for fuel deliveries have been obtained.

2.1.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8 and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of emission estimates using different approaches

The inventory agency should compare estimates of CO_2 emissions from fuel combustion prepared using the Sectoral Tier 1 and Tier 2 Approach with the Reference Approach, and account for any significant differences. In this comparative analysis, emissions from fuels other than by combustion, that are accounted for in other sections of a GHG inventory, should be subtracted from the Reference Approach (See Appendix 2.1A.1).

Activity data check

- The inventory agency should construct national energy balances expressed in mass units, and mass balances of fuel conversion industries. The time series of statistical differences should be checked for systematic effects (indicated by the differences persistently having the same sign) and these effects eliminated where possible. This task should be done by, or in cooperation with, the national agency in charge of energy statistics.
- The inventory agency should also construct national energy balances expressed in energy units and energy balances of fuel conversion industries. The time series of statistical differences should be checked, and the calorific values cross-checked with IEA values (see Figure 2.2, Decision Tree for Selecting Calorific Values and Carbon Emission Factors). This step will only be of value where different calorific values for a particular fuel (for example, coal) are applied to different headings in the balance (such as production, imports, coke ovens and households). Statistical differences that change in magnitude or sign significantly from the corresponding mass values provide evidence of incorrect calorific values.
- The inventory agency should confirm that gross carbon supply in the Reference Approach has been adjusted for fossil fuel carbon from imported or exported non-fuel materials in countries where this is expected to be significant.
- Energy statistics should be compared with those provided to international organisations to identify inconsistencies.
- There may be routine collections of emissions and fuel combustion statistics at large combustion plants for pollution legislation purposes. If possible, the inventory agency can use these plant-level data to cross-check national energy statistics for representativeness.

Emission factors check

- The inventory agency should construct national energy balances expressed in carbon units and carbon balances of fuel conversion industries. The time series of statistical differences should be checked. Statistical differences that change in magnitude or sign significantly from the corresponding mass values provide evidence of incorrect carbon content.

- Monitoring systems at large combustion plants may be used to check the emission and oxidation factors in use at the plant.

Evaluation of direct measurements

- The inventory agency should evaluate the quality control associated with facility-level fuel measurements that have been used to calculate site-specific emission and oxidation factors. If it is established that there is insufficient quality control associated with the measurements and analysis used to derive the factor, continued use of the factor may be questioned.

Appendix 2.1A.1 Reporting of emissions of fossil carbon-based molecules according to the *Revised 1996 IPCC Guidelines* source categories

The following table shows where fossil carbon is accounted for and may be used to help identify and eliminate double counting as discussed in Section 2.1.1.3. It may also help explain any difference between the Reference Approach and Sectoral Approach calculations.

TABLE 2.1

REPORTING OF EMISSIONS OF FOSSIL CARBON-CONTAINING MOLECULES ACCORDING TO THE *REVISED* 1996 IPCC *GUIDELINES* SOURCE CATEGORIES[7]

From fossil fuel carbon	From other fossil carbon
1A Fuel combustion	
All fossil carbon for combustion purposes	
1B Fugitive emissions	
Escapes and releases from fossil carbon flows from extraction point through to final oxidation	
2 Industrial Processes	**2 Industrial Processes**
Ammonia	Cement
Silicon carbide	Lime production
Calcium carbide	Limestone use
Soda ash production, Solvay process (emissions from calcining)	Soda ash production (natural process)
Iron/steel and ferroalloys	Soda ash use
Aluminium	
Other metals (see *IPCC Guidelines* Reference Manual, Table 2-21, Production Processes for Some Metals)	
Production and use of halocarbons	
Organic chemical manufacture	
Asphalt manufacture and use	
Adipic acid	
3 Solvents	
6 Waste	
Short-life wastes comprising used oils, used solvents and plastics	
Long-life wastes comprising plastics entering heat raising and incineration and degradation in landfills (*products manufactured before the inventory year)*	

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[7] Numbers before source categories correspond to the numbering system of the *Revised 1996 IPCC Guidelines*, Reporting Instructions, Common Reporting Framework.

Appendix 2.1A.2 Method to estimate carbon content based on API[8] gravity and sulfur content

The following formula is based on the analyses of 182 crude oil samples and may be used to estimate the carbon content of crude oil. (Source: USDOE/EIA. URL: http://www.eia.doe.gov/oiaf/1605/gg98rpt/appendixb.html)

EQUATION 2.1

$$\text{Carbon Content} = 76.99 + (10.19 \bullet SG) - (0.76 \bullet \text{Sulfur Content})$$

Where:

SG denotes the specific gravity of the oil

Carbon and Sulfur content are measured in percent by weight

Specific Gravity may be calculated from the API gravity figure using:

EQUATION 2.2

$$SG = 141.5 / (API + 131.5)$$

Inferred carbon content is calculated based on the specific gravities and the API values in the first 2 columns of the following table using the above formula. Note that inferred values may differ from measured values.

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[8] API: Arbitrary scale designating an oil's specific gravity, or the ratio of the weights of equal volumes of oil and pure water; it is the standard specific gravity scale of the petroleum industry. As volume is dependent on temperature and pressure, these must be specified. In the United States they are generally 60 degrees F (16 degrees C) and one atmosphere (101.3 kPa) pressure. The API gravity scale, whose units are degrees API, does not vary linearly with the specific gravity or its related properties (e.g. viscosity), high specific gravity values give low API gravity values using the relationship

degrees API = (141.5 / specific gravity at 60 degrees F) – 131.5

Water with a specific gravity of 1 has an API gravity of 10 degrees. The API scale has the advantage of allowing hydrometers, which measure specific gravity, to be calibrated linearly. The Baumé scale, originally developed by Antoine Baumé for this purpose, was found to be in error and the API scale replaced it in 1921. The Baumé scale, still used in parts of Europe, is given by the relationship

degrees Baumé = (140 / specific gravity at 60 degrees F) – 130.

Source: adapted from Encyclopaedia Britannica.

TABLE 2.2
TYPICAL API GRAVITY AND SULFUR CONTENT FOR VARIOUS CRUDE OIL STREAMS

	Crude Category	Typical API Gravity		Typical Sulfur Content (% wt)		Inferred Carbon Content (% wt)	
		mean or lower value	upper value	mean or lower value	upper value	mean or lower value	upper value
Middle East							
Abu Dhabi	Murban	39.8		0.8		84.8	
	Umm Shaif	37.5		1.4		84.5	
	Upper Zakum	34		1.8		84.3	
	Lower Zakum	40		1.1		84.6	
	Other Abu Dhabi	46.7		0.8		84.5	
Dubai	Dubai	31	32	1.9		84.4	84.4
Sharjah		62.5		0.1		84.3	
Iran	Iranian Light	34		1.4		84.6	
	Iranian Heavy	31		1.6		84.6	
	Other Iran	32.6		2.1		84.2	
Iraq	Basrah Light	34		2.1		84.1	
	Kirkuk	36		2		84.1	
	Other Iraq	36.1		2		84.1	
Kuwait	Kuwait Blend	30	31	2.5		84.0	84.0
Neutral Zone	Offshore (Khafji/Hout)	28	33	1.9	2.9	83.6	84.6
	Onshore	23	25	3.3	3.9	83.2	83.8
Oman	Oman	34		0.8		85.1	
Qatar	Qatar Marine	36		1.5		84.5	
	Qatar Land	41		1.2		84.4	
Saudi Arabia	Arab Light	33	34	1.7		84.4	84.5
	Arab Medium	30	31.5	2.3		84.1	84.2
	Arab Heavy	27	28	2.8		83.9	84.0
	Berri (Extra Light)	37	38	1.1	1.2	84.6	84.7
	Other Saudi Arabia	52.3		0.7		84.3	
Syria	Syria Light	36		0.6		85.1	
	Souedie	24		3.9		83.3	
Yemen	Marib Light	40		0.1		85.3	
	Masila Blend	30	31	0.6		85.4	85.5
	Other Yemen	41		0.4		85.0	

TABLE 2.2 (CONTINUED)

TYPICAL API GRAVITY AND SULFUR CONTENT FOR VARIOUS CRUDE OIL STREAMS

	Crude Category	Typical API Gravity		Typical Sulfur Content (% wt)		Inferred Carbon Content (% wt)	
		mean or lower value	upper value	mean or lower value	upper value	mean or lower value	upper value
Other Middle East		31.7		2.1		84.2	
Africa							
Algeria	Saharan Blend	44		0.1		85.1	
	Other Algeria	45.1		0.1		85.1	
Cameroon		32		0.15		85.7	
Congo		37.4		0.1		85.5	
Egypt	Medium/Light (30-40^o)	31.1		1.9		84.4	
	Heavy (<30^o API)	27.9		2.1		84.4	
Gabon	Rabi/Rabi Kounga	34		0.1		85.6	
	Other Gabon	32.1		0.6		85.3	
Libya	Light (>40^o API)	41.7		0.2		85.2	
	Medium (30-40^o API)	37.2		0.3		85.3	
	Heavy (<30^o API)	26.2		1.7		84.8	
Nigeria	Medium (<33^o API)	29.6		0.2		85.8	
	Light (33-45^o API)	36.3		0.2		85.4	
	Condensate (>45^o API)	46.1		0.1		85.0	
Tunisia		36.1		0.6		85.1	
Zaire		31		0.2		85.7	
Other Africa		29.7		0.2		85.8	
Asia							
Brunei	Seria Light	36		0.1		85.5	
	Champion	25		0.1		86.1	
China	Daqing (Taching)	33		0.1		85.7	
	Shengli	24		1		85.5	
	Other China	32		0.2		85.7	
Indonesia	Minas	34		0.1		85.6	
	Cinta	33		0.1		85.7	
	Handil	33		0.1		85.7	
	Duri	20		0.2		86.4	
	Arun Condensate	54		0.02		84.7	
	Other Indonesia	38		0.1		85.4	
Malaysia	Tapis	44		0.1		85.1	
	Labuan	33		0.1		85.7	
	Other Malaysia	38.9		0.1		85.4	

TABLE 2.2 (CONTINUED)

TYPICAL API GRAVITY AND SULFUR CONTENT FOR VARIOUS CRUDE OIL STREAMS

	Crude Category	Typical API Gravity		Typical Sulfur Content (% wt)		Inferred Carbon Content (% wt)	
		mean or lower value	upper value	mean or lower value	upper value	mean or lower value	upper value
Other Asia		52.6		0.04		84.8	
Australia	Gippsland	45		0.1		85.1	
	Other Australia	41.1		0.1		85.3	
Papua New Guinea		44.3		0.04		85.2	
Russia	Urals	31	32.5	1.2	1.4	84.7	85.0
	Other Russia	33.3		1.2		84.8	
Azerbaijan		47.7		0.01		85.0	
Kazakhstan		46.5		0.5		84.7	
Ukraine		40.1		0.9		84.7	
Other FSU		44.6		0.2		85.0	
Europe							
Denmark		33	34.5	0.3		85.4	85.5
Norway	Statfjord	37.5	38	0.28		85.3	85.3
	Gullfaks	29.3	29.8	0.44		85.6	85.6
	Oseberg	34		0.3		85.5	
	Ekofisk	43.4		0.14		85.1	
	Other Norway	32.3		0.3		85.6	
United Kingdom	Brent Blend	37	38	0.4		85.2	85.2
	Forties	39	40	0.34		85.1	85.2
	Flotta	34.7		1		84.9	
	Other UK	31.8		0.5		85.4	
Other Europe		35.9		1.3		84.6	
North America							
Canada	Light Sweet (>30^o API)	36.6		0.2		85.4	
	Heavy (<30^o API)	23.4		not available			
United States	Alaska	30.2		1.1		85.1	
	Other United States	39.5		0.2		85.3	

TABLE 2.2 (CONTINUED)

TYPICAL API GRAVITY AND SULFUR CONTENT FOR VARIOUS CRUDE OIL STREAMS

	Crude Category	**Typical API Gravity**		**Typical Sulfur Content (% wt)**		**Inferred Carbon Content (% wt)**	
		mean or lower value	**upper value**	**mean or lower value**	**upper value**	**mean or lower value**	**upper value**
Latin America							
Brazil		20.7		0.5		86.1	
Colombia	Cano Limon	30		0.5		85.5	
	Other Colombia	35.8		not available			
Ecuador	Oriente	28	29	0.9	1.0	85.2	85.3
	Other Ecuador	not available		not available			
Mexico	Maya	22.2		3.3		83.9	
	Isthmus	34.8		1.5		84.5	
	Olmeca	39.8		0.8		84.8	
Peru		20.2		1.3		85.5	
Venezuela	Light (>30^o API)	32.6		1.1		84.9	
	Medium (22-30^o API)	27.7		1.6		84.8	
	Heavy (17-22^o API)	19.5		2.5		84.6	
	Extra Heavy (<17^o API)	14.5		2.8		84.7	

Source for API gravity and sulfur content: International Energy Agency.

TABLE 2.3

AVERAGE API GRAVITY AND SULFUR CONTENT OF IMPORTED CRUDE OIL FOR SELECTED COUNTRIES LISTED IN ANNEX II OF THE UN FRAMEWORK CONVENTION ON CLIMATE CHANGE

	Average API Gravity	**Average Sulfur (% weight)**	**Inferred Carbon Content (% weight)**
Australia	39.9	0.34	85.1
Austria	37.4	0.84	84.9
Belgium	32.8	1.25	84.8
Canada	32.4	0.90	85.1
Denmark	40.9	0.22	85.2
Finland	35.8	0.54	85.2
France	35.8	1.01	84.8
Germany	36.5	0.76	85.0
Greece	33.9	1.65	84.5
Ireland	36.9	0.25	85.4
Italy	34.1	1.15	84.8
Japan	34.8	1.51	84.5
Netherlands	33.3	1.45	84.6
New Zealand	34.4	1.01	84.9
Norway	33.3	0.39	85.4
Portugal	33.2	1.39	84.7
Spain	31.5	1.36	84.8
Sweden	34.5	0.76	85.1
Switzerland	39.4	0.46	85.1
Turkey	34.2	1.48	84.6
United Kingdom	35.9	0.64	85.1
United States	30.3	not available	

Average API gravity and sulfur content has been calculated from imports into the above countries in 1998. Values will change over time due to changes in crude streams that are imported. Any domestic crude oil consumed in the country would also need to be taken into account.

Source for API gravity and sulfur content: International Energy Agency.

Appendix 2.1A.3
1990[a] country-specific net calorific values

The following table is an update from the table supplied in the *Revised 1996 IPCC Guidelines*. It contains more disaggregated information on coal. Some values have been revised by the International Energy Agency.

TABLE 2.4

1990[a] COUNTRY-SPECIFIC NET CALORIFIC VALUES[b]

(Terajoule per kilotonne)	Albania	Algeria	Angola Cabinda	Argentina	Armenia	Australia	Austria	Azer-baijan	Bahrain	Bangla-desh	Belarus
OIL											
Crude Oil	41.45	43.29	42.75	42.29	-	43.21	42.75	42.08	42.71	42.16	42.08
NGL	-	43.29	-	42.50	-	45.22	45.22	41.91	42.71	42.71	-
Refinery Feedst.	-	-	-	-	-	42.50	42.50	-	-	-	-
COAL											
Coking Coal											
Production	-	25.75	-	-	-	28.34	-	-	-	-	-
Imports	27.21	25.75	-	30.14	-	-	28.00	-	-	-	-
Exports	-	-	-	-	-	28.21	-	-	-	-	-
Other Bituminous Coal and Anthracite[c]											
Production	-	-	-	24.70	-	24.39	-	-	-	-	-
Imports	27.21	-	-	-	18.58	-	28.00	18.58	-	20.93	25.54
Exports	-	-	-	24.70	-	25.65	-	-	-	-	25.54
Sub-Bituminous Coal											
Production	-	-	-	-	-	17.87	-	-	-	-	-
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-	-
Lignite											
Production	9.84	-	-	-	-	9.31	10.90	-	-	-	-
Imports	-	-	-	-	-	-	10.90	-	-	-	-
Exports	9.84	-	-	-	-	-	10.90	-	-	-	-
Coal Products											
Patent Fuel	-	-	-	-	-	-	-	-	-	-	-
BKB	-	-	-	-	-	21.00	19.30	-	-	-	8.37
Coke Oven Coke	27.21	27.21	-	28.46	-	25.65	28.20	-	-	-	25.12
Gas Coke	-	-	-	-	-	-	-	-	-	-	-

[a] For the former Soviet and Yugoslav Republics, 1996 numbers have been used.

[b] The NCVs are those used by the IEA in the construction of energy balances.

[c] In IEA statistics, Anthracite is combined with Other Bituminous Coal – the NCVs given above reflect this combination.

Source: Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries.

OECD/IEA, Paris, 1998.

TABLE 2.4 (CONTINUED)

1990[a] COUNTRY-SPECIFIC NET CALORIFIC VALUES[b]

(Terajoule per kilotonne)	Belgium	Benin	Bolivia	Bosnia-Herzegovina	Brazil	Brunei	Bulgaria	Cameroon	Canada	Chile	China
OIL											
Crude Oil	42.75	42.58	43.33	-	45.64	42.75	42.62	42.45	42.79	42.91	42.62
NGL	-	-	43.33	-	45.22	42.75	-	-	45.22	42.87	-
Refinery Feedst.	42.50	-	-	-	-	41.87	-	-	-	-	-
COAL											
Coking Coal											
Production	-	-	-	-	26.42	-	-	-	28.78	-	20.52
Imports	29.31	-	-	-	30.69	-	24.70	-	27.55	28.43	20.52
Exports	-	-	-	-	-	-	-	-	28.78	-	20.52
Other Bituminous Coal and Anthracite [c]											
Production	25.00	-	-	-	15.99	-	24.70	-	28.78	28.43	20.52
Imports	25.00	-	-	-	-	-	24.70	-	27.55	28.43	20.52
Exports	25.00	-	-	-	-	-	-	-	28.78	-	20.52
Sub-Bituminous Coal											
Production	18.10	-	-	-	-	-	-	-	17.38	-	-
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	18.20	-	-	-	-	-	-	-	-	-	-
Lignite											
Production	-	-	-	8.89	-	-	7.03	-	14.25	17.17	-
Imports	21.56	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	14.25	-	-
Coal Products											
Patent Fuel	29.31	-	-	-	-	-	-	-	-	-	-
BKB	20.10	-	-	-	-	-	20.10	-	-	-	-
Coke Oven Coke	29.31	-	-	-	30.56	-	27.21	-	27.39	28.43	28.47
Gas Coke	-	-	-	-	-	-	-	-	-	-	-

[a] For the former Soviet and Yugoslav Republics, 1996 numbers have been used.

[b] The NCVs are those used by the IEA in the construction of energy balances.

[c] In IEA statistics, Anthracite is combined with Other Bituminous Coal – the NCVs given above reflect this combination.

Source: Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries.

OECD/IEA, Paris, 1998.

TABLE 2.4 (CONTINUED)
1990[a] COUNTRY-SPECIFIC NET CALORIFIC VALUES[b]

(Terajoule per kilotonne)	Colombia	Congo	Costa Rica	Croatia	Cuba	Cyprus	Czech Republic	Democratic Republic of Congo	Denmark	Dominican Republic
OIL										
Crude Oil	42.24	42.91	42.16	42.75	41.16	42.48	41.78	42.16	42.71	42.16
NGL	41.87	-	-	45.22	-	-	-	-	-	-
Refinery Feedst.	-	-	-	-	-	-	-	-	42.50	-
COAL										
Coking Coal										
Production	27.21	-	-	-	-	-	24.40	-	-	-
Imports	-	-	-	-	-	-	-	-	-	-
Exports	27.21	-	-	-	-	-	27.46	-	-	-
Other Bituminous Coal and Anthracite[c]										
Production	27.21	-	-	25.12	-	-	18.19	25.23	-	-
Imports	-	-	25.75	29.31	25.75	25.75	18.19	25.23	26.09	25.75
Exports	27.21	-	-	-	-	-	18.19	-	26.09	-
Sub-Bituminous Coal										
Production	-	-	-	-	-	-	12.29	-	-	-
Imports	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	21.28	-	-	-
Lignite										
Production	-	-	-	-	-	-	12.29	-	-	-
Imports	-	-	-	14.60	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-
Coal Products										
Patent Fuel	-	-	-	-	-	-	-	29.31	-	-
BKB	-	-	-	-	-	-	21.28	-	18.27	-
Coke Oven Coke	20.10	-	27.21	29.31	27.21	-	27.01	27.21	31.84	-
Gas Coke	-	-	-	-	-	-	-	-	-	-

[a] For the former Soviet and Yugoslav Republics, 1996 numbers have been used.

[b] The NCVs are those used by the IEA in the construction of energy balances.

[c] In IEA statistics, Anthracite is combined with Other Bituminous Coal – the NCVs given above reflect this combination.

Source: Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries.
OECD/IEA, Paris, 1998.

TABLE 2.4 (CONTINUED)

1990[a] COUNTRY-SPECIFIC NET CALORIFIC VALUES[b]

(Terajoule per kilotonne)	DPR of Korea	Ecuador	Egypt	El Salvador	Estonia	Ethiopia	Federal Republic of Yugoslavia	Finland	FYR of Macedonia	Former Yugoslavia	France
OIL											
Crude Oil	42.16	41.87	42.54	42.16	-	42.62	42.75	44.03	42.75	42.75	42.75
NGL	-	42.45	42.54	-	-	-	-	-	-	-	45.22
Refinery Feedst.	-	-	-	-	-	-	-	42.50	-	-	42.50
COAL											
Coking Coal											
Production	25.75	-	-	-	-	-	-	-	-	-	28.91
Imports	25.75	-	25.75	-	-	-	-	26.38	30.69	30.69	30.50
Exports	-	-	-	-	-	-	-	-	30.13	-	-
Other Bituminous Coal and Anthracite [c]											
Production	25.75	-	-	-	-	-	23.55	-	-	23.55	26.71
Imports	-	-	25.75	-	18.58	-	30.69	26.38	30.69	-	25.52
Exports	25.75	-	-	-	18.58	-	-	-	-	-	26.43
Sub-Bituminous Coal											
Production	17.58	-	-	-	-	-	-	-	-	-	-
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-	-
Lignite											
Production	-	-	-	-	9.44	-	8.89	-	8.89	8.89	17.94
Imports	-	-	-	-	9.44	-	-	-	16.91	16.91	17.94
Exports	-	-	-	-	9.44	-	-	-	16.90	16.90	-
Coal Products											
Patent Fuel	-	-	-	-	-	-	-	-	-	-	30.07
BKB	-	-	-	-	8.37	-	-	-	-	20.10	20.10
Coke Oven Coke	27.21	-	27.21	-	25.12	-	-	28.89	-	26.90	28.71
Gas Coke	-	-	-	-	-	-	-	-	-	-	-

[a] For the former Soviet and Yugoslav Republics, 1996 numbers have been used.

[b] The NCVs are those used by the IEA in the construction of energy balances.

[c] In IEA statistics, Anthracite is combined with Other Bituminous Coal – the NCVs given above reflect this combination.

Source: Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries.
OECD/IEA, Paris, 1998.

TABLE 2.4 (CONTINUED)

1990[a] COUNTRY-SPECIFIC NET CALORIFIC VALUES[b]

(Terajoule per kilotonne)	Gabon	Georgia	Germany	Ghana	Greece	Guatemala	Haiti	Honduras	Hong Kong, China	Hungary	Iceland
OIL											
Crude Oil	42.62	42.08	42.75	42.62	42.75	42.45	-	42.16	-	41.00	-
NGL	-	-	-	-	45.22	-	-	-	-	45.18	-
Refinery Feedst.	-	-	42.50	-	42.50	-	-	-	-	42.08	-
COAL											
Coking Coal											
Production	-	-	28.96	-	-	-	-	-	-	29.61	-
Imports	-	-	28.96	-	-	-	-	-	-	30.76	29.01
Exports	-	-	28.96	-	-	-	-	-	-	-	-
Other Bituminous Coal and Anthracite [c]											
Production	-	18.58	24.96	-	-	-	-	-	-	13.15	-
Imports	-	18.58	26.52	25.75	27.21	-	25.75	-	25.75	21.50	29.01
Exports	-	18.58	31.71	-	-	-	-	-	-	20.15	-
Sub-Bituminous Coal											
Production	-	-	-	-	-	-	-	-	-	-	-
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-	-
Lignite											
Production	-	-	8.41	-	5.74	-	-	-	-	9.17	-
Imports	-	-	14.88	-	-	-	-	-	-	15.46	-
Exports	-	-	8.40	-	-	-	-	-	-	-	-
Coal Products											
Patent Fuel	-	-	31.40	-	-	-	-	-	-	16.80	-
BKB	-	-	20.58	-	15.28	-	-	-	-	21.23	-
Coke Oven Coke	-	-	28.65	-	29.30	-	-	27.21	27.21	27.13	26.65
Gas Coke	-	-	-	-	-	-	-	-	-	-	-

[a] For the former Soviet and Yugoslav Republics, 1996 numbers have been used.

[b] The NCVs are those used by the IEA in the construction of energy balances.

[c] In IEA statistics, Anthracite is combined with Other Bituminous Coal – the NCVs given above reflect this combination.

Source: Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries.

OECD/IEA, Paris, 1998.

TABLE 2.4 (CONTINUED)

1990[a] COUNTRY-SPECIFIC NET CALORIFIC VALUES[b]

(Terajoule per kilotonne)	India	Indonesia	Iran	Iraq	Ireland	Israel	Italy	Ivory Coast	Jamaica	Japan	Jordan
OIL											
Crude Oil	42.79	42.66	42.66	42.83	42.83	42.54	42.75	42.62	42.16	42.62	42.58
NGL	43.00	42.77	42.54	42.83	-	-	45.22	-	-	46.05	-
Refinery Feedst.	-	-	-	-	42.50	-	42.50	-	-	42.50	-
COAL											
Coking Coal											
Production	19.98	-	25.75	-	-	-	-	-	-	30.63	-
Imports	25.75	-	25.75	-	29.10	-	30.97	-	-	30.23	-
Exports	-	-	-	-	-	-	-	-	-	-	-
Other Bituminous Coal and Anthracite[c]											
Production	19.98	25.75	25.75	-	26.13	-	26.16	-	-	23.07	-
Imports	25.75	25.75	-	-	29.98	26.63	26.16	-	25.75	24.66	-
Exports	19.98	25.75	-	-	26.13	-	-	-	-	-	-
Sub-Bituminous Coal											
Production	-	-	-	-	-	-	-	-	-	-	-
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-	-
Lignite											
Production	9.80	-	-	-	-	4.19	10.47	-	-	-	-
Imports	-	-	-	-	19.82	-	10.47	-	-	-	-
Exports	-	-	-	-	19.82	-	-	-	-	-	-
Coal Products											
Patent Fuel	-	-	-	-	-	-	-	-	-	27.05	-
BKB	20.10	-	-	-	20.98	-	-	-	-	-	-
Coke Oven Coke	27.21	27.21	27.21	-	32.66	-	29.30	-	-	28.64	-
Gas Coke	-	-	-	-	-	-	-	-	-	28.64	-

[a] For the former Soviet and Yugoslav Republics, 1996 numbers have been used.

[b] The NCVs are those used by the IEA in the construction of energy balances.

[c] In IEA statistics, Anthracite is combined with Other Bituminous Coal – the NCVs given above reflect this combination.

Source: Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries.
OECD/IEA, Paris, 1998.

TABLE 2.4 (CONTINUED)

1990[a] COUNTRY-SPECIFIC NET CALORIFIC VALUES[b]

(Terajoule per kilotonne)	Kazakhstan	Kenya	Korea	Kuwait	Kyrgyzstan	Latvia	Lebanon	Libya	Lithuania	Luxembourg	Malaysia
OIL											
Crude Oil	42.08	42.08	42.71	42.54	42.08	-	42.16	43.00	42.08	-	42.71
NGL	41.91	-	-	42.62	-	-	-	43.00	-	-	43.12
Refinery Feedst.	-	-	-	-	-	-	-	-	44.80	-	42.54
COAL											
Coking Coal											
Production	18.58	-	-	-	-	-	-	-	-	-	-
Imports	18.58	-	27.21	-	-	-	-	-	-	-	-
Exports	18.58	-	-	-	-	-	-	-	-	-	-
Other Bituminous Coal and Anthracite[c]											
Production	18.58	-	19.26	-	18.58	-	-	-	-	-	25.75
Imports	18.58	25.75	27.21	-	18.58	18.58	-	-	18.59	29.30	25.75
Exports	18.58	-	-	-	18.58	25.12	-	-	18.59	-	25.75
Sub-Bituminous Coal											
Production	-	-	-	-	-	-	-	-	-	-	-
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-	-
Lignite											
Production	14.65	-	-	-	14.65	-	-	-	-	-	-
Imports	18.58	-	-	-	14.65	-	-	-	-	20.03	-
Exports	18.58	-	-	-	-	-	-	-	-	-	-
Coal Products											
Patent Fuel	-	-	-	-	-	-	-	-	-	-	-
BKB	-	-	-	-	-	8.37	-	-	8.37	20.10	-
Coke Oven Coke	25.12	-	27.21	-	-	25.12	-	-	-	28.50	27.21
Gas Coke	-	-	-	-	-	-	-	-	-	-	-

[a] For the former Soviet and Yugoslav Republics, 1996 numbers have been used.

[b] The NCVs are those used by the IEA in the construction of energy balances.

[c] In IEA statistics, Anthracite is combined with Other Bituminous Coal - the NCVs given above reflect this combination.

Source: Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries.

OECD/IEA, Paris, 1998.

TABLE 2.4 (CONTINUED)

1990[a] COUNTRY-SPECIFIC NET CALORIFIC VALUES[b]

(Terajoule per kilotonne)	Malta	Mexico	Moldova	Morocco	Mozam-bique	Myanmar	Nepal	Nether-lands	Nether-lands Antilles	New Zealand	Nica-ragua
OIL											
Crude Oil	-	42.35	-	38.94	-	42.24	-	42.71	42.16	45.93	42.16
NGL	-	46.81	-	-	-	42.71	-	45.22	-	49.75	-
Refinery Feedst.	-	-	-	-	-	-	-	-	-	47.22	-
COAL											
Coking Coal											
Production	-	24.72	-	-	-	-	-	-	-	28.00	-
Imports	-	30.18	-	-	-	-	-	28.70	-	28.00	-
Exports	-	22.41	-	-	-	-	-	-	-	28.00	-
Other Bituminous Coal and Anthracite[c]											
Production	-	-	-	23.45	25.75	25.75	-	-	-	26.00	-
Imports	25.75	-	18.58	27.63	25.75	25.75	25.12	26.60	-	-	-
Exports	-	-	-	-	-	-	-	26.60	-	-	-
Sub-Bituminous Coal											
Production	-	18.20	-	-	-	-	-	-	-	21.30	-
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-	-
Lignite											
Production	-	-	-	-	-	8.37	-	-	-	14.10	-
Imports	-	-	-	-	-	-	-	20.00	-	-	-
Exports	-	-	-	-	-	-	-	20.00	-	-	-
Coal Products											
Patent Fuel	-	-	-	-	-	-	-	29.30	-	-	-
BKB	-	-	-	-	-	-	-	20.00	-	-	-
Coke Oven Coke	-	27.96	25.12	27.21	-	27.21	-	28.50	-	-	-
Gas Coke	-	-	-	-	-	-	-	-	-	-	-

[a] For the former Soviet and Yugoslav Republics, 1996 numbers have been used.

[b] The NCVs are those used by the IEA in the construction of energy balances.

[c] In IEA statistics, Anthracite is combined with Other Bituminous Coal – the NCVs given above reflect this combination.

Source: Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries.
OECD/IEA, Paris, 1998.

TABLE 2.4 (CONTINUED)
1990[a] COUNTRY-SPECIFIC NET CALORIFIC VALUES[b]

(Terajoule per kilotonne)	Nigeria	Norway	Oman	Pakistan	Panama	Paraguay	Peru	Philippines	Poland	Portugal	Qatar
OIL											
Crude Oil	42.75	42.96	42.71	42.87	42.16	42.54	42.75	42.58	41.27	42.71	42.87
NGL	42.75	45.22	42.71	42.87	-	-	42.75	-	-	-	43.00
Refinery Feedst.	-	42.50	-	-	-	-	-	-	44.80	42.50	-
COAL											
Coking Coal											
Production	-	-	-	-	-	-	-	-	-	-	-
Imports	-	-	-	27.54	-	-	29.31	-	-	29.30	-
Exports	-	-	-	-	-	-	-	-	-	-	-
Other Bituminous Coal and Anthracite [c]											
Production	25.75	28.10	-	18.73	-	-	29.31	20.10	22.95	-	-
Imports	-	28.10	-	-	25.75	-	-	20.52	29.41	26.59	-
Exports	25.75	28.10	-	-	-	-	-	-	25.09	-	-
Sub-Bituminous Coal											
Production	-	-	-	-	-	-	-	-	-	17.16	-
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-	-
Lignite											
Production	-	-	-	-	-	-	-	8.37	8.36	-	-
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	9.00	-	-
Coal Products											
Patent Fuel	-	-	-	-	-	-	-	-	22.99	-	-
BKB	-	-	-	-	-	-	-	-	17.84	-	-
Coke Oven Coke	27.21	28.50	-	27.21	-	-	27.21	27.21	27.85	28.05	-
Gas Coke	-	-	-	-	-	-	-	-	-	-	-

[a] For the former Soviet and Yugoslav Republics, 1996 numbers have been used.

[b] The NCVs are those used by the IEA in the construction of energy balances.

[c] In IEA statistics, Anthracite is combined with Other Bituminous Coal – the NCVs given above reflect this combination.

Source: Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries.
OECD/IEA, Paris, 1998.

TABLE 2.4 (CONTINUED)

1990[a] COUNTRY-SPECIFIC NET CALORIFIC VALUES[b]

(Terajoule per kilotonne)	Romania	Russia	Saudi Arabia	Senegal	Singa-pore	Slovak Republic	Slovenia	South Africa	Spain	Sri Lanka	Sudan
OIL											
Crude Oil	40.65	42.08	42.54	42.62	42.71	41.78	42.75	38.27	42.66	42.16	42.62
NGL	-	-	42.62	-	-	45.18	-	-	45.22	-	-
Refinery Feedst.	-	-	-	-	-	-	42.50	-	42.50	-	-
COAL											
Coking Coal											
Production	16.33	18.58	-	-	-	-	-	30.99	29.16	-	-
Imports	25.12	25.12	-	-	-	23.92	30.69	-	30.14	-	-
Exports	-	18.58	-	-	-	-	-	30.99	-	-	-
Other Bituminous Coal and Anthracite[c]											
Production	16.33	18.58	-	-	-	-	-	23.60	21.07	-	-
Imports	25.12	18.58	-	-	-	23.92	30.69	-	25.54	25.75	-
Exports	-	18.58	-	-	-	-	-	27.99	23.00	-	-
Sub-Bituminous Coal											
Production	-	-	-	-	-	-	8.89	-	11.35	-	-
Imports	-	-	-	-	-	-	16.91	-	11.35	-	-
Exports	-	-	-	-	-	-	16.90	-	-	-	-
Lignite											
Production	7.24	14.65	-	-	-	12.26	8.89	-	7.84	-	-
Imports	7.24	-	-	-	9.67	12.20	16.91	-	-	-	-
Exports	-	14.65	-	-	-	15.26	16.90	-	-	-	-
Coal Products											
Patent Fuel	14.65	-	-	-	-	-	-	-	29.30	-	-
BKB	14.65	20.10	-	-	-	21.28	-	-	20.22	-	-
Coke Oven Coke	20.81	25.12	-	-	27.21	27.01	26.90	27.88	30.14	-	-
Gas Coke	-	-	-	-	-	-	-	-	-	-	-

[a] For the former Soviet and Yugoslav Republics, 1996 numbers have been used.

[b] The NCVs are those used by the IEA in the construction of energy balances.

[c] In IEA statistics, Anthracite is combined with Other Bituminous Coal – the NCVs given above reflect this combination.

Source: Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries. OECD/IEA, Paris, 1998.

TABLE 2.4 (CONTINUED)

1990[a] COUNTRY-SPECIFIC NET CALORIFIC VALUES[b]

(Terajoule per kilotonne)	Sweden	Switzerland	Syria	Tajikistan	Tanzania	Thailand	Trinidad and Tobago	Tunisia	Turkey	Turk-menistan	Ukraine
OIL											
Crude Oil	42.75	43.22	42.04	42.08	42.62	42.62	42.24	43.12	42.79	42.08	42.08
NGL	-	-	-	41.91	-	46.85	-	43.12	-	41.91	-
Refinery Feedst.	42.50	43.70	-	-	-	-	-	-	42.50	-	-
COAL											
Coking Coal											
Production	-	-	-	-	25.75	-	-	-	32.56	-	21.59
Imports	30.00	-	-	-	-	-	-	-	33.54	-	-
Exports	-	-	-	-	-	-	-	-	-	-	21.59
Other Bituminous Coal and Anthracite[c]											
Production	14.24	-	-	-	25.75	-	-	-	30.04	-	21.59
Imports	26.98	28.05	-	18.58	-	26.38	-	25.75	27.89	18.58	25.54
Exports	26.98	28.05	-	-	-	-	-	-	-	-	21.59
Sub-Bituminous Coal											
Production	-	-	-	14.65	-	-	-	-	18.00	-	-
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-	-
Lignite											
Production	-	-	-	-	-	12.14	-	-	9.63	-	14.65
Imports	8.37	-	-	-	-	-	-	-	12.56	-	14.65
Exports	-	-	-	-	-	-	-	-	-	-	14.65
Coal Products											
Patent Fuel	-	28.05	-	-	-	-	-	-	-	-	29.31
BKB	20.10	20.10	-	-	-	-	-	-	20.93	-	-
Coke Oven Coke	28.05	28.05	-	-	27.21	27.21	-	27.21	29.31	-	25.12
Gas Coke	-	-	-	-	-	-	-	-	27.21	-	-

[a] For the former Soviet and Yugoslav Republics, 1996 numbers have been used.

[b] The NCVs are those used by the IEA in the construction of energy balances.

[c] In IEA statistics, Anthracite is combined with Other Bituminous Coal – the NCVs given above reflect this combination.

Source: Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries.

OECD/IEA, Paris, 1998.

TABLE 2.4 (CONTINUED)

1990[a] COUNTRY-SPECIFIC NET CALORIFIC VALUES[b]

(Terajoule per kilotonne)	United Arab Emirates	United Kingdom	United States	Uruguay	Uzbe-kistan	Venezuela	Vietnam	Yemen	Zambia	Zimbabwe
OIL										
Crude Oil	42.62	43.40	43.12	42.71	42.08	42.06	42.61	43.00	42.16	-
NGL	42.62	46.89	47.69	-	41.91	41.99	-	-	-	-
Refinery Feedst.	-	42.50	43.36	-	44.80	-	-	-	-	-
COAL										
Coking Coal										
Production	-	29.27	29.68	-	-	-	-	-	24.71	25.75
Imports	-	30.07	-	-	-	-	-	-	-	-
Exports	-	29.27	29.68	-	-	-	-	-	-	-
Other Bituminous Coal and Anthracite[c]										
Production	-	24.11	26.66	-	18.58	25.75	20.91	-	24.71	25.75
Imports	-	26.31	27.69	-	18.58	-	-	-	-	25.75
Exports	-	27.53	28.09	-	-	25.75	20.91	-	24.71	25.75
Sub-Bituminous Coal										
Production	-	-	19.43	-	-	-	-	-	-	-
Imports	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-
Lignite										
Production	-	-	14.19	-	14.65	-	-	-	-	-
Imports	-	-	-	-	14.65	-	-	-	-	-
Exports	-	-	14.19	-	14.65	-	-	-	-	-
Coal Products										
Patent Fuel	-	26.26	-	-	29.31	-	-	-	-	-
BKB	-	-	-	-	-	-	-	-	-	-
Coke Oven Coke	-	26.54	27.47	27.21	-	-	27.21	-	27.21	27.21
Gas Coke	-	-	-	-	-	-	-	-	-	-

[a] For the former Soviet and Yugoslav Republics, 1996 numbers have been used.

[b] The NCVs are those used by the IEA in the construction of energy balances.

[c] In IEA statistics, Anthracite is combined with Other Bituminous Coal – the NCVs given above reflect this combination.

Source: Energy Balances of OECD Countries, and Energy Statistics and Balances of Non-OECD Countries.
OECD/IEA, Paris, 1998.

2.2 NON-CO_2 EMISSIONS FROM STATIONARY COMBUSTION

2.2.1 Methodological issues

For stationary sources, some non-CO_2 emissions such as methane (CH_4), carbon monoxide (CO) and non-methane volatile organic compounds (NMVOC) result from the incomplete combustion of fuels. The *IPCC Guidelines* cover emissions of stationary combustion-related non-CO_2 greenhouse gases from five sectors (Energy and Manufacturing Industries, the Commercial/Institutional Sector, the Residential Sector and Agriculture/Forestry/Fishing sources). This section addresses only emissions of the direct greenhouse gases CH_4 and N_2O.

Fuel characteristics (including the calorific value), the type of technology (including the combustion, operating and maintenance regime, the size and the vintage of the equipment), and emission controls, are major factors determining rates of emissions of CH_4 and N_2O gases from stationary sources. Moisture content, carbon fraction, and combustion efficiencies are also important factors to consider.

2.2.1.1 CHOICE OF METHOD

The *IPCC Guidelines* describe the following general approach to estimate emissions from fuel combustion for each greenhouse gas and sub-source category:

EQUATION 2.3

$$\text{Emissions} = \sum (\text{Emission Factor}_{abc} \bullet \text{Fuel Consumption}_{abc})$$

Where:

a = fuel type

b = sector activity

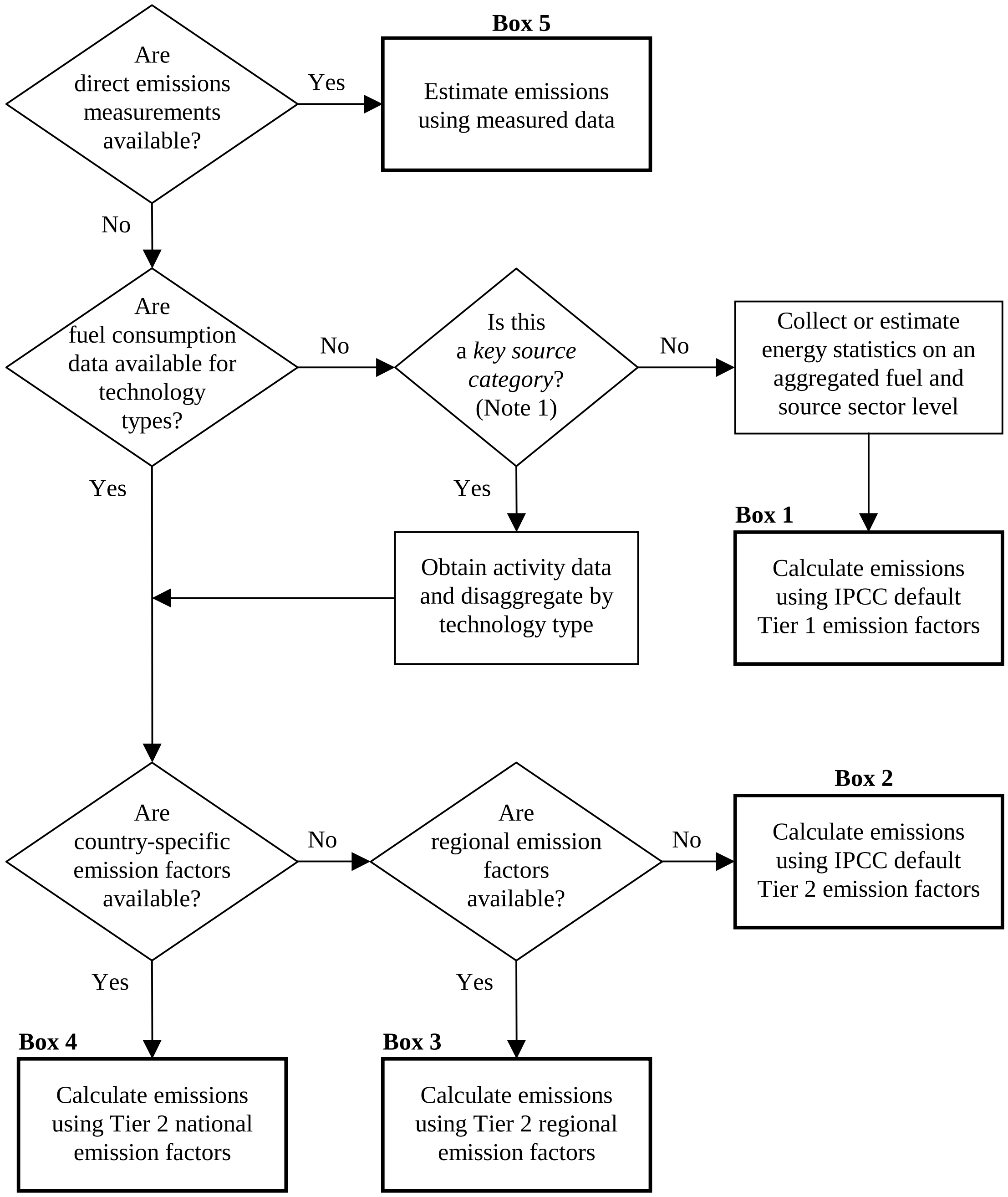
c = technology type

Given the dependence of emissions on unique combustion conditions and other characteristics, *good practice* is to disaggregate fuel consumption into smaller, more homogeneous categories, if data and specific emission factors are available. The *IPCC Guidelines* generally refer to such disaggregated estimation methods using country-specific emission factors as Tier 2, and more aggregated estimates as Tier 1 calculations. *Good practice* is to use the level of disaggregation that reflects the greatest level of detail in the energy statistics available in the country.

Figure 2.3, Decision Tree for Non-CO_2 Emissions from Stationary Combustion summarises *good practice* in methodological choice. It should be applied separately to each of the sub-source categories for each gas for which emissions exist in a country, because the availability of activity data and emission factors (and hence the outcome in terms of methodological choice) may differ significantly between sub-source categories.

Although continuous measurement of emissions is also consistent with *good practice*, continuous measurements of CH_4 and N_2O alone are not justified because of their comparatively high cost and because practical continuous monitoring systems are not easily available. Sufficiently accurate results may be obtained by using periodic measurements for CH_4 and N_2O. These measurements would help to improve emission factors. If monitors are already installed to measure other pollutants, they may deliver some useful parameters such as fluxes.

Figure 2.3 Decision Tree for Non-CO_2 Emissions from Stationary Combustion



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: The decision tree and *key source category* determination should be applied to methane and nitrous oxide emissions separately.

Proper use of the decision tree requires an inventory agency to undertake, beforehand, a thorough survey of available national activity data and national or regional emission factor data, by relevant source category. For some sub-source categories, activity and emissions data may be sparse. In this case, it is *good practice* to improve data quality if an initial calculation with a default method indicates a significant contribution to total national emissions or the presence of a high level of uncertainty.

Where direct measurements are available, reporting of implied emission factors cross referenced by technology type would be helpful, since this information could help others to estimate national emissions.

2.2.1.2 CHOICE OF EMISSION FACTORS

Good practice is to use the most disaggregated technology-specific and country-specific emission factors available, particularly those derived from direct measurements at the different stationary combustion sources. Using the Tier 2 approach, there are three possible types of emission factors:

- National emission factors.[9] These emission factors may be developed by national programmes already measuring emissions of indirect greenhouse gases such as NO_x, CO and NMVOC for local air quality;
- Regional emission factors;[10]
- IPCC default emission factors, provided that a careful review of the consistency of these factors with the country conditions has been made. IPCC default factors may be used when no other information is available.

If national activity data are not sufficiently disaggregated to enable the use of Tier 2, then aggregate Tier 1 emission factors should be applied, provided that no other referenced data are available that are more representative of combustion conditions within the country.

Emission factors for biomass fuels are not as well developed as those for fossil fuels. Preliminary results from an international biomass emission factor research project, focusing on developing countries (e.g. India, Kenya, and China) show emission factors for small biomass devices and carbonisation that are different from the IPCC defaults. Given the importance of biomass in many countries, it is suggested that country experts consider the new well-researched emission factors as soon as they are published (Smith *et al.*, 1993; Smith *et al.*, 1999; Smith *et al.*, 2000; Zhang *et al.*, 1999; Zhang *et al.*, 2000).

2.2.1.3 CHOICE OF ACTIVITY DATA

Due to the technology-specific nature of non-CO_2 formation, detailed fuel combustion technology statistics are needed in order to provide rigorous emission estimates. It is *good practice* to collect activity data in units of fuel used, and to disaggregate as far as possible into the share of fuel used by major technology types. Disaggregation can be achieved through a bottom-up survey of fuel consumption and combustion technology, or through top-down allocations based on expert judgement and statistical sampling. Specialised statistical offices or ministerial departments are generally in charge of regular data collection and handling. Inclusion of representatives from these departments in the inventory process could facilitate the acquisition of appropriate activity data.

Good practice for electricity autoproduction (self-generation) is to assign emissions to the source categories (or sub-source categories) where they were generated and to identify them separately from those associated with other end-uses such as process heat. In many countries, the statistics related to autoproduction are available and regularly updated. Therefore, activity data do not represent a serious obstacle to estimating non-CO_2 emissions in those countries.

For some source categories (e.g. energy use in agriculture), there may be some difficulties in separating fuel used in stationary equipment from fuel used in mobile machinery. Given the different emission factors of these two sources, *good practice* is to derive the energy use of each of these sources by using indirect data (e.g. number of pumps, average consumption, and needs for water pumping). Expert judgement and information available from other countries may also be relevant.

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[9] Since the associated uncertainty ranges are dependent on the instrumentation used and on the frequency of measurements, these should be described and reported.

[10] The sources of the regional emission factors should be documented and the uncertainty ranges reported.

2.2.1.4 COMPLETENESS

Completeness should be established by cross-referencing to the source categories used for reporting CO_2 emissions from stationary combustion. The same source categories should be used in cases where choice is possible (e.g. emissions from coke used in blast furnaces that can be reported either with industrial emissions or under stationary combustion depending on national circumstances as explained in Section 2.1.1.3 and below). Cross-referencing with CO_2 categories will not necessarily cover non-CO_2 emissions from biomass fuels, since CO_2 emissions from biomass fuels are reported as memo items but not included in national totals. Therefore, the national energy statistics agencies should be consulted about use of biomass fuels, including possible use of non-commercially traded biomass fuels. Biomass related issues are particularly important for the quality of inventories in developing countries. A major effort is required by country experts in order to improve related non-CO_2 estimates.

The reporting of emissions from coke use in blast furnaces requires attention. Crude iron is typically produced by the reduction of iron oxide ores in a blast furnace, using the carbon in coke (sometimes other fuels) as both the fuel and reductant. Since the primary purpose of coke oxidation is to produce pig iron, the emissions should be considered as coming from an industrial process if a detailed calculation of industrial emissions is being undertaken. It is important not to double-count the carbon from the combustion of coke. Therefore, if these emissions have been included in the Industrial Processes sector, they should not be included in the Energy sector. However, there are countries where industrial emissions are not addressed in detail. In these instances, the emissions should be included with Energy. *Good practice* is to state clearly whether non-CO_2 emissions from coke use in blast furnaces have been allocated to Energy or to Industrial Processes, to indicate that no double counting has occurred.

Uncontrolled situations that might affect estimates and sectoral distribution (e.g. statistical differences or thefts) require special consideration. Inventory agencies are encouraged to make the most appropriate interpretation of the related emissions.

2.2.1.5 DEVELOPING A CONSISTENT TIME SERIES

As improved emission factors and emission estimation methods are developed over time, base year emission estimates determination will be an important issue for non-CO_2 emissions from stationary combustion. *Good practice guidance* on ensuring time series consistency and base year determination is provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

Many countries, particularly developing ones, do not undertake annual surveys. Where data are missing for an inventory year, it may be necessary to estimate activity data through extrapolation for the current year or interpolation between years. These extrapolations or interpolations require regular cross-checking with survey data collected at least every three to five years. Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques, describes in more detail methods for making such calculations.

Biomass data may be incomplete, particularly for small combustion devices. If the data are missing for the inventory year, inventory agencies could extrapolate to the relevant year based on past trends, or interpolate, again using the methods described in Chapter 7.[11] Additional cross-checking should be done to ensure the consistency of the estimates with related data that are available annually (e.g. wood production potential from forests, and annual dung production).

2.2.1.6 UNCERTAINTY ASSESSMENT

Default uncertainty ranges for non-CO_2 stationary combustion emissions are not provided in the *IPCC Guidelines*. It is *good practice* to quantify the uncertainties associated with the inventory results regardless of the tier adopted.

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[11] Two recent meetings at the IEA addressed the issues of gathering and modelling biomass energy data. The findings are published in (i) Biomass Energy: Key Issues and Priority Needs. Conference Proceedings. IEA/OECD, Paris, France. 3-5 February 1997; (ii) Biomass Energy: Data, Analysis and Trends. Conference Proceedings. IEA/OECD, Paris, France. 23-24 March 1998.

EMISSION FACTOR UNCERTAINTIES

The default uncertainties shown in Table 2.5, derived from the EMEP/CORINAIR Guidebook ratings (EMEP/CORINAIR, 1999), may be used in the absence of country-specific estimates.

TABLE 2.5

DEFAULT UNCERTAINTY ESTIMATES FOR STATIONARY COMBUSTION EMISSION FACTORS

Sector	CH_4	N_2O
Public Power, co-generation and district heating	50-150%	Order of magnitude[a]
Commercial, Institutional & Residential combustion	50-150%	Order of magnitude
Industrial combustion	50-150%	Order of magnitude
Agriculture/forestry/fishing	Not reported	Not reported

[a] I.e. having an uncertainty range from one-tenth of the mean value to ten times the mean value.

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts; Stationary Combustion).

While these default uncertainties can be used for the existing emission factors (whether country-specific or taken from the *IPCC Guidelines*), there may be an additional uncertainty associated with applying emission factors that are not representative of the combustion conditions in the country. It is *good practice* to obtain estimates of these uncertainties from national experts taking into account the guidance concerning expert judgements provided in Chapter 6, Quantifying Uncertainties in Practice.

ACTIVITY DATA UNCERTAINTIES

Aggregate data related to energy consumption by fuel type are generally estimated accurately. There is more uncertainty for biomass and traditional fuels. Uncertainties associated with sectoral (or sub-sectoral) distribution of fuel use are also generally higher, and will vary with the approach (survey or extrapolation) used and the specificity of the country's statistical systems.

The activity data uncertainty ranges shown in Table 2.6, Level of Uncertainty Associated with Stationary Combustion Activity Data, may be used when reporting uncertainties. It is *good practice* for inventory agencies to develop, if possible, country-specific uncertainties using expert judgement or statistical analysis.

TABLE 2.6

LEVEL OF UNCERTAINTY ASSOCIATED WITH STATIONARY COMBUSTION ACTIVITY DATA

	Well Developed Statistical Systems		Less Developed Statistical Systems	
Sector	Surveys	Extrapolations	Surveys	Extrapolations
Public Power, co-generation and district heating	less than 1%	3-5%	1-2%	5-10%
Commercial, institutional, residential combustion	3-5%	5-10%	10-15%	15-25%
Industrial combustion (Energy intensive industries)	2-3%	3-5%	2-3%	5-10%
Industrial combustion (others)	3-5%	5-10%	10-15%	15-20%
Biomass in small sources	10-30%	20-40%	30-60%	60-100%

The inventory agency should judge which type of statistical system best describes their national circumstances.

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts; Stationary Combustion).

2.2.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Section 8.10.1 of Chapter 8, Quality Assurance and Quality Control.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and the steps in their calculation may be retraced.

The current IPCC reporting format (spreadsheet tables, aggregate tables) provides a balance between the transparency requirement and the level of effort that is realistically achievable by the inventory agency. *Good practice* involves some additional effort to fulfil the transparency requirements completely. In particular, if Tier 2 (or a more disaggregated approach) is used, additional tables showing the activity data that are directly associated with the emission factors should be prepared.

Most energy statistics are not considered confidential. If inventory agencies do not report disaggregated data due to confidentiality concerns, it is *good practice* to explain the reasons for these concerns, and report the data in a more aggregated form.

For a highly disaggregated stationary non-CO_2 estimate, it may be necessary to cite many different references or documents. It is *good practice* to provide citations for these references, particularly if they describe new methodological developments or emission factors for particular technologies or national circumstances.

It is *good practice* to state clearly whether non-CO_2 emissions from coke (or other fuels) used in crude iron production have been allocated to the Energy or to the Industrial Processes Sector, to show that no double counting has occurred. The attribution of emissions from blast furnaces and other industrial processes should be consistent between CO_2 and non-CO_2 emissions (see Section 2.1.1.4).

2.2.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8 and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of emission estimates using different approaches

- If a Tier 2 approach with country-specific factors is used, the inventory agency should compare the result to emissions calculated using the Tier 1 approach with default IPCC factors. This type of comparison may require aggregating Tier 2 emissions to the same sector and fuel groupings as the Tier 1 approach. The approach should be documented and any discrepancies investigated.
- If possible, the inventory agency should compare the consistency of the calculations in relation to the maximum carbon content of fuels that are combusted by stationary sources. Anticipated carbon balances should be maintained throughout the combustion sectors, and the non-CO_2 estimates should not contradict maximum theoretical quantities based on the total carbon content of the fuels.

Review of emission factors

- If country-specific emission factors are used, the inventory agency should compare them to the IPCC defaults, and explain and document differences.
- The inventory agency should compare the emission factors used with site or plant level factors, if these are available. This type of comparison provides an indication of how reasonable and representative the national factor is.

Review of direct measurements

- If direct measurements are used, the inventory agency should ensure that they are made according to good measurement practices including appropriate QA/QC procedures. Direct measurements should be compared to the results derived from using IPCC default factors.

Activity data check

- The inventory agency should compare energy statistics with those provided to international organisations to identify any inconsistencies that require explanation.
- If secondary data from national organisations are used, the inventory agency should ensure that these organisations have appropriate QA/QC programmes in place.

External review

- The inventory agency should carry out a review involving national experts and stakeholders in the different fields related to emissions from stationary sources, such as: energy statistics, combustion efficiencies for different sectors and equipment types, fuel use and pollution controls. In developing countries, expert review of emissions from biomass combustion is particularly important.

2.3 MOBILE COMBUSTION: ROAD VEHICLES

2.3.1 Methodological issues

Road transport emits significant amounts of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), as well as several other pollutants such as carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), sulfur dioxide (SO_2), particulate matter (PM) and oxides of nitrate (NO_x), which cause or contribute to local or regional air pollution problems. This chapter covers *good practice* in the development of estimates for the direct greenhouse gases CO_2, CH_4 and N_2O.

2.3.1.1 CHOICE OF METHOD

Emissions of CO_2 are best calculated on the basis of the amount and type of fuel combusted and its carbon content. Emissions of CH_4 and N_2O are more complicated to estimate accurately because emission factors depend on vehicle technology, fuel and operating characteristics. Both distance-based activity data (e.g. vehicle-kilometers travelled) and disaggregated fuel consumption may be considerably less certain than overall fuel consumption.

Figure 2.4, Decision Tree for CO_2 Emissions from Road Vehicles and Figure 2.5, Decision Tree for CH_4 and N_2O Emissions from Road Vehicles outline the process to calculate emissions from the Transport Sector. Two alternative approaches can be used, one based on vehicle kilometres travelled and the other based on fuel consumption. The inventory agency should choose the method on the basis of the existence and quality of data. Models can help ensure consistency and transparency because the calculation procedures are fixed in the software. It is *good practice* to clearly document any modifications to standardised models.

Figure 2.4 Decision Tree for CO_2 Emissions from Road Vehicles

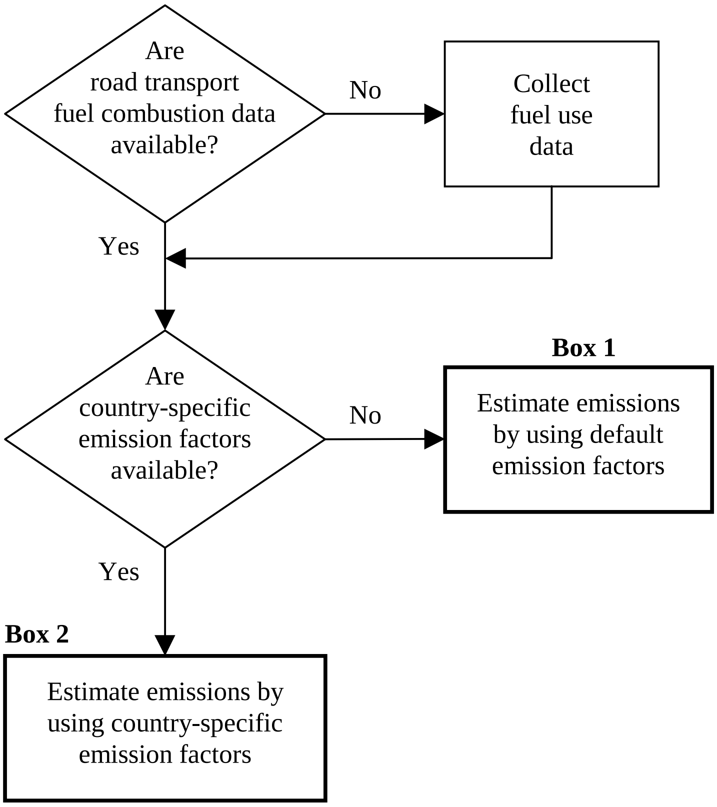
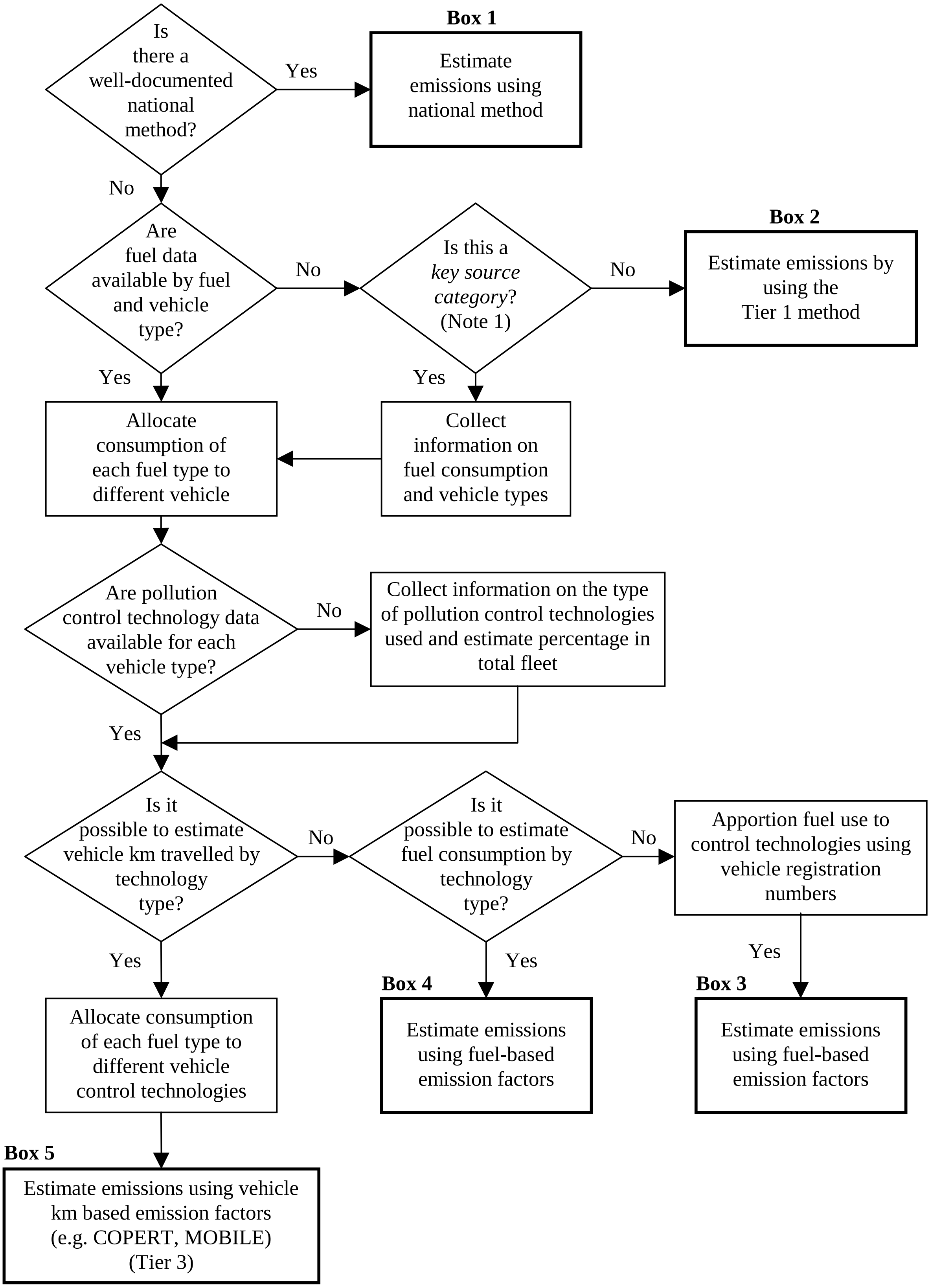


Figure 2.5 Decision Tree for CH_4 and N_2O Emissions from Road Vehicles



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: The decision tree and *key source category* determination should be applied to methane and nitrous oxide emissions separately.

CO_2 EMISSIONS

The *IPCC Guidelines* provide two methods to estimate CO_2 emissions from Road Transport. The Tier 1, or 'top down' approach calculates CO_2 emissions by estimating fuel consumption in a common energy unit, multiplying by an emission factor to compute carbon content, computing the carbon stored, correcting for unoxidised carbon and finally converting oxidised carbon to CO_2 emissions. The approach is shown in Equation 2.4.

EQUATION 2.4

$$\text{Emissions} = \sum_j [(\text{Emission Factor}_j \bullet \text{Fuel consumed}_j) - \text{Carbon Stored}] \bullet \text{Fraction Oxidised}_j \bullet 44/12$$

Where j = fuel type

Alternatively, a Tier 2, or 'bottom-up' approach estimates emissions in two steps. The first step (Equation 2.5) is to estimate fuel consumed by vehicle type i and fuel type j.

EQUATION 2.5

$$\text{Fuel Consumption}_{ij} = n_{ij} \bullet k_{ij} \bullet e_{ij}$$

Where:

i = vehicle type

j = fuel type

n = number of vehicles

k = annual kilometres travelled per vehicle

e = average litres consumed per kilometre travelled

The second step is to estimate total CO_2 emissions by multiplying fuel consumption by an appropriate emission factor for the fuel type and vehicle type (Equation 2.6).

EQUATION 2.6

$$\text{Emissions} = \sum_i \sum_j (\text{Emission Factor}_{ij} \bullet \text{Fuel Consumption}_{ij})$$

It is *good practice* to calculate CO_2 emissions on the basis of fuel consumption statistics using the Tier 1 (top down) approach. This is illustrated in the decision tree in Figure 2.4, Decision Tree for CO_2 Emissions from Road Vehicles. Except in rare cases (e.g. where there is extensive fuel smuggling), the top-down approach is more reliable for CO_2 estimates and is also much simpler to implement. The main issue is to ensure that double counting of agricultural and off-road vehicles is avoided.

It is also *good practice* to use the Tier 2 (bottom up) approach in parallel for the following reasons:

- First, use of these two approaches provides an important quality check. Significant differences between the results of the top-down and bottom-up approaches indicate that one or both approaches may have errors, and there is a need for further analysis. Areas of investigation to pursue when reconciling top down and bottom-up approaches are listed in Section 2.3.3, Inventory quality assurance/quality control (QA/QC).
- Second, a reliable and accurate bottom-up CO_2 emissions estimate increases confidence in the underlying activity data used for the bottom-up inventory. These in turn are important underpinnings for the 'bottom-up' calculation of CH_4 and N_2O emissions from road transport.

When calculating emissions using both the top-down and bottom-up approaches in parallel, it is *good practice*, where feasible, to develop the bottom-up estimates independently from the top-down estimates.

CH_4 AND N_2O EMISSIONS

CH_4 and N_2O emissions depend primarily on the distribution of emission controls in the fleet. *Good practice* is to use a bottom-up approach taking into account the various emission factors for different pollution control technologies. This approach should be applied if this is a *key source category*, as defined in Chapter 7, Methodological Choice and Recalculation.

2.3.1.2 CHOICE OF EMISSION FACTORS

In the *IPCC Guidelines*, CO_2 emission factors are developed on the basis of the carbon content of the fuel. It is *good practice* to follow this approach using country-specific data if possible. Default emission factors provided in the *IPCC Guidelines* may be used if there are no locally available data.

Developing emission factors for CH_4 and N_2O is more difficult because these pollutants require technology-based emission factors rather than aggregate default emission factors. It is *good practice* to calculate an emission factor for each fuel type and vehicle type (e.g. passenger cars, light trucks, heavy trucks, motorcycles) based on the local mix of engine types and the distribution of installed control technologies. Further refinements in the factors can then be made if additional local data (e.g. on average driving speeds, temperatures, altitude, pollution control devices) are available. It is *good practice* to document the basis for the data.

Recently published data indicate that the default emission factors in the *IPCC Guidelines* for US gasoline vehicles should be updated.[12] Based on this test data, the N_2O emission factors in the *IPCC Guidelines* for US vehicles (Tables I-27, Estimated Emission Factors for US Gasoline Passenger Cars to Table I-33, Estimated Emission Factors for US Motorcycles in the Reference Manual) should be replaced by the tables below.

TABLE 2.7

UPDATED EMISSION FACTORS FOR USA GASOLINE VEHICLES

Control Technology	**Emission Factor**	
	(g N_2O/kg fuel)	**(g N_2O/MJ)**
Low Emission Vehicle (low sulfur fuel)	0.20	0.0045
Three-Way Catalyst (USA Tier 1)	0.32	0.0073
Early Three-Way Catalyst (USA Tier 0)	0.54	0.012
Oxidation Catalyst	0.27	0.0061
Non-Catalyst Control	0.062	0.0014
Uncontrolled	0.065	0.0015

Source: Harvey Michael, (1999), US Environmental Protection Agency. Personal communication to Michael Walsh.

Notes:
Tier 0 and Tier 1 in this table refer to tiers used in the USA methodology, not to the IPCC tiers. These data have been rounded to two significant digits.

A database of technology dependent emission factors based on European data is available in the Copert tool at http://etc-ae.eionet.eu.int/etc-ae/index.htm.

To convert to g/km, multiply emission factor (g/kg) by the fuel density in kg/l and then divide by fuel economy in km/l. For example, if the emission factor is 0.32 g/kg, fuel density is 0.75 kg/l and fuel economy is 10 km/l, then the emission factor in g/km is (0.32 g/kg • 0.75 kg/l) / 10 km/l = 0.024 g/km.

In the *IPCC Guidelines*, Tables 1-37, Estimated Emission Factors for European Diesel Passenger Cars, to Table 1-39, Estimated Emission Factors for European Diesel Heavy-duty Vehicles, list N_2O emission factors for European diesels of 0.01, 0.02, and 0.03 g/km for cars, light trucks, and heavy duty vehicles respectively. These factors are order of magnitude estimates roughly following fuel economy differences. Emission factors from other countries may differ from the data provided in Table 2.7. The average value 0.172 g/kg is recommended for all USA diesel vehicles regardless of control technology**.** This corresponds to 0.0039 g/MJ, assuming 44 MJ/kg.

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[12] In order to refine the N_2O emission factors, the USEPA Office of Mobile Sources carried out an evaluation of available data supplemented by limited testing in June and July 1998. They determined emission factors for Early Three-Way Catalyst and previous vehicles primarily from the published literature. For (advanced) Three-Way Catalyst vehicles and Low-Emission Vehicle Technology, data were used from the testing program. USEPA also assessed the limited data that exist for trucks.

2.3.1.3 CHOICE OF ACTIVITY DATA

The first step in estimating CO_2 emissions using the top-down approach is to determine total fuel use in the transportation sector by major fuel type. These data should be available from national energy statistics. Following this, several issues must be addressed, including:

- Provision of data for fuels with minor distribution such as compressed natural gas or biofuels. These data should also be available from the national authority responsible for the energy statistics. According to the *IPCC Guidelines*, CO_2 emissions from biofuels are reported as memo items but not included in national totals. Non-CO_2 emissions from biofuels should be included in national totals.
- Provision of data to distinguish between fuel use for on-road vehicles from fuel use for off-road vehicles, which are reported in different source categories in the *IPCC Guidelines*. Two alternatives are suggested:
  - (i) A bottom-up calculation of fuel used by each road vehicle type. The difference between the road vehicle total (bottom-up) and the total transportation fuel used is ascribed to the off-road sector; or
  - (ii) The bottom-up calculation of fuel used by each road type is supplemented by special studies to determine off-road fuel use. The total fuel use in the transportation sector (top-down estimate) is then disaggregated according to each vehicle type and the off-road sector in proportion to the bottom-up estimates.
- Data for fuel that is sold for transportation uses but which then may be used for other purposes (or the opposite).
- Estimates of smuggling of fuels into or out of a country.

Some inventory agencies have or will have greater confidence in vehicle fuel consumption data by vehicle type and technology while others prefer vehicle kilometres. Either approach is acceptable so long as the basis for the estimates is clearly documented.

If non-CO_2 emissions from mobile sources are a *key source category*, more information is needed on factors that influence emissions such as:

- Vehicle type (cars, light duty trucks, heavy duty trucks and motorcycles) distribution in fleet;
- Emission control technologies fitted to vehicle types in the fleet;
- Fleet age distribution;
- Climate;
- Altitude of operation;
- Maintenance effects.

If the distribution of fuel use by vehicle and fuel type is unknown, it should be estimated based on the number of vehicles by type. If the number of vehicles by vehicle and fuel type is not known, it must be estimated from national statistics. If local data on annual kilometres travelled per vehicle and average fuel economies by vehicle and fuel type are available, they should be used.

2.3.1.4 COMPLETENESS

Lubricants should be accounted for in other emissions categories, as very little is combusted directly in the transportation sector.

Regarding the problem of purchase and consumption of fuels in different countries (i.e. fuel in tanks that are crossing a border) and the question of allocation, the *IPCC Guidelines* state: ‘Emissions from road vehicles should be attributed to the country where the fuel is loaded into the vehicle.’

Oxygenates and other blending agents should be carefully accounted for in making CO_2 estimates, if used in large quantities. It is important that all fossil carbon is accounted for, and that carbon from biomass is reported as a memo item but not included in national CO_2 totals, as required by the *IPCC Guidelines*.

2.3.1.5 DEVELOPING A CONSISTENT TIME SERIES

With the use of models and updates or revisions of models, it is important that time series remain consistent. When models are revised, it is *good practice* to recalculate the complete time series. A consistent time series with regard to initial collection of fleet technology data could be difficult. Extrapolation, possibly supported by the use of proxy data will be necessary in this case for early years. Inventory agencies should refer to the discussion Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques for general guidance.

2.3.1.6 UNCERTAINTY ASSESSMENT

Carbon dioxide is usually responsible for over 97% of the CO_2-equivalent emissions from the transportation sector.[13] Expert judgement suggests that the uncertainty of the CO_2 estimate is approximately ±5%, based on studies with reliable fuel statistics.[14] The primary source of uncertainty is the activity data rather than emission factors.

Nitrous oxide usually contributes approximately 3% to the CO_2-equivalent emissions from the transportation sector. Expert judgement suggests that the uncertainty of the N_2O estimate may be more than ±50%.The major source of uncertainty is related to the emission factors.

Methane usually contributes less than 1% of the CO_2-equivalent emissions from the transportation sector. Experts believe that there is an uncertainty of ±40% in the CH_4 estimate. The major source of uncertainty is again emission factors.

To reduce uncertainty, a comprehensive approach is needed that reduces uncertainties of emission factors as well as activity data, especially with regard to the bottom-up approach. By encouraging the use of locally estimated data, inventories will improve despite the large uncertainties that may surround national data.

Chapter 6, Quantifying Uncertainties in Practice, describes how to use national empirical data and expert judgement to estimate uncertainties, and how to combine uncertainty estimates for the inventory as a whole.

2.3.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Section 8.10.1 of Chapter 8, Quality Assurance and Quality Control.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

Confidentiality is not likely to be a major issue with regard to road emissions, although it is noted that in some countries the military use of fuel may be kept confidential. The composition of some additives is confidential, but this is only important if it influences greenhouse gas emissions.

2.3.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8 and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

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[13] According to 1990 data for Annex I countries in the UNFCCC secretariat's database on GHG emissions, updated September 1999.

[14] The percentages cited in this section represent an informal polling of assembled experts aiming to approximate the 95% confidence interval around the central estimate.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of emissions using alternative approaches

For CO_2 emissions, the inventory agency should compare estimates using both the top-down and bottom-up approaches. Any anomalies between the emission estimates should be investigated and explained. The results of such comparisons should be recorded for internal documentation. Revising the following assumptions could narrow a detected gap between the approaches:

- Off-road/non transportation fuel uses;
- Annual average vehicle mileage;
- Vehicle fuel efficiency;
- Vehicle breakdowns by type, technology, age, etc.;
- Use of oxygenates/biofuels/other additives;
- Fuel use statistics;
- Fuel sold/used.

Review of emission factors

If IPCC default factors are used, the inventory agency should ensure that they are applicable and relevant to the categories. If possible, the IPCC default factors should be compared to local data to provide further indication that the factors are applicable.

For non-CO_2 emissions, the inventory agency should ensure that the original data source for the local factors is applicable to the category and that accuracy checks on data acquisition and calculations have been performed. Where possible, the IPCC default factors and the local factors should be compared. If the IPCC default factors were used to estimate N_2O emissions, the inventory agency should ensure that the revised emission factors in Table 2.7, Updated Emission Factors for USA Gasoline Vehicles were used in the calculation.

Activity data check

The inventory agency should review the source of the activity data to ensure applicability and relevance to the category. Where possible, the inventory agency should compare the data to historical activity data or model outputs to look for anomalies. The inventory agency should ensure the reliability of activity data regarding fuels with minor distribution, fuel used for other purposes, on and off-road traffic, and illegal transport of fuel in or out of the country. The inventory agency should also avoid double counting of agricultural and off-road vehicles.

External review

The inventory agency should perform an independent, objective review of the calculations, assumptions, and documentation of the emissions inventory to assess the effectiveness of the QC programme. The peer review should be performed by expert(s) who are familiar with the source category and who understand the inventory requirements. The development of the factors for the non-CO_2 emission estimates is particularly important due to the associated uncertainty.

2.4 MOBILE COMBUSTION: WATER-BORNE NAVIGATION

2.4.1 Methodological issues

This source category includes all emissions from fuels used to propel water-borne vessels, including hovercraft and hydrofoils. Water-borne navigation gives rise to emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), as well as carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), sulfur dioxide (SO_2), particulate matter (PM) and oxides of nitrate (NO_x). This section focuses on the direct greenhouse gases CO_2, CH_4, and N_2O.

Parties to the UNFCCC have not made a final decision yet on the allocation to national GHG inventories of emissions from fuels used for international aviation and from international marine bunkers. For the moment, all emissions from these fuels are to be excluded from national totals, and are to be reported separately.

2.4.1.1 CHOICE OF METHOD

The *IPCC Guidelines* present two methodological tiers for estimating emissions of CO_2, CH_4, and N_2O from water-borne navigation. Both Tier 1 and Tier 2 rely on essentially the same analytical approach which is to apply emission factors to fuel consumption activity data. The fuel consumption data and emission factors in the Tier 1 method are fuel type and mode-specific (e.g. oil used for navigation). The Tier 2 method presents a variety of emission factors based on research in the United States and Europe, requiring varying degrees of specificity in the classification of modes (e.g. ocean-going ships and boats), fuel type (e.g. gasoline), and even engine type (e.g. diesel). Figure 2.6, Decision Tree for Emissions from Water-borne Navigation helps in making a choice between the two tiers.

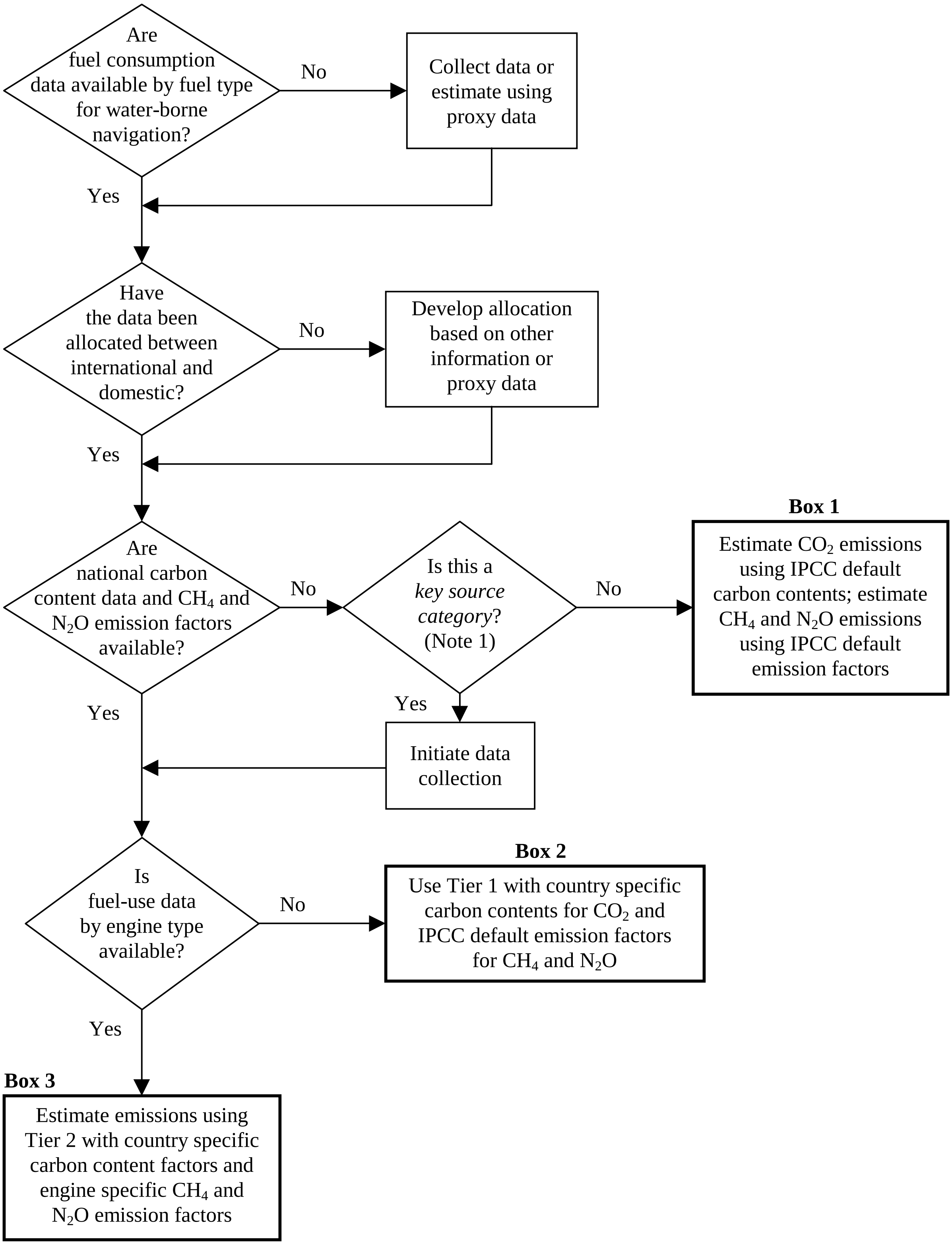
Good practice is to use Tier 1 for CO_2, and Tier 2 for CH_4 and N_2O. Tier 1 for CO_2 emissions is based on fuel consumption by fuel type, the carbon content of the fuel, and the fraction of the fuel left unoxidised. Tier 2 for non-CO_2 emissions also uses fuel consumption by fuel type, but provides a variety of generic and country-specific emission factors for selected fuel, engine, and vehicle types. National approaches may also be *good practice* if they are well documented and have been peer reviewed.

Until the uncertainties in the CH_4 and N_2O emission factors are reduced, more detailed methods will not necessarily reduce uncertainties in the emission estimates. Despite this limited reduction in uncertainty, however, these methods are likely to be desirable in the longer term for a number of other reasons. One reason is to harmonise with other emission inventory efforts that are more detailed. More detailed methods are also better able to account for changes in technologies and therefore emission factors in the future. If improved engine-specific and fuel-specific emission factors become available, a historic database of disaggregated fuel use will allow the backcasting of a trend to the base year.

MILITARY

The *IPCC Guidelines* do not provide a distinct method for calculating military marine emissions. Emissions from military marine fuel use can be estimated using the same ‘hybrid’ approach recommended for non-military shipping (i.e. Tier 1 approach for CO_2, Tier 2 approach for CH_4 and N_2O). However, military marine navigation may include unique operations, situations, and technologies without a civilian analogue (e.g. aircraft carriers, very large auxiliary power plants, and unique engine types). Therefore, inventory agencies should consult military experts to determine the most appropriate emission factors.

Figure 2.6 Decision Tree for Emissions from Water-borne Navigation



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

2.4.1.2 CHOICE OF EMISSION FACTORS

Carbon dioxide emission factors are based on the fuel type and carbon content as well as the fraction of fuel left unoxidised. It is *good practice* to use national carbon content and fraction oxidised factors for CO_2 when available. Default values can also be used when no other information is available (*IPCC Guidelines*, Workbook, Table 1-2, Carbon Emission Factors and Table 1-4, Fraction of Carbon Oxidised).

There is limited information on the emission factors for CH_4 and N_2O from marine shipping. The *IPCC Guidelines* provide factors for the USA and the EU as well as factors developed by Lloyd's Register (Table 1-47, Estimated Emission Factors for US Non-road Mobile Sources to Table 1-49, Estimated Emission Factors for European Non-road Mobile Sources and Machinery, Reference Manual). Large ocean-going cargo ships are driven primarily by large, slow speed and medium speed diesel engines and occasionally by steam and gas turbines. For CH_4 and N_2O emissions from large marine diesel engines consuming distillate or residual fuel oils, it is *good practice* to use the factors developed by Lloyd's Register. These factors are based on the most recent and extensive set of test data. As marine shipping engines are predominantly diesel, and do not vary by country, national emission factors are not likely to yield improved emission estimates unless they are based on peer reviewed studies. For other vessels, such as recreational craft on inland waterways, national emission factors should be used if available. Alternatively, the IPCC default factors from Lloyds, the USA or the EU can be used. The difference in emission rates illustrates the importance of characterising fleet engine types and fuel use for regional scale emissions.

MILITARY

Currently, emission factors for N_2O and CH_4 for military vessels are not available. The default emission factors for civilian shipping should be used unless national data are available of sufficient quality, taking into account the advice in Chapter 8, Quality Assurance and Quality Control.

2.4.1.3 CHOICE OF ACTIVITY DATA

Data on fuel consumption by fuel type and (for N_2O and CH_4) engine type are required to estimate emissions. In addition, in the current reporting procedures, emissions from domestic water-borne navigation are reported separately from international navigation which requires disaggregating the activity data to this level. For consistency, it is *good practice* to use similar definitions of domestic and international activities in the aviation and water-borne navigation estimates. These definitions are presented in Table 2.8, Criteria for Defining International or Domestic Marine Transport, and are consistent with the *IPCC Guidelines*. They are more precise, however, in order to make them workable with respect to the sources of activity data. The definitions in Table 2.8 are independent of the nationality or flag of the carrier.

TABLE 2.8

CRITERIA FOR DEFINING INTERNATIONAL OR DOMESTIC MARINE TRANSPORT

Journey Type	Domestic	International
Originates and terminates in same country	Yes	No
Departs from one country and arrives in another	No	Yes
Departs in one country, makes a 'technical' stop in the same country without dropping or picking up any passengers or freight, then departs again to arrive in another country	No	Yes
Departs in one country, stops in the same country and drops and picks up passengers or freight, then departs finally arriving in another country	Domestic segment	International segment
Departs in one country, stops in the same country and only picks up more passengers or freight and then departs finally arriving in another country	No	Yes
Departs in one country with a destination in another country, and makes an intermediate stop in the destination country where no passengers or cargo are loaded	No	Both segments international

Fuel use data may be obtained using several approaches. The most feasible approach will depend on the national circumstances, but some of the options provide more accurate results than others. Several likely sources of actual fuel or proxy data are listed below, in order of typically decreasing reliability:

- National energy statistics from energy or statistical agencies;
- Surveys of shipping companies;
- Surveys of fuel suppliers (e.g. quantity of marine fuels delivered to port facilities);
- Surveys of individual port and marine authorities;
- Surveys of fishing companies;
- Equipment counts, especially for small gasoline powered fishing and pleasure craft;
- Import/export records;
- Ship movement data and standard passenger and freight ferry schedules;
- Passenger counts and cargo tonnage data;
- International Maritime Organisation (IMO), engine manufacturers, or Jane's Military Ships Database.

It may be necessary to combine these data sources to get full coverage of shipping activities.

MILITARY

Due to confidentiality issues (see completeness and reporting), many inventory agencies may have difficulty obtaining data for the quantity of fuel used by the military. Military activity is defined here as those activities using fuel purchased by or supplied to the military authority of the country. It is *good practice* to apply the rules defining civilian national and international operations in navigation to military operations where they are comparable. Where they are not comparable, decisions on national and international operations should be explained. Data on military fuel use may be obtained from government military institutions or fuel suppliers. If data on fuel split are unavailable, all the fuel sold for military activities should be treated as domestic.

According to Decision 2/CP3 of the Conference of the Parties (COP), multilateral operations should not be included in national totals but reported separately, although there is no clear operational definition of ‘multilateral operation’ available at this time.

2.4.1.4 COMPLETENESS

For water-borne navigation emissions, the methods are based on total fuel use. Since countries generally have effective accounting systems to measure total fuel consumption, the largest area of possible incomplete coverage of this source category is likely to be associated with misallocation of navigation emissions in another source category. For instance, for small watercraft powered by gasoline engines, it may be difficult to obtain complete fuel use records and some of the emissions may be reported as industrial (when industrial companies use small watercraft), other off-road mobile or stationary power production. Estimates of water-borne emissions should include not only fuel for marine shipping, but also for passenger vessels, ferries, recreational watercraft, other inland watercraft, and other gasoline-fuelled watercraft. Misallocation will not affect completeness of the total CO_2 emissions inventory. It will affect completeness of the total non-CO_2 emissions inventory, because non-CO_2 emission factors differ between source categories.

Completeness may also be an issue where military data are confidential, unless military fuel use is aggregated with another source category.

There are additional challenges in distinguishing between domestic and international emissions. As each country's data sources are unique for this category, it is not possible to formulate a general rule regarding how to make an assignment in the absence of clear data. *Good practice* is to specify clearly the assumptions made so that the issue of completeness can be evaluated.

2.4.1.5 DEVELOPING A CONSISTENT TIME SERIES

For *good practice* guidance on determining base year emissions and ensuring consistency in the time series, see Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques. It is *good practice* to determine fuel use using the same method for all years. If this is not possible, data collection should overlap sufficiently in order to check for consistency in the methods employed.

If it is not possible to collect activity data for the base year (e.g. 1990), it may be appropriate to extrapolate data backwards using trends in freight and passenger kilometres, total fuel used or supplied, or import/export records.

Emissions of CH_4 and N_2O will depend on engine type and technology. Unless technology-specific emission factors have been developed, it is *good practice* to use the same fuel-specific set of emission factors for all years.

Mitigation activities resulting in changes in overall fuel consumption will be readily reflected in emission estimates if actual fuel activity data are collected. Mitigation options that affect emission factors, however, can only be captured by using engine-specific emission factors, or by developing control technology assumptions. Changes in emission factors over time should be well documented.

2.4.1.6 UNCERTAINTY ASSESSMENT

ACTIVITY DATA

Much of the uncertainty in emissions estimates is related to the difficulty of distinguishing between domestic and international fuel consumption. With complete survey data, the uncertainty may be low, while for estimations or incomplete surveys the uncertainties may be considerable. The uncertainty will vary widely from country to country and is difficult to generalise. The use of global data sets may be helpful in this area, and it is expected that reporting will improve for this category in the future.

EMISSION FACTORS

Experts believe that CO_2 emission factors for fuels are generally well determined within ±5%, as they are primarily dependent on the carbon content of the fuel.[15] The uncertainty for non-CO_2 emissions, however, is much greater. The uncertainty of the CH_4 emission factor may be as a high as a factor of two. The uncertainty of the N_2O emission factor may be an order of magnitude (i.e. a factor of 10).

2.4.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Section 8.10.1 of Chapter 8, Quality Assurance and Quality Control.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

Some examples of specific documentation and reporting issues relevant to this source category are provided below.

Emissions related to water-borne navigation are reported in different categories depending on their nature. For *good practice*, the categories to use are:

- Civilian domestic activities;
- Military domestic activities;
- International bunker fuels;
- Fishing.

The *IPCC Guidelines* require that emissions from international navigation be reported separately from domestic, and not be included in the national total.

Emissions related to commercial fishing are not reported under water-borne navigation. These emissions are to be reported under the Agriculture/Forestry/Fishing category in the Energy sector. By definition, all fuel supplied to commercial fishing activities in the reporting country is considered domestic, and there is no international bunker fuel category for commercial fishing, regardless of where the fishing occurs.

Military marine emissions should be clearly specified to improve the transparency of national greenhouse gas inventories.

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[15] The uncertainty ranges cited in this section represent an informal polling of assembled experts aiming to approximate the 95% confidence interval around the central estimate.

In addition to reporting emissions, it is *good practice* to provide:

- Source of fuel and other data;
- Method used to separate domestic and international navigation;
- Emission factors used and their associated references;
- Analysis of uncertainty or sensitivity of results or both to changes in input data and assumptions.

2.4.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8 and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of emissions using alternative approaches

If possible, the inventory agency should compare estimates determined for water-borne navigation using both Tier 1 and Tier 2 approaches. The inventory agency should investigate and explain any anomaly between the emission estimates. The results of such comparisons should be recorded.

Review of emission factors

The inventory agency should ensure that the original data source for national factors is applicable to each category and that accuracy checks on data acquisition and calculations have been performed. For the IPCC default factors, the inventory agency should ensure that the factors are applicable and relevant to the category. If possible, the IPCC default factors should be compared to national factors to provide further indication that the factors are applicable and reasonable.

If emissions from military use were developed using data other than default factors, the inventory agency should check the accuracy of the calculations and the applicability and relevance of the data.

Check of activity data

The source of the activity data should be reviewed to ensure applicability and relevance to the category. Where possible, the data should be compared to historical activity data or model outputs to look for anomalies. Data could be checked with productivity indicators such as fuel per unit of marine traffic performance (freight and passenger kilometres) compared with other countries.

In preparing the inventory estimates, the inventory agency should take steps to ensure reliability of the activity data used to allocate emissions between domestic and international water-borne navigation and to ensure that all fuel sold in the country for water-borne navigation is accounted for in the estimates. A comparison of the activity data should be conducted between multiple references due to the high uncertainty associated with this data.

External review

The inventory agency should carry out an independent, objective review of calculations, assumptions or documentation or both of the emissions inventory to assess the effectiveness of the QC programme. The peer review should be performed by expert(s) who are familiar with the source category and who understand national greenhouse gas inventory requirements.

2.5 MOBILE COMBUSTION: AIRCRAFT

2.5.1 Methodological issues

The IPCC source category for civil aviation includes emissions from all civil commercial use of airplanes (international and domestic) consisting of scheduled and charter traffic for passengers and freight, including air taxiing, as well as general aviation[16] (e.g. agricultural airplanes, private jets or helicopters). Methods discussed in this section can be used also to estimate emissions from military aviation, but emissions should be reported under the IPCC category 1A 5 ’Other‘. Stationary combustion and ground transport at airports are to be included in other appropriate categories.

Aircraft emit carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), as well as carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), sulfur dioxide (SO_2), particulate matter (PM) and nitrogen oxides (NO_x). This section focuses on the direct greenhouse gases CO_2, CH_4 and N_2O. For more information on the impact of aviation on the global atmosphere see IPCC (1999).

Parties to the UNFCCC have not made a final decision yet on the allocation to national GHG inventories of emissions from fuels used for international aviation and from international marine bunkers. For the moment, all emissions from these fuels are to be excluded from national totals, and are to be reported separately.

2.5.1.1 CHOICE OF METHOD

One Tier 1 and two Tier 2 methods (designated Tier 2a and 2b) are outlined in the *IPCC Guidelines*. All methods are based on distinguishing between domestic fuel use and international fuel use. Tier 1 is purely fuel based, while the Tier 2 methods are based on the number of landing/take-off cycles (LTOs) and fuel use. The CO_2 estimate depends on carbon content of fuel and the fraction oxidised and therefore should not vary significantly with the tier. Given the current limited knowledge of emission factors, more detailed methods will not significantly reduce uncertainties for CH_4 and N_2O emissions. However, reasons for choosing to use a higher tier include estimation of emissions jointly with other pollutants (e.g. NO_x), harmonisation of methods with other inventories, and the possibility of accounting for changes in technologies (and therefore emission factors) in the future.

All three methods will capture changes in technology that influence fuel consumption. However, only Tier 2b can capture the effects on CH_4 and N_2O emissions of changing emission factors. National approaches can also be used if they are well documented and have been peer reviewed. The choice of method will depend on national circumstances particularly the availability of data (see the decision trees in Figure 2.7 and Figure 2.8).

The simple Tier 1 method is based on an aggregate figure of fuel consumption for civil aviation multiplied by average emissions factors. The emissions factors have been averaged over all flying phases based on the assumption that 10% of the fuel[17] is used in the LTO[18] (landing/take-off) phase of the flight. Emissions are calculated according to Equation 2.7:

EQUATION 2.7

$$\text{Emissions} = \text{Fuel Consumption} \bullet \text{Emission Factor}$$

The Tier 2 method is only applicable for jet fuel use in jet engines. Aviation gasoline is only used in small aircraft and generally represents less than 1% of fuel consumption from aviation. In the Tier 2 method a

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[16] ICAO’s ‘Manual on the ICAO Statistics Programme’ defines ‘general aviation’ as all civil operations other than scheduled air services and non-scheduled air transport operations for remuneration or hire. For ICAO statistical purposes, the general aviation activities are classified into instructional flying, business and pleasure flying, aerial work and other flying.

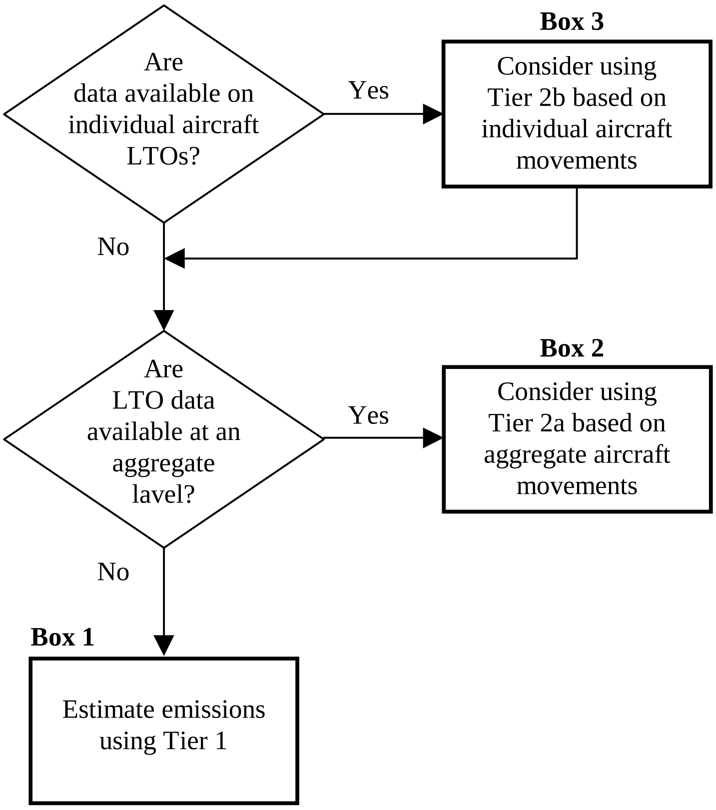
[17] Source: Olivier, 1995. This percentage will vary according to national circumstances and countries are encouraged to make their own assessment.

[18] Both a single landing together with a single take-off define one LTO operation that includes all activities near the airport that take place under an altitude of 914 m (3000 feet): engines running idle, taxi-in and out, take-off, climbing and descending. Aircraft operations above 914 m are defined as ‘cruise’.

distinction is made between emissions below and above 914 m (3000 feet) to increase the accuracy of the estimates as emission factors and fuel use factors vary between phases of the flight. The emissions in these two flying phases are estimated separately, in order to harmonise with methods that were developed for air pollution programmes that cover only emissions below 3000 feet. Emissions and fuel used in the LTO phase are estimated from statistics on the number of LTOs (aggregate or per aircraft type) and default emission factors or fuel use factors per LTO cycle (average or per aircraft type).

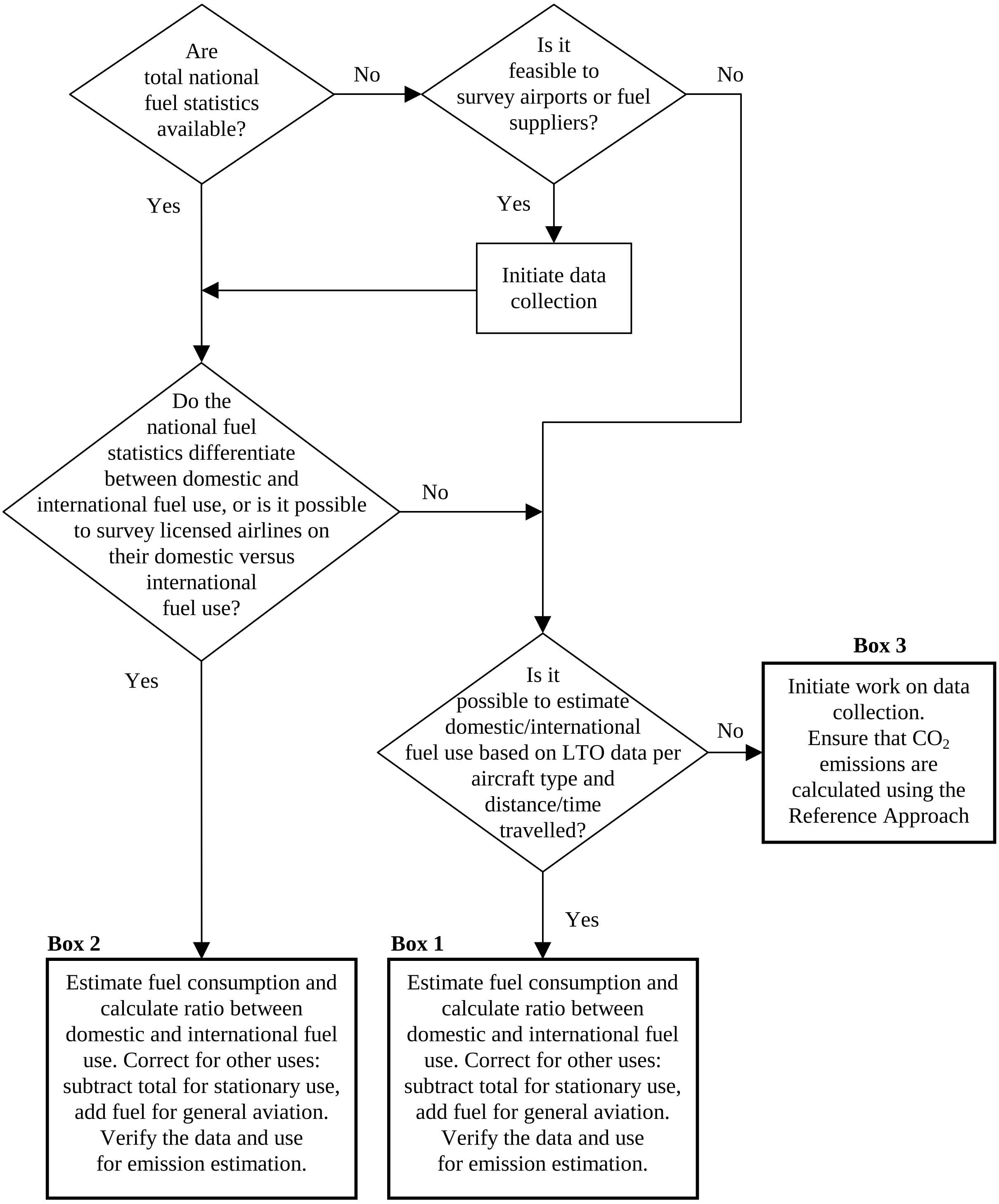
There may be significant discrepancies between the results of a bottom-up approach and a top-down fuel-based approach for aircraft. An example is presented in Daggett *et al*. (1999).

Figure 2.7 Methodology Decision Tree for Aircraft



Note 1: There is no key source decision in this decision tree because there is no gain in inventory quality by moving from Tier 1 to Tier 2 if activity data are not complete. Inventory agencies should use the most appropriate method, given the availability of data.

Figure 2.8 Activity Data Decision Tree for Aircraft



Both Tier 2 approaches use Equations 2.8 to 2.11 to estimate emissions:

EQUATION 2.8

$$\text{Emissions} = \text{LTO Emissions} + \text{Cruise Emissions}$$

Where

EQUATION 2.9

$$\text{LTO Emissions} = \text{Number of LTOs} \bullet \text{Emission Factor}_{\text{LTO}}$$

EQUATION 2.10

$$\text{LTO Fuel Consumption} = \text{Number of LTOs} \bullet \text{Fuel Consumption per LTO}$$

EQUATION 2.11

$$\text{Cruise Emissions} = (\text{Total Fuel Consumption} - \text{LTO Fuel Consumption}) \bullet \text{Emission Factor}_{\text{CRUISE}}$$

These equations can be applied at either the aggregated level of all aircraft (Tier 2a) or at the level of individual aircraft types (Tier 2b). For the Tier 2b approach, the estimate should include all aircraft types frequently used for domestic and international aviation. For the Tier 2a approach, all aircraft are included and the *IPCC Guidelines* provide aggregate emission factors per LTO. The aggregated emission factors are proposed for national and international aviation separately, and for an old and average fleet.

Cruise emissions depend on the length of the flight among other variables. In the Tier 2 method the fuel used in the cruise phase is estimated as total fuel use minus fuel used in the LTO phase of the flight as shown in Equation 2.11. Fuel use is estimated for domestic and international aviation separately. The estimated fuel use is multiplied by aggregate emission factors (average or per aircraft type) in order to estimate the emissions.

The resource demand for the various tiers depends on the number of air traffic movements and the availability of the data in the country. Tier 1 and Tier 2a, based on aggregate LTO data, should not require considerable resources, while Tier 2b, based on individual aircraft, may be very time consuming.

2.5.1.2 CHOICE OF EMISSION FACTORS

It is *good practice* to use emission factors from the *IPCC Guidelines*. National emission factors for CO_2 should not deviate much from the default values because the quality of jet fuel is well defined. However, there is limited information on the emission factors for CH_4 and N_2O from aircraft, and the IPCC default values are similar to values found in the literature. Since aircraft technologies do not vary by country, national emission factors should generally not be used unless based on peer reviewed studies.

Within this sector, different types of aircraft/engine combinations have specific emission factors and these factors may also vary according to distance flown. It has been assumed that all aircraft have the same emission factors for CH_4 and N_2O based on the rate of fuel consumption. This assumption has been made because more disaggregated emission factors are not available.

MILITARY

Emissions from military aviation may be estimated by the Tier 1 approach (total fuel use and average emission factors). However, the term ‘military aircraft’ covers very different technologies (e.g. transport planes, helicopters and fighters) and the use of a more detailed method is encouraged if data are available. No emission factors for N_2O and CH_4 have been developed for military aviation. However, many types of military transport aircraft and helicopters have fuel and emissions characteristics similar to civil types. The default emission factors for civil aircraft should be used for military aviation unless better data are available. For fuel use factors see ‘Choice of activity data’ below.

2.5.1.3 CHOICE OF ACTIVITY DATA

According to the *IPCC Guidelines*, emissions from domestic aviation are reported separately from international aviation. For this reason, it is necessary to disaggregate fuel use into domestic and international components. Table 2.9, Distinction between Domestic and International Flights presents *good practice* in flight classification. These definitions are a precision of the ones given the *IPCC Guidelines*. These definitions should be applied irrespective of the nationality of the carrier.[19]

TABLE 2.9

DISTINCTION BETWEEN DOMESTIC AND INTERNATIONAL FLIGHTS

	Domestic	**International**
Depart and arrive in same country	Yes	No
Depart from one country and arrive in another	No	Yes
Depart in one country, stop in the same country without dropping or picking up any passengers or freight, then depart again to arrive in another country	No	Yes
Depart in one country, stop in the same country and drop and pick up passengers or freight, then depart finally arriving in another country	Domestic stage	International stage
Depart in one country, stop in the same country, only pick up more passengers or freight and then depart finally arriving in another country	No	Yes
Departs in one country with a destination in another country, and makes an intermediate stop in the destination country where no passengers or cargo are loaded.	No	Both segments international

For consistency, it is *good practice* to use similar definitions of domestic and international activities in the aviation and water-borne navigation estimates.

Fuel use data distinguished between domestic and international aviation may be obtained in different ways. What is feasible will depend on national circumstances, but some data sources (e.g. energy statistics or surveys) will give more accurate results than others. The following data sources should be evaluated:

Bottom-up data can be obtained from surveys of airline companies for fuel used, or estimates from aircraft movement data and standard tables of fuel consumed or both.

Top-down data can be obtained from national energy statistics or surveys of:

- Airports for data covering the delivery of aviation kerosene and aviation gasoline;
- Fuel suppliers (quantity of aviation fuel delivered);
- Refineries (production of aviation fuels), to be corrected for import and export.

Fuel consumption factors for aircraft (fuel used per LTO and per nautical mile cruised) can be used for estimates and may be obtained from the airline companies. Table 2.10, Fuel Use and Average Sector Distance for Representative Types of Aircraft, shown in Appendix 2.5A.1 shows the data derived for the sixteen aircraft types used to represent the world's commercial passenger fleet in the ANCAT/EC2 global inventory[20] (ANCAT/EC2, 1998) plus three aircraft which subsequently came into revenue service (Falk, 1999). Similar data could be

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[19] The treatment of domestic and international aviation, both in the *IPCC Guidelines* and in Table 2.9 above, differs from that recommended to states by the International Civil Aviation Organization for the purposes of classifying flight stages when reporting air carrier statistical data (ICAO, 1997). In this context, ICAO defines as domestic, all flight stages flown between domestic points by an air carrier whose principal place of business is in that state and therefore (i) includes flight stages between domestic points that precede a flight stage to another country, and (ii) excludes flights between domestic points by foreign carriers.

[20] The ANCAT/EC2 global inventory was a programme that was part-funded by the EC to produce a world-wide 3D gridded inventory of fuel used and NO_x produced from civil commercial and bizjet aircraft, cargo planes and military operations. The base year was 1991/92 and the forecast year was 2015. The data were gridded into $1^o \bullet 1^o \bullet 1$ km boxes by summing individual movements. The results of the ANCAT/EC2 and NASA inventories were similar to each other.

obtained from other sources (e.g. EMEP/CORINAIR inventory guidebook, second edition, 1999). The equivalent data for turboprop and piston engine aircraft need to be obtained from other sources. The relationship between actual aircraft and representative aircraft is shown in Table 2.11, Correspondence between Representative Aircraft and Other Aircraft Types in Appendix 2.5A.2.

Aircraft movement data may be obtained from:

- Statistical offices or transport ministries as a part of national statistics;
- Airport records;
- ATC (Air Traffic Control) records, for example EUROCONTROL statistics;
- OAG (Official Airline Guide), published by Reed Publishing (monthly) which contains timetable passenger and freight movements, but does not contain non-scheduled traffic (e.g. passenger charter and non-scheduled freight operations);
- Passenger numbers and cargo tonnage data (these are not very reliable because of variations in load factor and type of aircraft used).

Note that some of these sources do not cover all flights (e.g. charter flights may be excluded). On the other hand, airline guide data may count some flights more than once (Baughcum *et al*., 1996). Whatever data source is used, inventory agencies must assure completeness. If fuel data for domestic aviation are not readily available, both data collection and estimation will usually be time consuming to perform.

MILITARY

Due to confidentiality concerns, it may be difficult to obtain data covering the quantity of fuel used by the military. This will have consequences for transparency and possibly completeness. Military activity is defined as those activities for which aviation fuel has been purchased by, or supplied to, the military authority of the country. It is *good practice* to apply the rules defining civilian national and international operations in aviation to military operations where they are comparable. Where they are not comparable, it is *good practice* to explain decisions on national and international operations. Unless better information is available, all the fuel should be allocated as domestic. Data on military fuel use may be sought from the military authorities themselves and the fuel suppliers.

The *IPCC Guidelines* do not provide a method to assess the quantity of fuel from military aviation although military fuel use should be available from national data sources. An estimate of fuel used for military aviation is given in ANCAT/EC2 (1998) (transport and tanker, fighter/bomber and light aircraft/helicopters) together with the method used to obtain it. Methods for estimating CH_4 and N_2O emissions are not included.

Alternatively, fuel use may be estimated from the hours in operation. Default fuel consumption factors are given in Table 2.12, Fuel Consumption Factors for Military Aircraft shown in Appendix 2.5A.3.

According to COP Decision 2/CP3 a multilateral operation should not be included in national totals but reported separately, although there is no clear operational definition of ‘multilateral operation’ available at this time.

2.5.1.4 COMPLETENESS

Regardless of method, it is important to account for all fuel sold for aviation in the country. The methods are based on total fuel use, and should completely cover CO_2 emissions. However, the Tier 2 methods focus on passenger and freight carrying scheduled and charter flights, and not all aviation. In addition, they do not automatically include non-scheduled flights and general aviation such as agricultural airplanes, private jets or helicopters, which should be added if the quantity of fuel is significant. Completeness may also be an issue where military data are confidential, unless military fuel use is aggregated with another source category.

2.5.1.5 DEVELOPING A CONSISTENT TIME SERIES

Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques provides more information on how to develop emission estimates in cases where the same data sets or methods cannot be used during every year of the time series. If activity data are unavailable for the base year (e.g. 1990) an option may be to extrapolate data to this year by using changes in freight and passenger kilometres, total fuel used or supplied, or the number of LTOs (aircraft movements).

Emissions trends of CH_4 and NO_x (and by inference N_2O) will depend on aircraft engine technology and the change in composition of a country's fleet. This change in fleet composition may have to be accounted for in the future, and this is best accomplished using the Tier 2b method based on individual aircraft types for 1990 and subsequent years. If fleet composition is not changing, the same set of emission factors should be used for all years.

Every method should be able to reflect accurately the results of mitigation options that lead to changes in fuel use. Only the Tier 2b method, based on individual aircraft, can capture the effect of mitigation options that result in lower emission factors.

2.5.1.6 UNCERTAINTY ASSESSMENT

ACTIVITY DATA

The uncertainty in the reporting will be strongly influenced by the accuracy of the data collected on domestic aviation separately from international aviation. With complete survey data, the uncertainty may be very low (less than 5%) while for estimates or incomplete surveys the uncertainties may become large, perhaps a factor of two for the domestic share.[21]

EMISSION FACTORS

The CO_2 emission factors should be within a range of ±5%, as they are dependent only on the carbon content of the fuel and fraction oxidised. The uncertainty of the CH_4 emission factor may be as a high as a factor of 2. The uncertainty of the N_2O emission factor may be of several orders of magnitude (i.e. a factor of 10, 100 or more).

2.5.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Section 8.10.1 of Chapter 8, Quality Assurance and Quality Control.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

Some examples of specific documentation and reporting relevant to this source category are provided below.

The *IPCC Guidelines* require that inventory agencies report emissions from international aviation separately from domestic aviation, and exclude international aviation from national totals. It is expected that all countries have aviation activity and should therefore report emissions from this category. Though countries covering small areas might not have domestic aviation, emissions from international aviation should be reported.

Transparency would be improved if inventory agencies report emissions from LTO separately from cruise operations (defined here as operations above 3000 feet or 914 m).

Emissions from military aviation should be clearly specified, so as to improve the transparency on national greenhouse gas inventories.

In addition to the standard reporting required in the *IPCC Guidelines*, provision of the following data would increase transparency:

- Sources of fuel data and other essential data (e.g. fuel consumption factors) depending on the method used;
- The number of flight movements split between domestic and international;
- Emission factors used, if different from default values. Data sources should be referenced.

Inventory agencies should provide the definition of international and domestic that has been used and document why and how it was applied.

Confidentiality may be a problem if only one or two airline companies operate domestic transport in a given country. Confidentiality may also be a problem for reporting military aviation in a transparent manner.

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[21] The uncertainty ranges cited in this section represent an informal polling of assembled experts aiming to approximate the 95% confidence interval around the central estimate.

2.5.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8 and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of emissions using alternative approaches

The inventory agency should compare the emission estimates for aircraft using both Tier 1 and Tier 2 approaches. Any anomaly between the emission estimates should be investigated and explained. The results of such comparisons should be recorded for internal documentation.

Review of Emission factors

If national factors are used rather than the default values, directly reference the QC review associated with the publication of the emission factors, and include this review in the QA/QC documentation to ensure that the procedures are consistent with *good practice*. If possible, the inventory agency should compare the IPCC default values to national factors to provide further indication that the factors are applicable. If emissions from military use were developed using data other than the default factors, the accuracy of the calculations and the applicability and relevance of the data should be checked.

Activity data check

The source of the activity data should be reviewed to ensure applicability and relevance to the source category. Where possible, the inventory agency should compare current data to historical activity data or model outputs to look for anomalies. In preparing the inventory estimates, the inventory agency should ensure the reliability of the activity data used to allocate emissions between domestic and international aviation.

Data could be checked with productivity indicators such as fuel per unit of traffic performance (per passenger km or ton km). Where data from different countries are being compared, the band of data should be small.

External review

The inventory agency should perform an independent, objective review of calculations, assumptions or documentation of the emissions inventory to assess the effectiveness of the QC programme. The peer review should be performed by expert(s) (e.g. aviation authorities, airline companies, and military staff) who are familiar with the source category and who understand inventory requirements.

Appendix 2.5A.1 Fuel use and average sector distance for representative types of aircraft

TABLE 2.10

FUEL USE AND AVERAGE SECTOR DISTANCE FOR REPRESENTATIVE TYPES OF AIRCRAFT

	Aircraft								
	A310	**A320**	**A330 300 LR**	**A340**	**BAC1-11**	**BAe 146**	**B727**	**B737 100-200**	**B737 400**
Average sector distance in nautical miles (nm)									
Total flight	1 228	663	1 087	2 860	465	327	583	504	531
Climb	81	159	113	111	143	106	117	127	100
Cruise	1 034	393	832	2 615	234	152	384	291	339
Descent	113	111	142	134	88	69	82	86	92
Fuel use (kg)									
Total flight	12 160	4 342	15 108	37 317	2 965	2 272	6 269	3 747	3 750
LTO (flight < 3000 ft)	1 541	802	2 232	2 020	682	570	1 413	920	825
Flight minus LTO (flight > 3000 ft)	10 620	3 539	12 876	35 298	2 284	1 702	4 856	2 827	2 925
Fuel use (kg per nm)									
Flight minus LTO (flight > 3000 ft)	8.65	5.34	11.85	12.34	4.91	5.21	8.33	5.61	5.51

These data should be used with care as national circumstances may vary from those assumed in this table. In particular, distances travelled and fuel consumption may be affected by national route structures, airport congestion and air traffic control practices. Fuel consumption may also be affected by wind. For example, since westbound transatlantic flights usually take more time and burn more fuel than eastbound ones, use of the averages in the table (or those in the *IPCC Guidelines*) may underestimate fuel consumption of westbound flights (reported by e.g. European countries) and overestimate eastbound (reported by e.g. USA or Canada).

TABLE 2.10 (CONTINUED)

FUEL USE AND AVERAGE SECTOR DISTANCE FOR REPRESENTATIVE TYPES OF AIRCRAFT

	Aircraft									
	B747 100-300	**B747 400**	**B757**	**B767 300 ER**	**B777**	**F28**	**F100**	**DC9**	**DC10-30**	**MD 82-88**
Average sector distance in nautical miles (nm)										
Total flight	2 741	2 938	958	1 434	1 579	295	360	384	2 118	557
Climb	152	95	106	100	112	131	118	118	117	161
Cruise	2 480	2 727	744	1 205	1 325	91	158	182	1 902	306
Descent	109	116	108	129	141	73	84	84	99	90
Fuel use (kg)										
Total flight	60 705	58 325	8 111	14 806	23 627	2 104	2 597	3 202	35 171	4 872
LTO (flight < 3000 ft)	3 414	3 402	1 253	1 617	2 563	666	744	876	2 381	1 003
Flight minus LTO (flight > 3000 ft)	57 291	54 923	6 858	13 189	21 064	1 438	1 853	2 326	32 790	3 869
Fuel use (kg per nm)										
Flight minus LTO (flight > 3000 ft)	20.90	18.69	7.16	9.20	13.34	4.87	5.15	6.06	15.48	6.95

Source: ANCAT/EC2 and UK Department of Trade and Industry (DTI/EID3cC/199803).

Appendix 2.5A.2 Correspondence between representative aircraft and other aircraft types

TABLE 2.11
CORRESPONDENCE BETWEEN REPRESENTATIVE AIRCRAFT AND OTHER AIRCRAFT TYPES

Generic aircraft type	ICAO	IATA aircraft in group	Generic aircraft type	ICAO	IATA aircraft in group	Generic aircraft type	ICAO	IATA aircraft in group	Generic aircraft type	ICAO	IATA aircraft in group
BAe 146	BA46	141	Airbus A320	A320	320	Boeing 747-400	B744	744	McDonnell Douglas DC10	DC10	D10
		143			32S	Boeing 757		757			D11
		146			321			75F			D1C
		14F	Airbus A319	A319	319			TR2			D1F
Airbus A310	A310	310	Airbus A330	A330	330	Boeing 767		762			L10
		312			332			763			L11
		313			333			767			L12
		A31	Airbus A340	A340	340			AB3			L15
Boeing 727-100	B721	721			342			AB6			M11
Boeing 727-200	B722	722			343			A3E			M1F
Boeing 727-300	B727	727	BAe 111	BA11	B11			ABF	McDonnell Douglas DC8		DC8
		72A			B15			AB4			D8F
		72F			CRV	Boeing 777		777			D8M
		72M			F23	Boeing 777-200	B772	772			D8S
		72S			F24	Boeing 777-300	B773	773			707
		TU5			YK4	McDonnell Douglas DC-9		D92			70F
Boeing 737-200	B732	732	Boeing 747-100-300	B741	741			D93			IL6
Boeing 737-500	B735	735		B742	742			D94			B72
		73A		B743	743			D95			
		73B			747			D98			
		73F			74D			D9S			
		73M			74E			DC9			
		73S			74F			F21			
		D86			A4F			TRD			
		JET			74L			YK2			
		DAM			74M	McDonnell Douglas M81-88	MD81-88	M80			

TABLE 2.11 (CONTINUED)
CORRESPONDENCE BETWEEN REPRESENTATIVE AIRCRAFT AND OTHER AIRCRAFT TYPES

Generic aircraft type	ICAO	IATA aircraft in group	Generic aircraft type	ICAO	IATA aircraft in group	Generic aircraft type	ICAO	IATA aircraft in group	Generic aircraft type	ICAO	IATA aircraft in group
Boeing 737-300	B733	733			IL7			M82			
Boeing 737-700	B737	737			ILW			M83			
Fokker 100	F100	100			NIM			M87			
Fokker F-28	F28	F28			VCX			M88			
		TU3			C51						

MD90 goes as MD81-88 and B737-600 goes as B737-400. DC8 goes as double the B737-100.

Source: Falk (1999b) and EMEP/CORINAIR (1999).

Appendix 2.5A.3 Fuel consumption factors for military aircraft

TABLE 2.12

FUEL CONSUMPTION FACTORS FOR MILITARY AIRCRAFT

Group	Sub-group	Representative type	Fuel flow (kg/hour)
Combat	Fast Jet - High Thrust	F16	3 283
	Fast Jet - Low Thrust	Tiger F-5E	2 100
Trainer	Jet trainers	Hawk	720
	Turboprop trainers	PC-7	120
Tanker/Transport	Large Tanker/Transport	C-130	2 225
	Small Transport	ATP	499
Other	MPAs, Maritime Patrol	C-130	2 225

Source: Tables 3.1 and 3.2 of ANCAT/EC2 1998, British Aerospace/Airbus.

TABLE 2.13

ANNUAL AVERAGE FUEL CONSUMPTION PER FLIGHT HOUR FOR UNITED STATES MILITARY AIRCRAFT ENGAGED IN PEACETIME TRAINING OPERATIONS

Aircraft Type	Aircraft Description	Fuel Use (Litres per Hour)
A-10A	Twin engine light bomber	2 331
B-1B	Four engine long-range strategic bomber. Used by USA only	13 959
B-52H	Eight engine long-range strategic bomber. Used by USA only.	12 833
C-12J	Twin turboprop light transport. Beech King Air variant.	398
C-130E	Four turboprop transport. Used by many countries.	2 956
C-141B	Four engine long-range transport. Used by USA only	7 849
C-5B	Four engine long-range heavy transport. Used by USA only	13 473
C-9C	Twin engine transport. Military variant of DC-9.	3 745
E-4B	Four engine transport. Military variant of Boeing 747.	17 339
F-15D	Twin engine fighter.	5 825
F-15E	Twin engine fighter-bomber	6 951
F-16C	Single engine fighter. Used by many countries.	3 252
KC-10A	Three engine tanker. Military variant of DC-10	10 002
KC-135E	Four engine tanker. Military variant of Boeing 707.	7 134
KC-135R	Four engine tanker with newer engines. Boeing 707 variant.	6 064
T-37B	Twin engine jet trainer.	694
T-38A	Twin engine jet trainer. Similar to F-5.	262

These data should be used with care as national circumstances may vary from those assumed in this table. In particular, distances travelled and fuel consumption may be affected by national route structures, airport congestion and air traffic control practices.

Source: US Environmental Protection Agency, Inventory of US Greenhouse Gas Emissions and Sinks, 1990-1998, EPA-236-R-00-001 (Forthcoming, April 2000). Data provided by the US Department of Defense.

2.6 FUGITIVE EMISSIONS FROM COAL MINING AND HANDLING

2.6.1 Methodological issues

The geological process of coal formation also produces methane (CH_4), some of which remains trapped in the coal seam until it is mined. Generally, deeper underground coal seams contain more *in-situ* methane than shallower surface seams. Consequently, the majority of emissions come from deep underground mines. Additional emissions come from open-pit mines and post-mining activities.

2.6.1.1 CHOICE OF METHOD

Those coal-mining countries whose major production is from underground mining, particularly longwall operations, the emissions from this sub-source category will dominate and efforts should focus on this part of the overall coal estimate. However, where there is extensive open-cut mining such as in Australia, emissions from this activity can also be significant. Figure 2.9, Decision Tree for Surface Coal Mining and Handling, to Figure 2.11, Decision Tree for Post-mining provide guidance in choosing the appropriate method for all sources of coal mine methane. The *IPCC Guidelines* give the following general equation for estimating emissions:

EQUATION 2.12

$$\text{Emissions} = \text{Coal Production (Surface or Underground)} \bullet \text{Emission Factor}$$

The Tier 2 approach is to use country or basin-specific emission factors that reflect the average methane content of coal actually mined. The Tier 1 default approach requires that countries choose from a global average range of emission factors, and is more uncertain as a consequence. For underground mines, actual measurement data may be available. Although not specified explicitly as Tier 3 in the coal chapter of the *IPCC Guidelines*, the use of measurement data is generally regarded as a Tier 3 approach.

Total annual emissions are calculated according to the following equation:

EQUATION 2.13

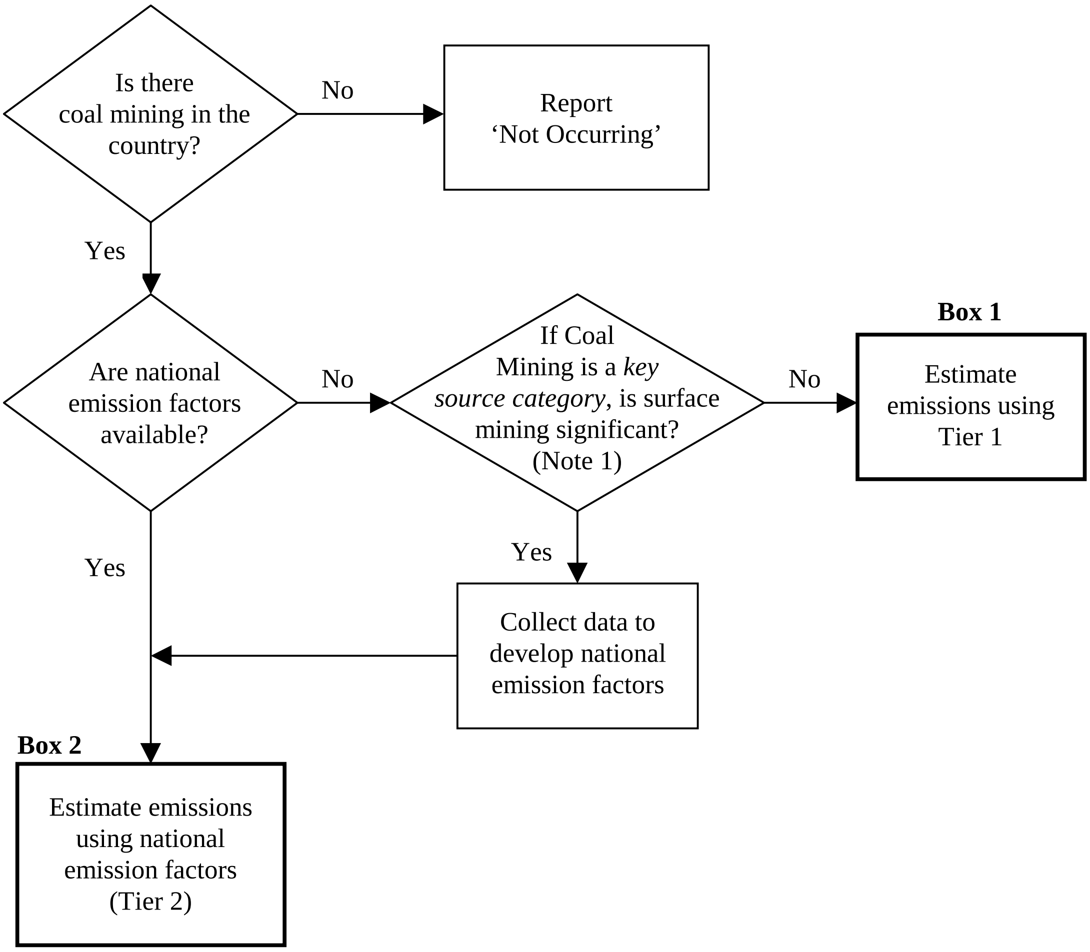
$$\text{Total Emissions} = \text{Underground Mining Emissions} + \text{Surface Mining Emissions} + \text{Post-Mining Emissions} - \text{Methane Recovered and Used or Flared}$$

UNDERGROUND MINING

Emissions from underground mining come from ventilation systems and degasification systems. Ventilation systems are a safety requirement at underground mines and dilute the ambient methane concentration of mine air below a dangerous level by flushing the mine with air from the surface. Degasification systems are wells drilled before, during, and after mining to drain methane from the coal seam itself.

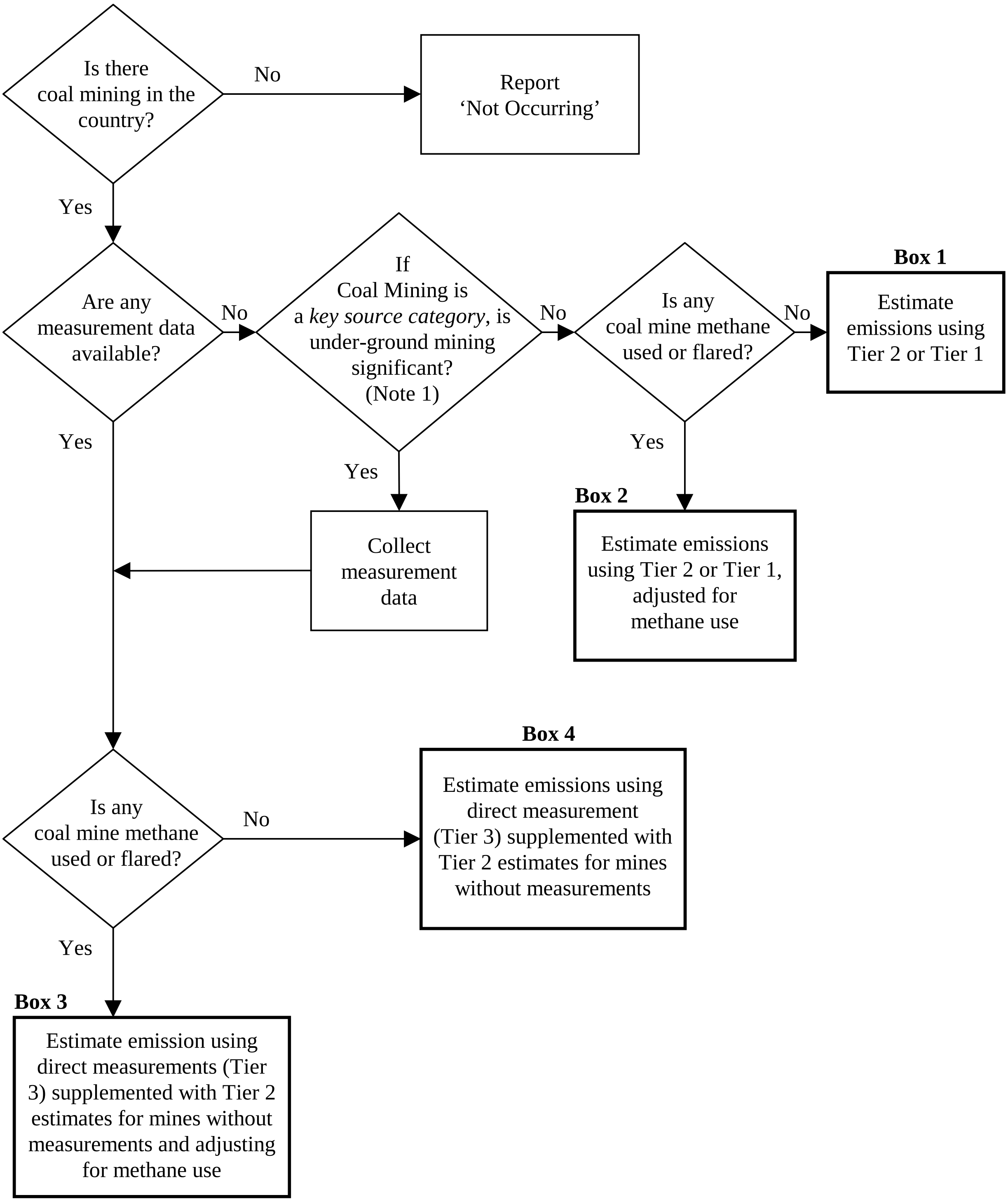
For countries with underground mining operations, it is *good practice* to collect data for the Tier 3 method if the mine-specific measurement data are available for safety reasons. Mine-specific data, based on ventilation air measurements and degasification system measurements, reflect actual emissions on a mine-by-mine basis, and therefore produce a more accurate estimate than emission factors. This is due to the variability of *in-situ* gas content of coal and its geological environment. As emissions vary greatly over the course of a year, *good practice* is to collect measurement data at least every two weeks to smooth out variations. Daily measurements would ensure a higher quality estimate. Continuous monitoring of emissions represents the highest stage of emission monitoring, and is implemented in some modern longwall mines, but it is not necessary for *good practice*.

Figure 2.9 Decision Tree for Surface Coal Mining and Handling



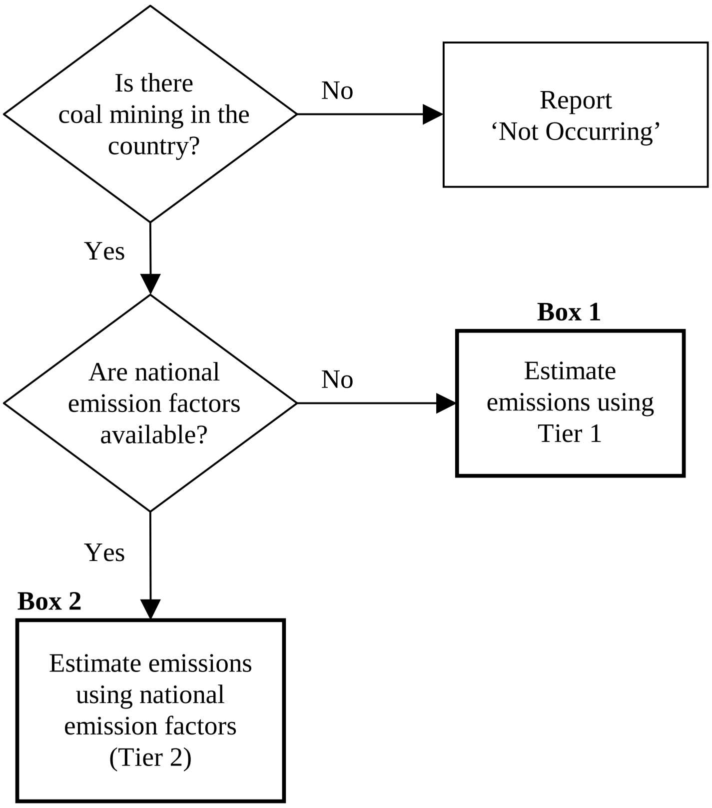
Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Figure 2.10 Decision Tree for Underground Coal Mining and Handling



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Figure 2.11 Decision Tree for Post-mining



High quality measurements of methane drained by degasification systems should also be available from mine operators for those mines where drainage is practised. If detailed data on drainage rates are absent, *good practice* is to obtain data on the efficiency of the systems (i.e. the fraction of gas drained) or to make an estimate of this fraction from a range (e.g. 30-50%, typical of many degasification systems). Another option is to compare conditions with associated mines where data are available. In cases where drainage occurs years in advance of mining, methane recovery should be accounted for in the year in which the source coal seam is extracted. Methane recovered from degasification systems and vented to the atmosphere prior to mining should be added to the amount of additional methane released through ventilation systems so that the total estimate is complete. In some cases, because degasification system data are considered confidential, it may be necessary to estimate degasification system collection efficiency, and then subtract known reductions to arrive at the net degasification system emissions.

An alternative hybrid Tier 3 - Tier 2 approach is appropriate in situations when mine-specific measurement data are available only for a subset of underground mines. For example, if only gassy mines report data, emissions from the remaining mines can be calculated with Tier 2 emission factors. These factors could be based on specific emission rates derived from Tier 3 data if the mines are operating within the same basin as the Tier 3 mines, or on the basis of mine-specific properties, such as the average depth of the coal mines.

Comprehensive mine-by-mine (i.e. Tier 3) data may be available for some but not all years. If there have been no major changes in the population of active mines, emissions can be scaled to production for the missing years. If there were changes in the mine population, the mines involved can be removed from the scaling extrapolation and handled separately. However, care must be taken in scaling because the coal being mined, the virgin exposed coal and the disturbed mining zone have different emission rates. Furthermore, mines may have a high background emission level that is independent of production.

When no mine-by-mine data are available, inventory agencies should employ the Tier 2 method (country or basin-specific emission factors). For some countries, it may be necessary to separate the mine production into production from larger mines (Tier 2) and smaller independent mines (Tier 1) if smaller mines exhibit significantly different methane emission patterns (e.g. shallower seams).

SURFACE MINING

It is not feasible to collect mine-by-mine Tier 3 measurement data for surface mines. The alternative is to collect data on surface mine production and apply emission factors. For countries with significant coal production and multiple coal basins, disaggregation to the basin level will improve accuracy. Given the uncertainty of production-based emission factors, picking emission factors from the range specified by the *IPCC Guidelines* can provide a reasonable estimate.

POST-MINING

Methane still present in the coal after mining will escape to the atmosphere eventually. Measurement of post-mining emissions is not feasible, however, so an emission factor approach must be used. The Tier 2 and Tier 1 methods in the *IPCC Guidelines* should be reasonable for this source, given the difficulty of obtaining better data.

RECOVERY OF METHANE FOR UTILISATION OR FLARING

If methane is drained from coal seams and subsequently flared or used as a fuel, it is *good practice* to subtract this amount from the total estimate of emissions. (Emissions from combustion of recovered methane should be accounted for appropriately in the combustion section.) Where utilisation data are not directly available from mine operators, gas sales could be used as a proxy. If gas sales are unavailable, the alternative is to estimate the amount of utilised methane from the known efficiency specifications of the drainage system.

In some countries, it is common practice to drain and utilise coal bed methane many years prior to mining. In other instances, gas wells are drilled in coal seams that are too deep to be mined. Fugitive emissions up to the point of utilisation should be counted in coal mining activities. Subsequent downstream emissions should be allocated to the source category appropriate to the manner of utilisation. Examples include oil and natural gas when the methane is fed to the natural gas grid and to electricity autoproducers when used to generate electricity. Note that where coal seam methane is recovered with no intention of mining the coal, emissions fall within the oil and natural gas source category.

The estimate of CH_4 emissions from coal mining may or may not need to be corrected for the amount of gas released depending on whether:

- The coal is extracted a few years later and the CH_4 emissions estimate for that year is based on average emission factors that do not take account of early gas draining; in this case a correction is needed for the year of extraction;
- The coal is extracted a few years later and the CH_4 emissions estimate is based on direct emissions measurements. In this case no correction is needed;
- The coal is never extracted (e.g. due to changes in plans or because it was never the intention). In this case no correction is needed.

Flaring is an option for reducing methane emissions from coal mines, and is practised at some coal mines. Data on the amount of methane flared should be obtained from mine operators with the same frequency of measurement as pertains to underground mine emissions generally.

2.6.1.2 CHOICE OF EMISSION FACTORS

UNDERGROUND MINING

Tier 3: The Tier 3 method does not use production-based emission factors, but rather actual measurement data that account for the temporal and spatial variability in coal mine emissions. As this is by far the most reliable method, inventory agencies should make every effort to collect these data if underground mining is a *key sub-source category*.

Tier 2: Country-specific emission factors can be obtained from sample ventilation air data, or from a quantitative relationship that accounts for the gas content of the coal seam and the surrounding strata affected by the mining process. For a typical longwall operation, the amount of gas released comes from the coal being extracted and from the coal and any other gas bearing strata 150 m above and 50 m below the mined seam. Where such relationships are used, they should be peer-reviewed and well documented.

Tier 1: Inventory agencies choosing from the emission factor range (10-25 m^3/tonne) in the Tier 1 methodology should consider country-specific variables such as depth of major coal seams. As gas content of coal usually increases with depth, the low end of the range should be chosen for average mining depths of <200 m, and for depths of > 400 m the high value is appropriate. For intermediate depths, intermediate values can be chosen.

SURFACE MINING

There are few measurements of methane emissions from surface mining. They are difficult and expensive to carry out and no routine methods are currently available. Data on *in-situ* gas contents before overburden removal are also very scarce, and in freshly uncovered coal the gas content is often close to zero. Where local data on emissions are available, they should be used.

For the Tier 1 approach, it is *good practice* to use the low end of the specific emission range for those mines with average overburden depths of <25 m and the high end for overburden depths over 50 meters. For intermediate depths, intermediate values for the emission factors may be used. In the absence of data on overburden thickness, it is *good practice* to use an emission factor towards the high end of the range, namely 1.5 m^3/tonne.

POST-MINING EMISSIONS – UNDERGROUND

Measurements on coal as it emerges on a conveyor from a mine without pre-mining degasification indicate that 25-40% of the *in-situ* gas is still in the coal (Williams and Saghafi, 1993). For mines that practice pre-drainage, the amount of gas in coal will be less by some unknown amount.

For mines with no pre-drainage, but with knowledge of the *in-situ* gas content, it is reasonable to set the post mining emission factor at 30% of this value. For mines with pre-drainage, an emission factor of 10% of the *in-situ* gas content is suggested. Where there are no *in-situ* gas content data or where pre-drainage is practised, but to an unknown extent, a reasonable approach is to increase overall underground emissions by 3% (Williams *et al*., 1993; Riemer, 1999).

POST-MINING EMISSIONS – SURFACE MINING

Unless there are data to the contrary, emissions from this sub-source category are assumed to be negligible, as the gas content of surface coal are typically very low. Emissions can be viewed as being accommodated within the surface emission factor.

2.6.1.3 CHOICE OF ACTIVITY DATA

For the Tier 3 method, coal production data are not necessary because actual measurements are available. However, it is *good practice* to collect and report these data to illustrate the relationship, if any, between underground coal production and actual emissions on an annual basis.

The activity data for Tiers 1 and 2 are coal production. Mine operators are likely to know more about coal production than methane emissions, but inventory agencies need to consider how the information is collected. For example, using cleaned coal production data instead of raw coal production data will change the final emissions estimate because emission factors are expressed in cubic meters per ton. Variable moisture content is another important issue.

If the data on raw coal production are available these should be used. If coal is not sent to a coal preparation plant or washery (used to upgrade the raw ‘run of mine’ coal by removing some of the mineral matter), then raw coal production equals the amount of saleable coal.

Where coal is upgraded, some coal is rejected in the form of coarse discards containing high mineral matter and also in the form of unrecoverable fines. The amount of waste is typically around 20% of the weight of raw coal feed, but may vary considerably by country. Where activity data are in the form of saleable coal, some effort should be made to determine the amount of production that is washed. Raw coal production is then estimated by increasing the amount of ‘saleable coal’ by the fraction lost through washing.

An alternative approach that may be more suitable for mines whose raw coal output contains rock from the roof or floor as a deliberate part of the extraction process, is to use saleable coal data, provided the emission factors used refer to clean coal not raw coal. This should be noted in the inventory.

2.6.1.4 COMPLETENESS

UNDERGROUND MINING

The estimate of emissions from underground mining should include both ventilation systems and degasification systems when both are present.

ABANDONED MINES

No method currently exists for estimating emissions from this sub-source category. For mines that are flooded, emissions are likely to be prevented, but some leakage is likely in mines that are sealed mechanically. *Good practice* is to record the date of mine closure and the method of sealing. Data on the size and depth of such mines would be useful for any post hoc estimation.

CO_2 IN SEAM GAS

Countries with significant quantities of CO_2 in their coal seam gas should make efforts to evaluate or quantify these emissions.

COAL FIRES, COMBUSTION AND OXIDATION OF WASTE COAL AND OTHER CARBONACEOUS MATERIALS (CO_2)

IPCC recognises that there are emissions from these sub-source categories, but does not provide methods. Emissions could be significant, but are very difficult to estimate.

2.6.1.5 DEVELOPING A CONSISTENT TIME SERIES

In cases where an inventory agency moves from a Tier 1 or Tier 2 to a Tier 3 method, it may be necessary to calculate implied emissions factors for years with measurement data, and apply these emission factors to coal production for years in which these data do not exist. It is important to consider if the composition of the mine population has changed dramatically during the interim period, because this could introduce uncertainty. For mines that have been abandoned since 1990, data may not be archived if the company disappears. These mines should be treated separately when adjusting the time series for consistency. For *good practice guidance* on ensuring time series consistency, see Chapter 7, Methodological Choice and Recalculation.

2.6.1.6 UNCERTAINTY ASSESSMENT

EMISSIONS

Tier 3

Methane emissions from underground mines have a significant natural variability. Spot measurements of $[CH_4]$ (the square brackets denote concentration) in ventilation air are probably accurate to ±20% depending on the equipment used. Time series data or repeat measurements will significantly reduce the uncertainty of annual emissions to ±5% for continuous monitoring, and 10-15% for every two weeks.[22] Ventilation airflows are usually fairly accurately known (±2%).

Spot measurement of $[CH_4]$ in drained gas (degasification systems) is likely to be accurate to ±2% because of its higher concentration. Measurements should be made with a frequency comparable to those for ventilation air to get representative sampling. Degasification flows are probably known to ±5%. Degasification flows based on gas sales are also likely to have an uncertainty of at least ±5% due to the tolerances in pipeline gas quality.

As the gas liberated (gas make) by longwall mining can vary by a factor of two during the life of a longwall panel (a 1-2 km long x 200 m wide block of coal that is extracted in the course of 6-9 months by a single longwall machine), it is necessary to make frequent measurements of underground mine emissions. Frequent measurements will also reduce the intrinsic errors in the measurement techniques. Mines with multiple longwall

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[22] The uncertainty ranges cited in this section represent an informal polling of assembled experts aiming to approximate the 95% confidence interval around the central estimate.

machines will be less subject to such wide fluctuations. There may also be uncertainty concerning utilisation of any methane gas drained years before the source coal seam is extracted.

For a single longwall operation, with continuous or daily emission measurements, the accuracy of monthly or annual average emissions data is probably ±5%. The accuracy of spot measurements performed every two weeks is ±10%, at 3-monthly intervals ±30%. Aggregating emissions from mines based on the less frequent type of measurement procedures will reduce the uncertainty caused by fluctuations in gas make. However, as fugitive emissions are often dominated by contributions from only a small number of mines, it is difficult to estimate the extent of this improvement.

Tiers 1 and 2

If a Tier 2 emission factor for underground mining is derived from Tier 3 data, then the errors or uncertainty in the Tier 3 data can flow through to the derived emission factor for Tier 2. The following table gives some impression of likely uncertainties:

TABLE 2.14

LIKELY UNCERTAINTIES OF COAL MINE METHANE EMISSION FACTORS

Method	Underground	Surface	Post-Mining
Tier 2	±50-75%	factor of 2	±50%
Tier 1	factor of 2	factor of 3	factor of 3

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts; Fugitive Emissions from Coal Mining and Handling).

ACTIVITY DATA

Coal production: Tonnages are likely to be known to 1-2%, but if raw coal data are not available, then the uncertainty will increase to about ±5%, when converting from saleable coal production data. The data are also influenced by moisture content, which is usually present at levels between 5-10%, and may not be determined with great accuracy.

Apart from measurement uncertainty, there can be further uncertainties introduced by the nature of the statistical databases that are not considered here. In countries with a mix of regulated and unregulated mines, activity data may have an uncertainty of ±10%.

2.6.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Section 8.10.1 of Chapter 8, Quality Assurance and Quality Control.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

To ensure transparency, the following information should be supplied:

- Emissions by underground, surface, and post-mining components of CH_4 and CO_2 (where appropriate), the method used for each of the sub-source categories, the number of active mines in each sub-source category and the reasons for the chosen EFs (e.g. depth of mining, data on *in-situ* gas contents etc.). The amount of drained gas and the degree of any mitigation or utilisation should be presented with a description of the technology used, where appropriate.

- Activity data: Specify the amount and type of production, underground and surface coal, listing raw and saleable amounts where available.

- Where issues of confidentiality arise, the name of the mine need not be disclosed. Most countries will have more than three mines, so mine-specific production cannot be back calculated from the emission estimates.

2.6.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8 and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of emissions using alternative approaches

The inventory agency should compare the emission estimates for fugitive methane emissions from coal mining and handling using both Tier 1 and Tier 2 approaches. If direct measurements are available, these should also be compared to the Tier 1 and 2 estimates. Large discrepancies between the emission estimates should be investigated and explained. The results of such comparisons should be recorded for internal documentation.

Review of direct emission measurements

If direct measurements are used to develop country-specific emission factors, it should be established whether measurements at the sites were made according to internationally recognised, standard methods. If the measurement practices fail this criterion, then the use of these emissions data should be carefully evaluated, uncertainty estimates reconsidered, and qualifications documented. Frequent measurements are usually required by regulatory bodies. In the absence of such regulations, measurements should be done frequently enough (weekly if possible), as emissions rates may vary considerably over the year.

Emission factors check

The inventory agency should compare measurement-based factors to IPCC defaults and factors developed by other countries with similar coal mining and handling characteristics. The QA/QC review associated with the original data should be directly referenced in the documentation.

If IPCC default factors are used, the inventory agency should ensure that they are applicable and relevant to the category. If possible, the IPCC default factors should be compared to national or local data to provide further indication that the factors are applicable.

Activity data check

The inventory agency should ensure that the data reflects raw coal production. Where possible, the data should be compared to historical activity data to look for anomalies. Compare activity data between multiple references (e.g. national statistics and mill-level data). To check methane utilisation consistency, gas or electricity sales could be used as a cross-check.

External review

The inventory agency should arrange for an independent, objective review of calculations, assumptions, and/or documentation of the emissions inventory to be performed to assess the effectiveness of the QC programme. The peer review should be performed by expert(s) who are familiar with the source category and who understand inventory requirements.

2.7 FUGITIVE EMISSIONS FROM OIL AND GAS OPERATIONS

2.7.1 Methodological issues

Fugitive emissions from oil and natural gas activities include all emissions from the exploration, production, processing, transport, and use of oil and natural gas, and from non-productive combustion (e.g. flaring and waste-gas incineration). It excludes use of oil and gas or derived products to provide energy for internal use, in energy production, processing and transport. The latter are considered fuel consumption and are addressed separately in the *IPCC Guidelines* (Sections 1.3 to 1.5).

Fugitive emissions of methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) from oil and gas operations are a source of direct and indirect greenhouse gas emissions in many countries. Unfortunately, these emissions are difficult to quantify accurately. This is largely due to the diversity of the industry, the large number and variety of potential emission sources, the wide variations in emission-control levels, and the limited availability of emission-source data. The main emission assessment issues are:

- The use of simple production-based emission factors introduces excessive error;
- The application of rigorous bottom-up approaches requires expert knowledge and detailed data that may be difficult and costly to obtain;
- Measurement programmes are time consuming and very costly to perform.

If a rigorous bottom-up approach is chosen, then it is *good practice* to involve technical representatives from the industry in the development of the inventory.

2.7.1.1 CHOICE OF METHOD

The *IPCC Guidelines* describe two methods to calculate CH_4 emissions from both the oil and gas industries (called Tier 1 and Tier 3), and one additional method (called Tier 2) to calculate CH_4 emissions only from oil systems. The Tier 3 method is a rigorous source-specific evaluation, requiring detailed inventories of infrastructure, and detailed bottom-up emission factors. The Tier 2 approach for CH_4 emissions from the oil industry is based on a mass balance estimate of the maximum amount of CH_4 that could be emitted. The Tier 1 method uses aggregate production-based emission factors and national production data.[23]

Good practice is to disaggregate the industry into the applicable segments and subcategories indicated in Table 2.15, Major Categories and Subcategories in the Oil and Gas Industry, and then evaluate the emissions separately for each of these parts. The approach to estimate emissions from each segment should be commensurate with the emissions level and the available resources. Consequently, it may be appropriate to apply different approaches to different parts of the industry, and possibly even include some direct monitoring of emission sources. The overall approach, over time, should be one of progressive refinement to address the areas of greatest uncertainty and consequence, and to capture the impact of specific control measures.

Figure 2.12 provides a general decision tree for Natural Gas Systems for selecting an appropriate approach for a given segment of the natural gas system. Similarly, Figures 2.13 and 2.14 apply to oil production and transport systems, and to oil upgraders and refineries, respectively.

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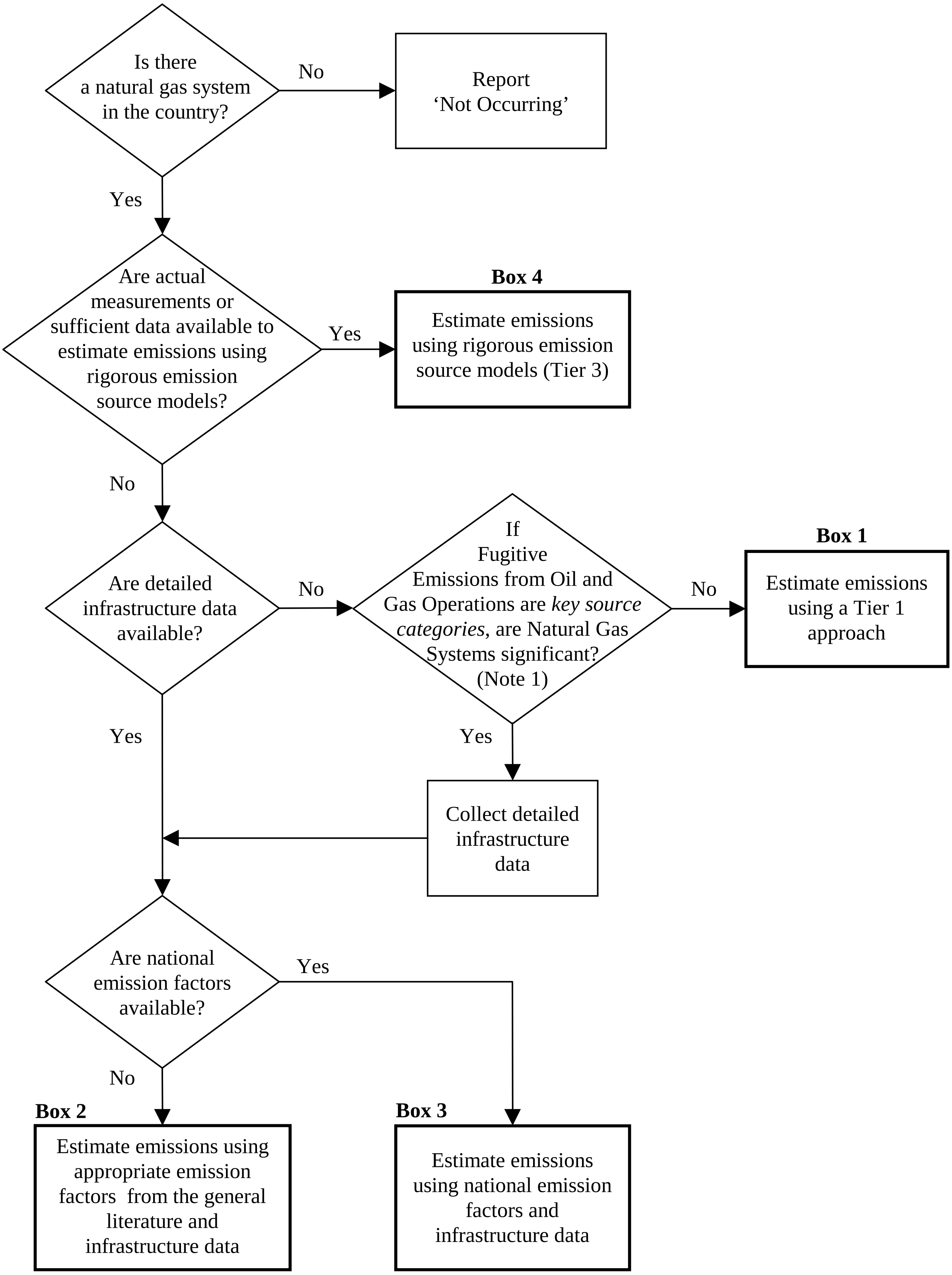
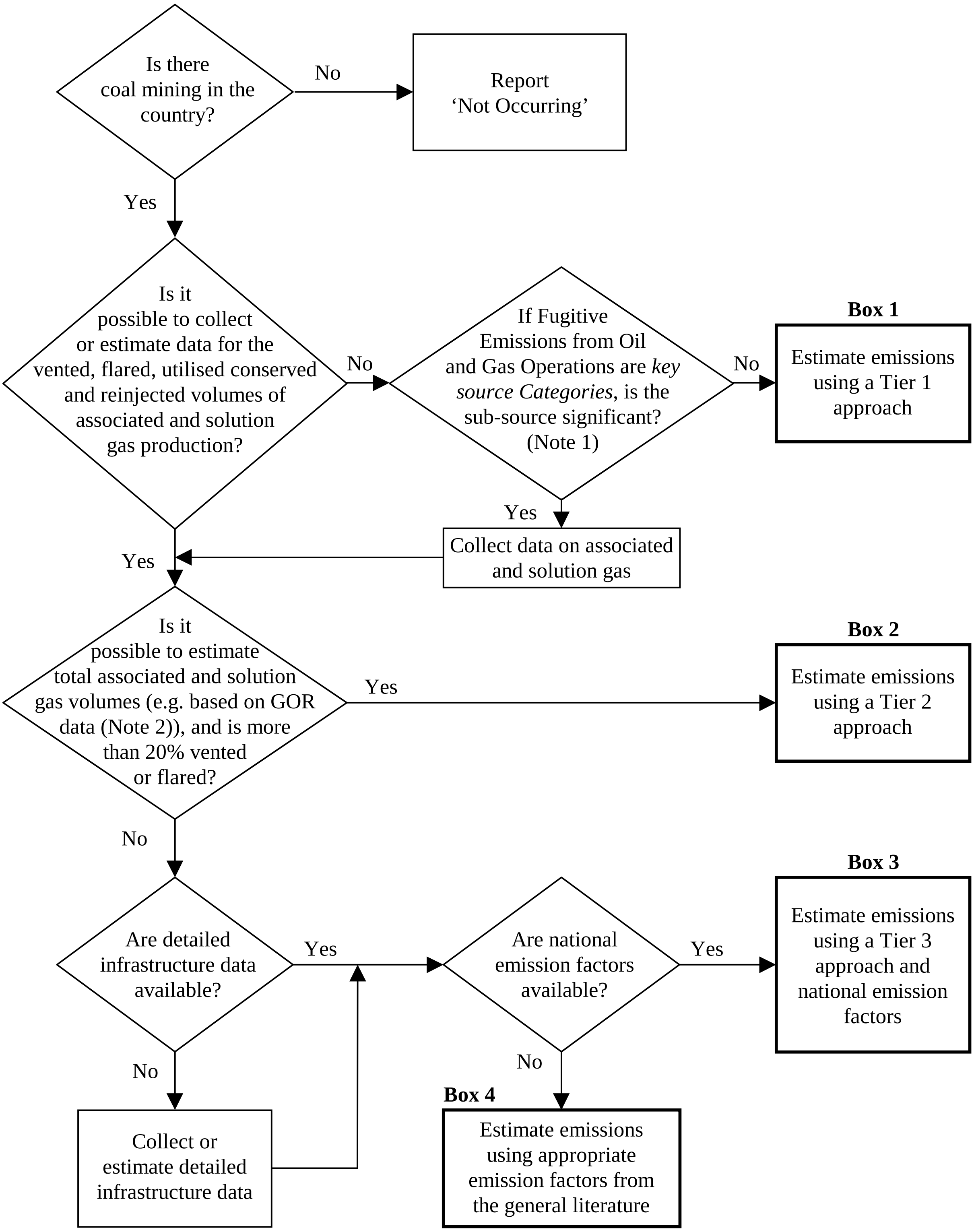
[23] There is no Tier 2 method for natural gas systems in the *IPCC Guidelines*.

Figure 2.12 Decision Tree for Natural Gas Systems



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

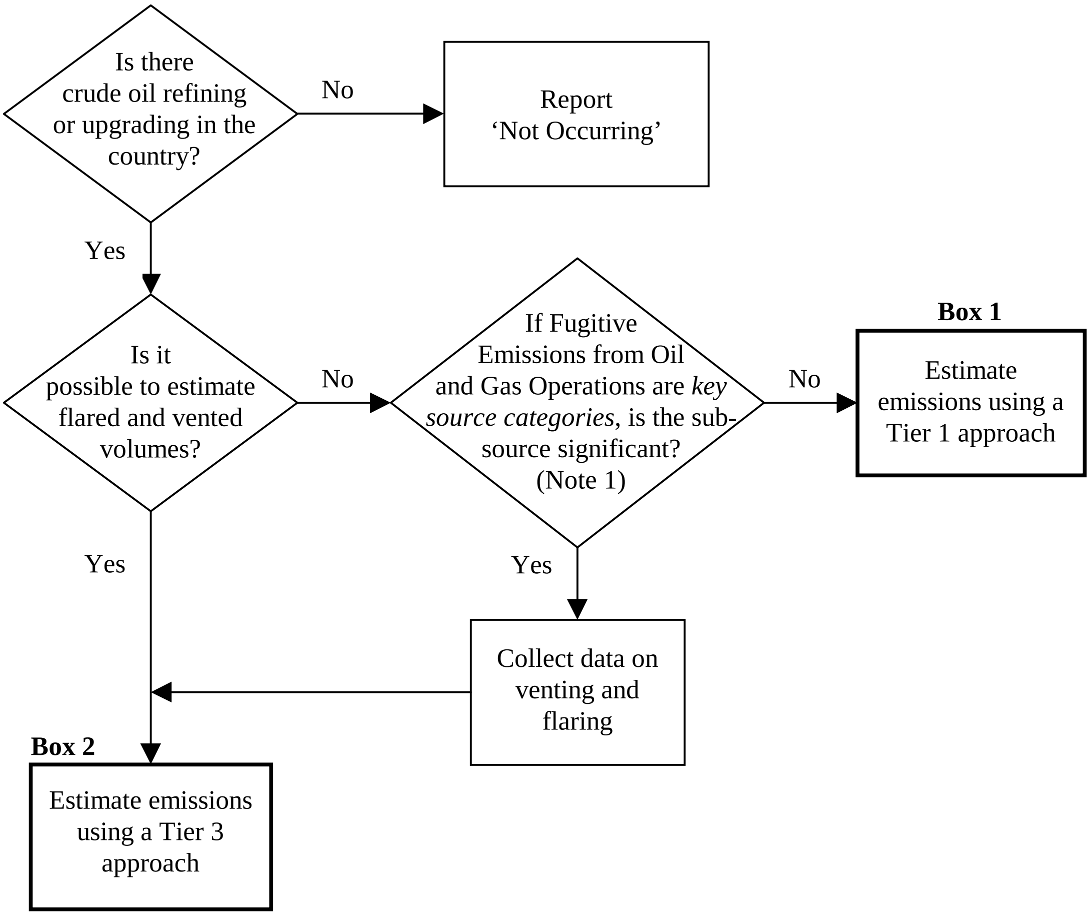
Figure 2.13 Decision Tree for Crude Oil Production and Transport



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: GOR stands for Gas/Oil Ratio.

Figure 2.14 Decision Tree for Crude Oil Refining and Upgrading



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

TABLE 2.15

MAJOR CATEGORIES AND SUBCATEGORIES IN THE OIL AND GAS INDUSTRY

Industry Segment	**Sub-Categories**
Wells	Drilling Testing Servicing
Gas Production	Dry Gas[a] Sweet Gas[b] Sour Gas[c]
Gas Processing	Sweet Gas Plants Sour Gas Plants Deep-cut Extraction Plants
Gas Transmission & Storage	Pipeline Systems Storage Facilities
Gas Distribution	Rural Distribution Urban Distribution
Liquefied Gases Transport	Condensate Liquefied Petroleum Gas (LPG) Liquefied Natural Gas (LNG) (including associated liquefaction and gasification facilities)
Oil Production	Conventional Oil Heavy Oil (Primary Production) Heavy Oil (Enhanced Production) Crude Bitumen Synthetic Crude Oil (From Oilsands) Synthetic Crude Oil (From Oil Shales)
Oil Upgrading	Crude Bitumen Heavy Oil
Waste Oil Reclaiming	None
Oil Transport	Marine Pipelines Tanker Trucks and Rail Cars
Oil Refining	Heavy Oil Conventional and Synthetic Crude Oil

[a] Dry gas is natural gas that does not require any hydrocarbon dew-point control to meet sales gas specifications. However, it may still require treating to meet sales specifications for water and acid gas (i.e. H_2S and CO_2) content. Dry gas is usually produced from shallow (less than 1000 m deep) gas wells.

[b] Sweet gas is natural gas that does not contain any appreciable amount of H_2S (i.e. does not require any treatment to meet sales gas requirements for H_2S).

[c] Sour gas is natural gas that must be treated to satisfy sales gas restrictions on H_2S content.

It is *good practice* to use the Tier 3 approach which will produce the most accurate emissions estimate. However, the ability to use a Tier 3 approach will depend on the availability of detailed production statistics and infrastructure data, and it may not be possible to apply it under all circumstances. A Tier 2 (mass balance) approach is primarily intended for application to oil systems where the majority of the associated and solution gas production is vented or flared. While much less reliable when applied to oil systems with gas conservation or to gas systems, a crude mass balance approach based on national production statistics may sometimes offer a greater degree of confidence than that offered by the Tier 1 approach. In such cases, the net balancing term (i.e. unaccounted-for losses) may be comparable to total fugitive emissions from non-venting or flaring sources. The Tier 1 approach is susceptible to substantial uncertainties and may easily be in error by an order-of-magnitude or more. For this reason, it should only be used as a last resort option.

2.7.1.2 CHOICE OF EMISSION FACTORS

Emission factors for conducting Tier 2 and Tier 3 assessments are not provided in the *IPCC Guidelines* due to the large amount of such information. Moreover, these data are continually being updated to include additional measurement results and to reflect development and penetration of new control technologies and requirements. Regular reviews of the literature should be conducted to ensure that the best available factors are being used, and the references for the chosen values should be clearly documented. Typically, emission factors are developed and published by environmental agencies and industry associations, and it will be necessary to develop inventory estimates in consultation with these organisations.

The selected emission factors must be valid for the given application and be expressed on the same basis as the activity data. It also may be necessary to apply other types of factors to correct for site and regional differences in operating conditions and design and maintenance practices, for example:

- Composition profiles of gases from particular oil and gas fields to correct for the amount of CH_4, raw CO_2 and other target pollutants in the emissions;
- Annual operating hours to correct for the amount of time a source is in active service;
- Efficiencies of the specific control measures used.

The following are additional matters to consider in choosing emission factors:

- It is important to assess the applicability of the selected factors for the target application to ensure similar/comparable source behaviour and characteristics;
- In the absence of better data, it may sometimes be necessary to apply factors reported for other regions that practice similar levels of emission control and feature comparable types of equipment;
- Where measurements are performed to develop new emission factors, only recognised or defensible test procedures should be applied. The method and quality assurance (QA)/quality control (QC) procedures should be documented, the sampled sources should be representative of typical variations in the overall source population, and a statistical analysis should be conducted to establish the 95% confidence interval on the average results.

New Tier 1 emission factors are presented in Table 2.16, Refined Tier 1 Emission Factors based on North American Data. Although still a simplified means of estimating fugitive emissions, the new factors allow for improved correlation of emissions with commonly-available activity data, and may be expected to limit uncertainties to within an order of magnitude. The improved correlations are achieved through increased disaggregation of the industry and, in several cases, by switching to different activity parameters. For example, fugitive emissions from gas transmission and distribution systems do not correlate well with throughput, and are better related to lengths of pipeline.

The new factors are derived from detailed emission inventory results for Canada and the United States, and are presented as examples. Notwithstanding this, these values may be applied to regions outside of North America that practice similar levels of emissions control and feature comparable types and quality of equipment. Even where moderate regional differences exist, the new factors may still offer more reliable results than that obtained from use of the factors given in the *IPCC Guidelines*. Nonetheless, it is *good practice* to consider the impact of regional differences before adopting a specific set of factors. In the absence of data for a particular industry segment or where conditions in the United States and Canada are not representative, the emission factors given in the *IPCC Guidelines*, Reference Manual Tables 1-57, Summary of Methane Emission Factors, and Table 1-58, Revised Regional Emission Factors for Methane from Oil and Gas Activities should be used.

In general, the developed factors reflect the following practices and state of the oil and gas industry:

- Most associated gas is conserved;
- Sweet waste gas is vented;
- Sour waste gas is flared;
- Many gas transmission companies are voluntarily implementing programmes to reduce methane losses due to fugitive equipment leaks;
- The oil and gas industry is mature and actually in decline in many areas;
- System reliability is high;
- Equipment is generally well maintained and high-quality components are used;
- Line breaks and well blowouts are rare;
- The industry is highly regulated and these regulations are generally well enforced.

TABLE 2.16

REFINED TIER 1 EMISSION FACTORS FOR FUGITIVE EMISSIONS FROM OIL AND GAS OPERATIONS BASED ON NORTH AMERICAN DATA

Category	**Sub-Category**	**Emission Type**	**Default emission factor[a,b]**			**Units of Measure**
			CH_4	**CO_2**	**N_2O**	
Wells	Drilling	All[c]	4.3E-07	2.8E-08	0	Gg per number of wells drilled
	Testing	All	2.7E-04	5.7E-03	6.8E-08	Gg per number of wells drilled
	Servicing	All	6.4E-05	4.8E-07	0	Gg/yr per number of producing and capable wells
Gas Production	All	Fugitives[d]	2.6E-03 to 2.9E-03	9.5E-05	0	Gg per 10^6 m^3 gas production
		Flaring[e]	1.1E-05	1.8E-03	2.1E-08	Gg per 10^6 m^3 gas production
Gas Processing	Sweet Gas Plants	Fugitives	6.9E-04 to 10.7E-04	2.7E-05	0	Gg per 10^6 m^3 gas receipts
		Flaring	1.3E-05	2.1E-03	2.5E-08	Gg per 10^6 m^3 gas receipts
	Sour Gas Plants	Fugitives	2.1E-04	2.9E-05	0	Gg per 10^6 m^3 gas receipts
		Flaring	2.9E-05	4.6E-03	5.4E-08	Gg per 10^6 m^3 gas receipts
		Raw CO_2 Venting	0	7.1E-02	0	Gg per 10^6 m^3 gas receipts
	Deep-cut Extraction Plants	Fugitives	1.0E-05	3.0E-07	0	Gg per 10^6 m^3 gas receipts
		Flaring	6.2E-06	9.7E-04	1.2E-08	Gg per 10^6 m^3 gas receipts
Gas Transmission & Storage	Transmission	Fugitives[f]	2.1E-03 to 2.9E-03	1.6E-05	0	Gg per year and per km of transmission pipeline
		Venting[g]	0.8E-03 to 1.2E-03	8.5E-06	0	Gg per year and per km of transmission pipeline
	Storage	All	4.3E-04 to 42.0E-04	0	0	Gg per year and per 10^6 m^3 gas withdrawals
Gas Distribution	All	All	5.2E-04 to 7.1E-04	0	0	Gg per year and per km of distribution mains
Natural Gas Liquids Transport	Condensate	All	1.1E-04	7.2E-06	0	Gg per 10^3 m^3 Condensate and Pentanes Plus
	Liquefied Petroleum Gas	All	0	4.3E-04	2.2E-09	Gg per 10^3 m^3 LPG
Oil Production	Conventional Oil	Fugitives	1.4E-03 to 1.5E-03	2.7E-04	0	Gg per 10^3 m^3 conventional oil production
		Venting	6.2E-05 to 270E-05	1.2E-05	0	Gg per 10^3 m^3 conventional oil production
		Flaring	0.5E-05 to 27E-05	6.7E-02	6.4E-07	Gg per 10^3 m^3 conventional oil production
	Heavy Oil	Fugitives	0.8E-04 to 12E-04	6.7E-06	0	Gg per 10^3 m^3 heavy oil production
		Venting	2.1E-02 to 2.7E-02	5.0E-05	0	Gg per 10^3 m^3 heavy oil production
		Flaring	0.5E-04 to 2.0E-04	4.9E-02	4.6E-07	Gg per 10^3 m^3 heavy oil production

TABLE 2.16 (CONTINUED)

REFINED TIER 1 EMISSION FACTORS FOR FUGITIVE EMISSIONS FROM OIL AND GAS OPERATIONS BASED ON NORTH AMERICAN DATA

Category	Sub-Category	Emission Type	Default emission factor[a,b]			Units of Measure
			CH_4	CO_2	N_2O	
Oil Production (continued)	Crude Bitumen	Fugitives	1.0E-04	1.2E-04	0	Gg per 10^3 m^3 crude bitumen production
		Venting	1.0E-03	1.2E-03	0	Gg per 10^3 m^3 crude bitumen production
		Flaring	8.8E-05	2.2E-02	2.4E-07	Gg per 10^3 m^3 crude bitumen production
	Synthetic Crude (from Oilsands)	All	2.3E-03	0	0	Gg per 10^3 m^3 synthetic crude production from oilsands
	Synthetic Crude (from Oil Shale)	All	NA	NA	NA	Gg per 10^3 m^3 synthetic crude production from oil shale
Oil Upgrading	All	All	ND	ND	ND	Gg per 10^3 m^3 oil upgraded
Oil Transport	Pipelines	All	5.4E-06	4.9E-07	0	Gg per 10^3 m^3 oil transported by pipeline
	Tanker Trucks and Rail Cars	Venting	2.5E-05	2.3E-06	0	Gg per 10^3 m^3 oil transported by Tanker Truck
	Loading of Off-shore Production on Tanker Ships	Venting	NA[h]	NA[h]	NA[h]	Gg per 10^3 m^3 oil transported by Tanker Truck

NA - Not Applicable ND - Not Determined

[a] While the presented emission factors may all vary appreciably between countries, the greatest differences are expected to occur with respect to venting and flaring, particularly for oil production due to the potential for significant differences in the amount of gas conservation and utilisation practised.

[b] The range in values for fugitive emissions is attributed primarily to differences in the amount of process infrastructure (e.g. average number and sizes of facilities) per unit of gas throughput.

[c] 'All' denotes all fugitive emissions as well as venting and flaring emissions.

[d] 'Fugitives' denotes all fugitives emissions including those from fugitive equipment leaks, storage losses, use of natural gas as the supply medium for gas-operated devices (e.g. instrument control loops, chemical injection pumps, compressor starters, etc.), and venting of still-column off-gas from glycol dehydrators.

[e] 'Flaring' denotes emissions from all continuous and emergency flare systems. The specific flaring rates may vary significantly between countries. Where actual flared volumes are known, these should be used to determine flaring emissions rather than applying the presented emission factors to production rates. The emission factors for direct estimation of CH_4, CO_2 and N_2O emissions from reported flared volumes are 0.012, 2.0 and 0.000023 Gg, respectively, per 10^6 m^3 of gas flared based on a flaring efficiency of 98% and a typical gas analysis at a gas processing plant (i.e. 91.9% CH_4, 0.58% CO_2, 0.68% N_2 and 6.84% non-methane hydrocarbons by volume).

[f] The larger factor reflects the use of mostly reciprocating compressors on the system while the smaller factor reflects mostly centrifugal compressors.

[g] 'Venting' denotes reported venting of waste associated and solution gas at oil production facilities and waste gas volumes from blowdown, purging and emergency relief events at gas facilities. Where actual vented volumes are known, these should be used to determine venting emissions rather than applying the presented emission factors to production rates. The emission factors for direct estimation of CH_4 and CO_2 emissions from reported vented volumes are 0.66 and 0.0049 Gg, respectively, per 10^6 m^3 of gas vented based on a typical gas analysis for gas transmission and distribution systems (i.e. 97.3% CH_4, 0.26% CO_2, 1.7% N_2 and 0.74% non-methane hydrocarbons by volume).

[h] While no factors are available for marine loading of offshore production for North America, Norwegian data indicate a CH_4 emission factor of 1.0 to 3.6 Gg/10^3 m^3 of oil transferred (derived from data provided by Norwegian Pollution Control Authority, 2000).

Sources: Canadian Association of Petroleum Producers (1999); GRI/US EPA (1996); US EPA (1999).

2.7.1.3 CHOICE OF ACTIVITY DATA

The activity data required to estimate fugitive emissions from oil and gas activities may include production statistics, infrastructure data (e.g. inventories of facilities/installations, process units, pipelines, and equipment components), and reported emissions from spills, accidental releases, and third-party damages. The basic activity data required for each tier and each type of primary source are summarised in Table 2.17, Typical Activity Data Requirements for each Assessment Approach by Type of Primary Source Category. Specific matters to consider in compiling this information include the following:

- Production statistics should be disaggregated to capture changes in throughputs (e.g. due to imports, exports, reprocessing, withdrawals, etc.) in progressing through oil and gas systems.

- Production statistics or disposition analyses[24] may not agree between different reporting agencies even though they are based on the same original measurement results (e.g. due to possible differences in terminology and potential errors in summarising these data). These discrepancies may be used as an indication of the uncertainty in the data. Additional uncertainty will exist if there is any inherent bias in the original measurement results (for example, sales meters are often designed to err in favour of the customer, and liquid handling systems will have a negative bias due to evaporation losses). Random metering and accounting errors may be assumed to be negligible when aggregated over the industry.

- Production statistics provided by national bureaux should be used in favour of those available from international bodies, such as the IEA or the UN, due to their generally better reliability and disaggregation. Regional, provincial/state and industry reporting groups may offer even more disaggregation.

- Reported vented and flared volumes may be highly suspect since these values are usually estimates and not based on actual measurements. Additionally, the values are often aggregated and simply reported as flared volumes. Operating practices of each segment of the industry should be reviewed to determine if the reported volumes are actually vented or flared, or to develop appropriate apportioning of venting relative to flaring. Audits or reviews of each industry segment should also be conducted to determine if all vented/flared volumes are actually reported (for example, solution gas emissions from storage tanks and treaters, emergency flaring/venting, leakage into vent/flare systems, and blowdown and purging volumes may not necessarily be accounted for).

- Infrastructure data are more difficult to obtain than production statistics. Information concerning the numbers and types of major facilities and the types of processes used at these facilities may often be available from regulatory agencies and industry groups, or directly from the actual companies.

- Information on minor facilities (e.g. numbers of field dehydrators and field compressors) usually is not available, even from oil and gas companies. Consequently, assumptions must be made, based on local design practices, to estimate the numbers of these facilities. This may require some fieldwork to develop appropriate estimation factors or correlations.

- Many companies use computerised inspection-and-maintenance information management systems. These systems can be a very reliable means of counting major equipment units (e.g. compressor units, process heaters and boilers, etc.) at selected facilities. Also, some departments within a company may maintain databases of certain types of equipment or facilities for their own specific needs (e.g. tax accounting, production accounting, insurance records, quality control programmes, safety auditing, license renewals, etc.). Efforts should be made to identify these potentially useful sources of information.

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[24] A disposition analysis provides a reconciled accounting of produced hydrocarbons from the wellhead, or point of receipt, through to the final sales point or point of export. Typical disposition categories include flared/vented volumes, fuel usage, system losses, volumes added to/removed from inventory/storage, imports, exports, etc.

TABLE 2.17

TYPICAL ACTIVITY DATA REQUIREMENTS FOR EACH ASSESSMENT APPROACH FOR FUGITIVE EMISSIONS FROM OIL AND GAS OPERATIONS BY TYPE OF PRIMARY SOURCE CATEGORY

Assessment Tier	Primary Source Category	Minimum Required Activity Data
1	All	Oil and Gas Throughputs
2	Oil Systems	Gas to Oil Ratios Flared and Vented Volumes Conserved Gas Volumes Reinjected Gas Volumes Utilised Gas Volumes Gas Compositions
3	Process Venting/Flaring	Reported Volumes Gas Compositions Proration Factors for Splitting Venting from Flaring
	Storage Losses	Solution Gas Factors Liquid Throughputs Tank Sizes Vapour Compositions
	Equipment Leaks	Facility/Installation Counts by Type Processes Used at Each Facility Equipment Component Schedules by Type of Process Unit Gas/Vapour Compositions
	Gas-Operated Devices	Schedule of Gas-operated Devices by Type of Process Unit Gas Consumption Factors Type of Supply Medium Gas Composition
	Accidental Releases & Third-Party Damages	Incident Reports/Summaries
	Gas Migration to the Surface & Surface Casing Vent Blows	Average Emission Factors & Numbers of Wells
	Drilling	Number of Wells Drilled Reported Vented/Flared Volumes from Drill Stem Tests Typical Emissions from Mud Tanks
	Well Servicing	Tally of Servicing Events by Types
	Pipeline Leaks	Type of Piping Material Length of Pipeline
	Exposed Oilsands/Oil Shale	Exposed Surface Area Average Emission Factors

Component counts by type of process unit may vary dramatically between facilities and countries due to differences in design and operating practices. Thus, while initially it may be appropriate to use values reported in the general literature, countries should strive to develop their own values.

Use of consistent terminology and clear definitions is critical in developing counts of facilities and equipment components, and to allow any meaningful comparisons of the results with others.

Some production statistics may be reported in units of energy (based on their heating value) and will need to be converted to a volume basis, or vice versa, for application of the available emission factors. Typically, where production values are expressed in units of energy, it is in terms of the gross (or higher) heating value of the product. However, where emission factors are expressed on an energy basis it is normally in terms of the net (or lower) heating value of the product. To convert from energy data on a GCV basis to a NCV basis, the International Energy Agency assumes a difference of 5% for oil and 10% for natural gas. Individual natural gas streams that are either very rich or high in impurities may differ from the average value given above. Emission factors and activity data must be consistent with each other.

In comparing fugitive emissions from the oil and gas industry in different countries it is important to consider the impact of oil and gas imports and exports, as well as the types of oil and gas activities and the levels of emission control. Otherwise, emissions viewed on either a per-unit-consumption or a per-unit-production basis will be misleading.

Production activities will tend to be the major contributor to fugitive emissions from oil and gas activities in countries with low import volumes relative to consumption and export volumes. Gas transmission and distribution and petroleum refining will tend to be the major contributors to these emissions in countries with high relative import volumes. Overall, net importers will tend to have lower specific emissions than net exporters.

2.7.1.4 COMPLETENESS

Completeness is a significant issue in developing an inventory of fugitive emissions for the oil and gas industry. It can be addressed through direct comparisons with other countries and, for refined inventories, through comparisons between individual companies in the same industry segment and subcategory. This requires use of consistent definitions and classification schemes. In Canada, the upstream petroleum industry has adopted a benchmarking scheme that compares the emission inventory results of individual companies in terms of production-energy intensity and production-carbon intensity. Such benchmarking allows companies to assess their relative environmental performance. It also flags, at a high level, anomalies or possible errors that should be investigated and resolved.

The indicative factors presented in Table 2.18 may be used to help assess completeness and to qualify specific methane losses as being low, medium or high. Specific methane losses which are appreciably less than the low benchmark or greater than the high benchmark should be explained. The ranking of specific methane losses relative to the presented activity data should not be used as a basis for choosing the most appropriate assessment approach; rather, total emissions (i.e. the product of activity data and emission factors), the complexity of the industry and available assessment resources should all be considered.

TABLE 2.18

CLASSIFICATION OF GAS LOSSES AS LOW, MEDIUM OR HIGH AT SELECTED TYPES OF NATURAL GAS FACILITIES

Facilities	Activity data	Yearly emission factors			
		Low	**Medium**	**High**	**Units of Measure**
Production and Processing	Net gas production (i.e. marketed production)	0.05	0.2	0.7	% of net production
Transmission Pipeline Systems	Length of transmission pipelines	200	2 000	20 000	m^3/km/yr
Compressor Stations	Installed compressor capacity	6 000	20 000	100 000	m^3/MW/yr
Underground Storage	Working capacity of underground storage stations	0.05	0.1	0.7	% of working gas capacity
LNG Plant (liquefaction or regasification)	Gas throughput	0.005	0.05	0.1	% of throughput
Meter and Regulator Stations	Number of stations	1 000	5 000	50 000	m^3/station/yr
Distribution	Length of distribution network	100	1 000	10 000	m^3/km/yr
Gas Use	Number of gas appliances	2	5	20	m^3/appliance/yr

Source: Adapted from currently unpublished work by the International Gas Union, and based on data for a dozen countries including Russia and Algeria.

Smaller individual sources, when aggregated nationally over the course of a year, may often be significant total contributors. Therefore, *good practice* is not to disregard them unless their collective contribution to total fugitive emissions is proven to be negligible. Conversely, once a thorough assessment has been done, a basis exists for simplifying the approach and better allocating resources in the future to best reduce uncertainties in the results.

2.7.1.5 DEVELOPING A CONSISTENT TIME SERIES

Ideally, emission estimates will be prepared for the base year and subsequent years using the same method. Where some historical data are missing it should still be possible to use source-specific measurements combined with backcasting techniques to establish an acceptable relationship between emissions and activity data in the base year. Approaches for doing this will depend on the specific situation, and are discussed in general terms in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

While establishing base year emission levels is meaningful and important at a regional or national level, it is often a misleading indicator at the company level due to frequent mergers, divestitures and acquisitions in many areas. This may be an issue where national inventories are developed based on a rollup of company-level inventories, and some extrapolations or interpolations are required.

Where changes in methods and emission factors are substantial, the whole time series should be recalculated and reported in a transparent manner.

2.7.1.6 UNCERTAINTY ASSESSMENT

Sources of error occur in the following areas:

- Measurement errors;
- Extrapolation errors;
- Inherent uncertainties of the selected estimation techniques;
- Missing or incomplete information regarding the source population and activity data;

- Poor understanding of temporal and seasonal variations in the sources;
- Over or under accounting due to confusion or inconsistencies in category divisions and source definitions;
- Misapplication of activity data or emission factors;
- Errors in reported activity data;
- Missed accounting of intermediate transfer operations and reprocessing activities (e.g. repeat dehydration of gas streams [in the field, at the plant, and following storage], treating of slop and foreign oil receipts) due to poor or no documentation of such activities;
- Variances in the effectiveness of control devices and missed accounting of control measures;
- Data-entry and calculation errors.

Due to the complexity of the oil and gas industry, it is difficult to quantify the net uncertainties in the overall inventories, emission factors and activity data. While some semi-quantitative analyses have been conducted, a more thorough quantitative analysis is warranted.

High-quality refined emissions factors for most gases may be expected to have errors in the order of ±25 percent.[25] Factors based on stochiometric ratios may be much better (e.g. errors of ±10%). Gas compositions are usually accurate to within ±5% on individual components. Flow rates typically have errors of ±3% or less for sales volumes and ±15% or more for other volumes.

A high-quality bottom-up (Tier 3) inventory of fugitive methane losses from either oil or gas activities might be expected to have errors of ±25 to ±50%. In comparison, default production-based emission factors for methane losses may easily be in error by an order of magnitude or more. Inventories of fugitive CH_4 and CO_2 emissions from venting and flaring activities will be quite reliable if the raw gaseous composition and actual vented and flared volumes are accurately known. Estimates of fugitive N_2O emissions will be least reliable but will only be a minor contributor to total fugitive greenhouse gas emissions from oil and gas activities.

Estimates of emission reductions from individual control actions may be accurate to within a few percent to ±25% depending on the number of subsystems or sources considered.

2.7.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Section 8.10.1 of Chapter 8, Quality Assurance and Quality Control.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

Some examples of specific documentation and reporting relevant to this source category are provided below.

Documentation is particularly important where a Tier 3 approach is used since the *IPCC Guidelines* do not describe a standard Tier 3 approach for the oil and gas sector. There is a wide range in what potentially may be classified as a Tier 3 approach, and correspondingly, in the amount of uncertainty in the results.

If available, summary performance and activity indicators should be reported to help put the results in perspective (e.g. total production levels and transportation distances, net imports and exports, and specific energy, carbon and emission intensities). Reported emission results should also include a trend analysis to show changes in emissions and activity data over time. The expected accuracy of the results should be stated and the areas of greatest uncertainty clearly noted. This is critical for proper interpretation of the results and any claims of net reductions.

The current trend by some government agencies and industry associations is to develop detailed methodology manuals and reporting formats for specific segments and subcategories of the industry. This is perhaps the most practical means of maintaining, documenting and disseminating the subject information. However, all such initiatives must conform to the common framework established in the *IPCC Guidelines* so that the emission results can be compared across countries.

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[25] The percentages cited in this section represent an informal polling of assembled experts aiming to approximate the 95% confidence interval around the central estimate.

Since emission factors and estimation procedures are continually being improved and refined, it is possible for changes in reported emissions to occur without any real changes in actual emissions. Accordingly, the basis for any changes in results between inventory updates should be clearly discussed and those due strictly to changes in methods and factors should be highlighted.

The issue of confidential business information will vary from region to region depending on the number of firms in the market and the nature of the business. The significance of this issue tends to increase in progressing downstream through the oil and gas industry. A common means to address such issues where they do arise is to aggregate the data using a reputable independent third party.

2.7.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8 and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Emission inventories for large, complex oil and gas industries will be susceptible to significant errors due to missed or unaccounted sources. To minimise such errors, it is important to obtain active industry involvement in the preparation and refinement of these inventories.

Review of direct emission measurements

If direct measurements are used to develop country-specific emission factors, the inventory agency should establish whether measurements at the sites were made according to recognised standard methods. If the measurement practices fail this criterion, then the use of these emissions data should be carefully evaluated, estimates reconsidered, and qualifications documented.

Emission factors check

The inventory agency should compare measurement-based factors to IPCC default factors and factors developed by other countries with similar industry characteristics. If IPCC default factors are used, the inventory agency should ensure that they are applicable and relevant to the category. If possible, the IPCC default factors should be compared to national or local data to provide further indication that the factors are applicable.

Activity data check

Several different types of activity data may be required for this source category, depending on which method is used. The inventory agency should check different types of activity data against each other to assess reasonableness. Where possible, multiple sources of data (i.e. from national statistics and industry organisations) should be compared. Significant differences in data should be explained and documented. Trends in main emission drivers and activity data over time should be checked and any anomalies investigated.

External review

Emission inventories for large, complex oil and gas industries will be susceptible to significant errors due to missed or unaccounted for sources. To minimise such errors, it is important to obtain active industry involvement in the preparation and refinement of these inventories.

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CONTRIBUTORS

Rainer Bitsch (Germany), Lowell Brothers (USA), Eric Dolin (USA), Kathryn Ellerton (USA), Jochen Harnisch (Germany), Petra Mahrenholtz (Germany), Bill Palmer (Canada), Natalya Parasyuk (Ukraine), Ewald Preisegger (Germany), Michael Strogies (Germany), Takuya Suizu (Japan), and Chen Zhenlin (China)

Expert Group: PFC, HFC and SF_6 Emissions from Semiconductor Manufacturing

CO-CHAIRS

Alexey Kokorin (Russian Federation) and Sally Rand (USA)

AUTHORS OF BACKGROUND PAPERS

Scott Bartos (USA) and C. Shepherd Burton (USA)

CONTRIBUTORS

Kenneth Aitchison (USA), Scott Bartos (USA), Laurie Beu (USA), Shepherd Burton (USA), David Green (USA), Philippe Levavasseur (France), Michael Mocella (USA), Jerry Meyers (USA), Toshiaki Ohgita (Japan), Emmanuel Riviere (France), Deborah Ottinger Schaefer (USA), and Pieter du Toit (South Africa)

Expert Group: Emissions of Substitutes for Ozone Depleting Substances (ODS Substitutes)

CO-CHAIRS

Archie McCulloch (UK) and Reynaldo Forte Jr. (USA)

AUTHORS OF BACKGROUND PAPERS

Reynaldo Forte, Jr. (USA), Archie McCulloch (UK), and Pauline Midgley (UK)

CONTRIBUTORS

Radhy Agarwal (India), Paul Ashford (UK), Ward Atkinson (USA), James Baker (USA), Pierre Boileau (Canada), Marvin Branscome (USA), Margreet van Brummelen (Netherlands), Nick Campbell (UK), Anita Cicero (USA), Denis Clodic (France), Yuichi Fujimoto (Japan), Francis Grunchard (Belgium), Toshio Hirata (Japan), Niklas Höhne (UNFCCC Secretariat), Eliisa Irpola (Finland), Mike Jeffs (Belgium), Fred Keller (USA), Alexey Kokorin (Russian Federation), Candido Lomba (Brazil), Julia Martinez (Mexico), Thomas Martinsen

(IPCC/OECD), Arthur Naujock (USA), Yutaka Obata (Japan), John Owens (USA), Christophe Petitjean (France), Marit Viktoria Pettersen (Norway), Ewald Preisegger (Germany), Erik Rasmussen (Denmark), Masataka Saburi (Japan), Deborah Ottinger Schaefer (USA), Stephen Seidel (USA), Len Swatkowski (USA), Dwayne Taylor (USA), Gary Taylor (Canada), Daniel Verdonik (USA), and Duncan Yellen (UK)

Expert Group: Estimation of HFC-23 Emissions from HCFC-22 Manufacture

CO-CHAIRS

Nick Campbell (UK) and Julia Martinez (Mexico)

AUTHORS OF BACKGROUND PAPERS

Marvin Branscombe (USA) and William Irving (USA)

CONTRIBUTORS

Marvin Branscome (USA), Mark Christmas (USA), Taka Hiraishi (Japan), William Irving (USA), Stephen Seidel (USA), Matthew Williamson (USA), and Wei Zhihong (China)

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OVERVIEW

This chapter deals with the industrial process source categories described in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines). Good practice guidance* is provided for major emissions source categories – including: Cement production, lime production, iron and steel industry, adipic acid and nitric acid production, aluminium production, magnesium production, sulfur hexafluoride (SF_6) emissions from electrical equipment, and from other sources, perfluorocarbons (PFC), hydrofluorocarbons (HFC) and SF_6 emissions from semiconductor manufacturing, emissions of substitutes for ozone depleting substances (ODS substitutes) including seven sub-source categories, and HCFC-22 manufacture.

Good practice guidance has not yet been developed for the following source categories described in the *IPCC Guidelines*, Chapter 2, Industrial Processes: limestone and dolomite use (including use in the iron and steel industry), soda ash production and use, production and use of miscellaneous mineral products, ammonia production, carbide production, production of other chemicals, ferroalloys, CO_2 emissions from aluminium, other metal production, SF_6 used in aluminium and magnesium foundries; pulp and paper industries; and food and drink industries. Inventory agencies should of course continue to use the *IPCC Guidelines* for these source categories. The cross-cutting parts of the *good practice guidance* in Chapters 6 to 8, and the Annexes can also be applied to those source categories.

According to the *IPCC Guidelines* all emissions of HFCs, PFCs and SF_6 – including those occurring in non-industry sectors – should be included in the Industrial Processes Sector (see guidance described in Sections 3.3 to 3.8). The 'amount of destruction' should be considered in each emission equation. At present, there are few practices of treatments that destroy HFCs, PFCs, or SF_6. However, in the future, destruction treatments may be developed in order to reduce emissions.

To improve clarity in this chapter sometimes tier numbers are introduced as alternative names for methods that are described in the *IPCC Guidelines* but not numbered. Further, additional tiers have in some cases been described through the process of defining *good practice guidance* for a particular source category. For the industrial process source categories, the tiered approach as described in the sections and the decision trees should be interpreted as follows (see the guidance in Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories).

- If the source category is not a *key source category*, but the data and resources of the inventory agency allow an emission calculation to be performed with Tier 2 or higher methods, the inventory agency is, of course, encouraged to do so (instead of applying the Tier 1 approach).

- If the source category is a *key source category*, but the inventory agency is unable to collect the data and use the method (or tier) suggested for *good practice*, it is considered *good practice* to use the Tier 1 method for the emission calculation and document the reason for using that method.

3.1 CO_2 EMISSIONS FROM INDUSTRY

In the *IPCC Guidelines*, Vol. 3, Section 2.1, Industrial Processes Overview, the separation of feedstock and energy uses and the identification of any fuel by-products from processes have been identified as a particularly difficult area of energy statistics. To avoid double-counting or omissions of carbon dioxide (CO_2), the compilers of energy and industry-related emissions should cooperate closely and compare their basic fuel use data. Close cooperation is particularly important for the iron and steel industry where, according to the *IPCC Guidelines*, coke (or coal) consumption is considered to be industrial, since the primary purpose of coke (or coal) oxidisation is to produce pig iron, not to produce process heat. Another possible area of double-counting is 'CO_2 emissions from the use of limestone and dolomite' that should be accounted for in its specific section (*IPCC Guidelines*, Vol. 3, Section 2.5, Limestone and Dolomite Use), not in the other Industrial Processes source categories of the *IPCC Guidelines* where usage is mentioned, such as in the Iron and Steel Sub-source Category.

3.1.1 Cement production

3.1.1.1 Methodological issues

Emissions of CO_2 occur during the production of *clinker* that is an intermediate component in the cement manufacturing process. During the production of clinker, limestone, which is mainly (95%) calcium carbonate ($CaCO_3$), is heated (calcined) to produce lime (CaO) and CO_2 as a by-product. The CaO then reacts with silica, aluminium, and iron oxides in the raw materials to make the clinker minerals (that are dominantly hydraulic calcium silicates) but these reactions do not emit further CO_2. The main challenge in the estimation of CO_2 emissions from cement production is to overcome the difficulty that both the fraction of clinker in cement and CaO content in clinker may vary.

CHOICE OF METHOD

The decision tree in Figure 3.1, Decision Tree for Estimation of CO_2 Emissions from Cement Production, describes *good practice* in choosing the most appropriate method. As CO_2 emissions occur during the intermediate production of clinker, *good practice* is to estimate CO_2 emissions using data for clinker production and the CaO content of the clinker and correct for the loss of so-called Cement Kiln Dust (CKD) (Tier 2). If it is not possible to obtain clinker production data directly, clinker production should be inferred from cement production and a correction for clinker import and export statistics should be applied (Tier 1). Once an estimate of clinker production has been derived, the Tier 1 method estimates CO_2 emissions through a process similar to Tier 2. The simple method described in the *IPCC Guidelines* to multiply a default cement-based emission factor by cement production, without correction for import/export of clinker, is not considered to be a *good practice* method.

Tier 2 Method: Use of clinker production data

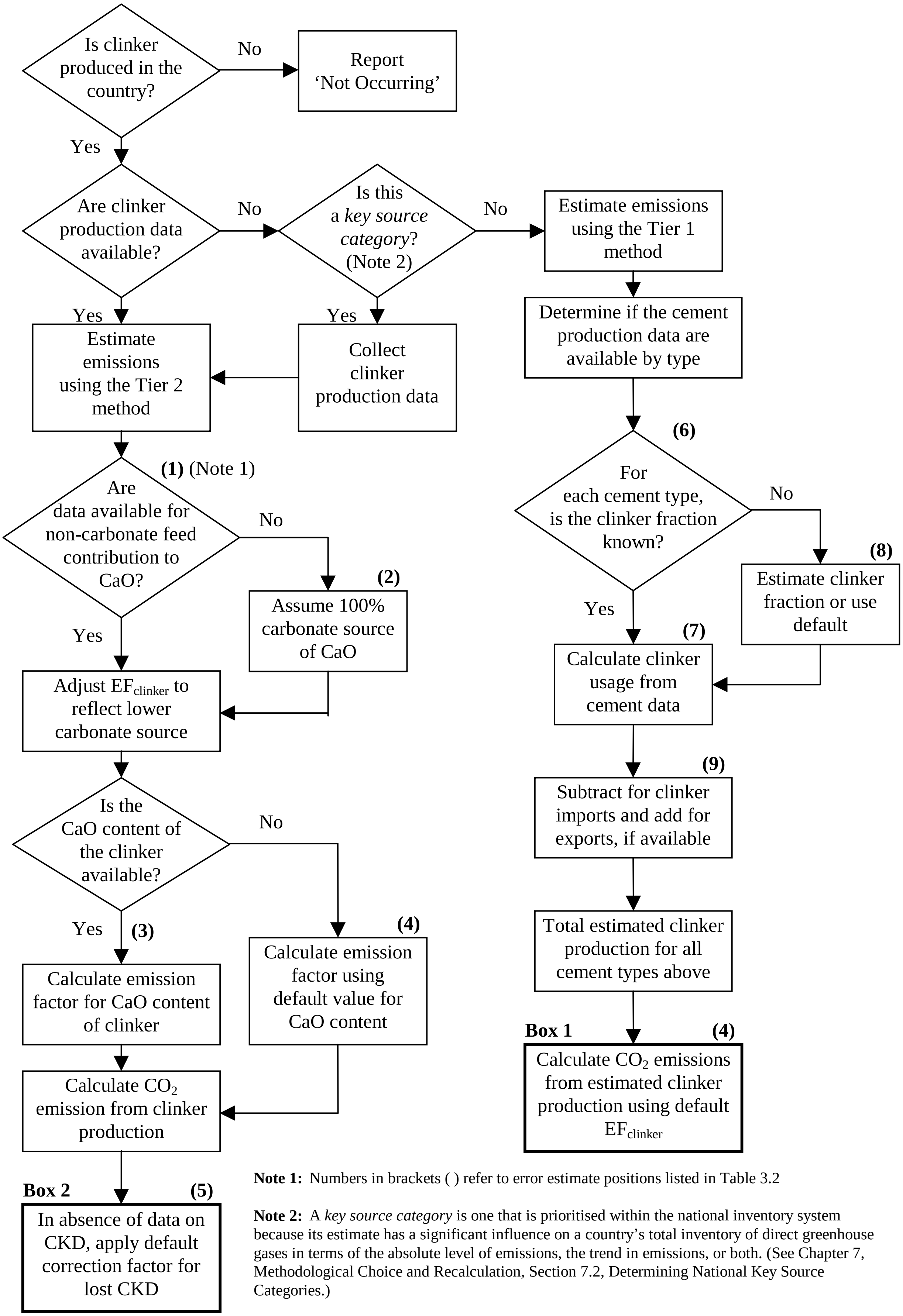
The most rigorous *good practice* method is to use aggregated plant or national clinker production data and data on the CaO content in clinker, expressed as an emission factor (EF), following Equation 3.1:

EQUATION 3.1

$$\text{Emissions} = EF_{\text{clinker}} \bullet \text{Clinker Production} \bullet \text{CKD Correction Factor}$$

This approach assumes that all of the CaO is from a carbonate source (e.g. $CaCO_3$ in limestone). If data on non-carbonate sources are available, an adjustment (decrease) should be made to the emission factor EF_{clinker}.

Figure 3.1 Decision Tree for Estimation of CO_2 Emissions from Cement Production



Note 1: Numbers in brackets ( ) refer to error estimate positions listed in Table 3.2

Note 2: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Cement Kiln Dust (CKD) is non-calcined to fully calcined dust produced in the kiln.[1] CKD may be partly or completely recycled to the kiln. Any CKD that is not recycled can be considered lost to the system in terms of CO_2 emissions. *Good practice* is to correct for the CO_2 contained in non-recycled (lost) calcined CKD because this CO_2 will not be accounted for by the clinker produced. The amount of CO_2 lost can vary, but would range typically from about 1.5% for a modern plant to about 8% for a plant losing a lot of highly calcinated CKD (van Oss, 1998). As data on CKD are very scarce, the default CKD correction factor is 1.02 (i.e. to add 2% to the CO_2 calculated for clinker). If no calcined CKD is believed to be lost to the system, the correction factor will be 1.00 (van Oss, 1998).

Tier 1 Method: Use of cement production data

As mentioned above, calculating CO_2 emissions directly from cement production (i.e. using a fixed cement-based emission factor) is not consistent with *good practice*. Instead, in the absence of national clinker production data, cement production data may be used to estimate clinker production taking into account the types of cement produced and including a correction for international clinker trade (exports, imports), where relevant, as shown in Equation 3.2:

EQUATION 3.2

$$\text{Estimated Clinker Production} = \text{Cement Production} \bullet \text{Clinker Fraction} - \text{Imported Clinker} + \text{Exported Clinker}$$

If readily available, plant-specific data for the clinker fraction should be collected, otherwise a default clinker fraction can be used. If cement production cannot be disaggregated by type and it is suspected that both blended and portland cement types are being produced, it is *good practice* to assume a clinker fraction of 75%. If the cement production is known to be essentially all portland cement, then it is *good practice* to use a default value of 95% clinker. The default value of 98.3% clinker fraction suggested in the *IPCC Guidelines* is too high.[2]

CHOICE OF EMISSION FACTORS

Both Tier 1 and Tier 2 require emission factors for clinker that are based on stoichiometry, as shown in Equation 3.3:

EQUATION 3.3

$$EF_{clinker} = 0.785 \bullet \text{CaO Content (Weight Fraction) in Clinker}$$

The multiplication factor (0.785) is the molecular weight ratio of CO_2 to CaO in the raw material mineral calcite ($CaCO_3$), from which most or all the CaO in clinker is derived. The CaO content can vary somewhat by country and by facility.

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[1] To some extent, all cement kilns produce Cement Kiln Dust that is largely a mix of calcined and uncalcined raw materials and clinker. There are few data available on total CKD production, composition or disposition; these are functions of plant technologies and can vary over time. In general, the amount of CKD produced can be estimated as equivalent to about 1.5-2.0% of the weight of clinker production (van Oss, 1998). CKD can be directly recycled, or it may be recovered via electrostatic precipitation or filtration (baghouses) from the exhaust stacks (it would be vented to the atmosphere only at basic plants in developing countries). The recovered CKD may be recycled to the kiln as a raw material, used for other purposes, or transferred to a landfill. The degree of return to the kiln can be limited by the fact that CKD tends to accumulate contaminants such as alkalis. Any CKD not recycled to the kiln is 'lost' to the cement system in terms of CO_2 emissions. The calcined, or partially calcined, carbonate fraction of the lost CKD represents a generation of calcination CO_2 that is not accounted for by the amount of clinker produced. For a developed country operating modern plants with moderate recycling of CKD to the kilns, this extra CO_2 is probably equivalent to about 1.5-2.0% of the CO_2 calculated for clinker (van Oss, 1998). For plants doing little recycling, the percentage would be somewhat higher (e.g. 3%), and if the lost CKD is mostly calcined material, the extra CO_2 could range higher still (e.g. 6-8%). For most countries, the practical maximum extra CO_2 is unlikely to exceed 5% of the clinker CO_2 (van Oss, 1998).

[2] This ratio was calculated from the default CaO content in cement (63.5%) and the default CaO fraction in clinker (64.6%), and results in a clinker-cement ratio higher than the ratio for most pure portland cements.

Tier 2 Method

In using the Tier 2 method, it is *good practice* to estimate the CaO content in clinker by collecting data from individual plants or companies. Generally, the average CaO content of clinker does not change significantly on an annual basis, so an estimate can be developed periodically (e.g. every 5 years) in each country.[3] In the event that country-specific data cannot be obtained for the CaO content, a default weight fraction of 0.65 can be used (see the *IPCC Guidelines*, Vol.3, Section 2.3, Cement Production).[4]

Equation 3.3 is based on the assumption that all the CaO in clinker is from $CaCO_3$. Limestone and related carbonate materials are the major source of CaO for clinker, but there may be additional CaO sources (e.g. ferrous slag feeds) for some plants. This assumption will generally produce only a small error at most, but if it is known that other sources of CaO are being used as kiln feed in substantial amounts, the CaO contribution of these non-carbonate feeds should be subtracted from the clinker. However, quantitative data on raw materials consumed for clinker production generally will be lacking.

Tier 1 Method

In Tier 1, it is *good practice* to use the same default CaO content of 65% as in Tier 2, resulting in an emission factor of 0.51 tonne CO_2 per tonne of clinker. However, if sufficient data on CaO content of clinker are available, the CO_2 emission factor should be estimated as described for Tier 2 (see Figure 3.1, Decision Tree for Estimation of CO_2 Emissions from Cement Production).

CHOICE OF ACTIVITY DATA

Tier 2 Method: Clinker production data

The goal of collecting activity data for this source category is to arrive at a value for clinker production. *Good practice* is to collect clinker production data directly from national statistics or preferably from individual plants. Plant data may include information on the CaO content of the clinker and possibly non-carbonate sources of CaO.

Tier 1 Method: Cement production data

If national clinker production data are not readily available and cannot be collected, the preferred alternative is to estimate clinker production from cement production data. This requires country-specific knowledge of cement production as well as cement and clinker composition. To use cement production and assume a default clinker fraction may introduce significant error in the emission calculation.

Several issues should be considered when estimating clinker production.

First, the choice between top-down and bottom-up data collection is important.[5] Collecting data from individual producers rather than using national totals will increase the accuracy of the estimate, because these data will account for variations in conditions at the plant level. This is particularly important for determining possible differences in cement composition and irregularities in annual production (i.e. using clinker feedstock instead of production at various times).

Second, the clinker content in cement and the CaO content in clinker should be considered. It is *good practice* to collect cement production data broken down by cement type because each type of cement will contain a different proportion of clinker. The clinker fraction varies among countries and care must be taken to ensure that it is consistent with the local definition of the types of cement (see Table 3.1, Percent Clinker in the Cement Production Mix, Table 3.3A, Examples of Clinker Fraction of Blended Cement 'Recipes' (Based on US Standards), and Table 3.3B, Classification of Cement Types (Based on European Standards (DIN 1164, part 1))). Determining the types of cement that are being produced or included in cement production data is of critical importance because a number of cement types other than common portland cement may be included in cement statistics. These cement types may have widely different clinker fractions. There may be variations in the CaO content of clinker for various types of cement produced but, for a given cement type, the CaO content of clinker

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[3] The average CaO content for clinker used in a country is the weighted average of the CaO contents of the clinker from various plants with the inferred production levels (i.e. multiplied by their CKD correction factor) being the weights. This average for the country should be reported for comparison and QA/QC purposes.

[4] Although the CaO content for a specific cement type will generally be closely controlled (to within 1-3%) by the plant, the CaO content of clinker may vary with the type of cement produced.

[5] In the context of cement production this means country-level versus plant-level accounting.

is likely to remain fairly constant from year to year. If plant-level data are available for both the clinker fraction and the CaO content, these data can be used to arrive either at a plant average or a country average.

Third, if cement production cannot be disaggregated by type and the clinker fraction in cement cannot be estimated reliably, default values for the clinker/cement ratio and its CaO fraction may be used. As shown in Table 3.1, Percent Clinker in the Cement Production Mix, the default value of 98.3% in the *IPCC Guidelines* will generally lead to an overestimation of CO_2 emissions. Many inventory agencies report hydraulic cement production data, but this term can include several types of cement and the assumption of 100% portland cement production may result in overestimates. The clinker fraction can range from a high of 95-97% for a straight portland cement, to 25% or less for a slag cement (see Table 3.3A, Examples of Clinker Fraction of Blended Cement 'Recipes' (Based on US Standards), and Table 3.3B, Classification of Cement Types (Based on European Standards (DIN 1164, part 1))). Therefore, if cement production cannot be disaggregated by type, and it is suspected that both blended and portland cements are being produced, it is *good practice* to assume a clinker fraction of 75%. If the cement production is known to be essentially all portland cement, *good practice* is to use a default value of 95% clinker. In either case, the default clinker is assumed to have a 65% CaO fraction.

TABLE 3.1
PERCENT CLINKER IN THE CEMENT PRODUCTION MIX

Country Production Mix (PC/blend)[a]	**Percent Additives (Pozzolan + Slag) in the Blended Cement**[b]				
	10%	**20%**	**30%**	**40%**	**75%**
0/100	85	76	66	57	24
15/85	87	79	71	63	26
25/75	88	81	74	66	42
30/70	88	82	75	68	45
40/60	89	84	78	72	52
50/50	90	85	81	76	60
60/40	91	87	84	80	66
70/30	92	89	86	84	74
75/25	93	90	88	85	77
85/15	94	92	91	89	84
100/0	Straight Portland cement having 95% clinker fraction				

[a] Country production mix refers to the range of products of a country, e.g. '75/25' means 75% of total production is portland and the rest is blended. It is assumed that all the hydraulic cement is portland or blended or both, or pure pozzolan. Masonry would approximate a product mix of 60/40 to 70/30 portland/blended, for the 75% additive column. Other hydraulic cements (e.g. aluminous) are assumed to be nil.

[b] The inclusion of slag allows for a base to the blend of portland or portland blast furnace slag cement or both. All portland in blended cement is assumed to be 95% clinker. Values calculated as: % PC • 95% + % Blend • [100 – additive %] • 95%.

Source: Calculated by van Oss (1998).

COMPLETENESS

Clinker production plants are generally large and well known in each country. As a result, clinker production data may be available in national statistical databases, or could be easily collected, even if such data have not been published in national statistics. Cement or clinker production data from national statistics may not be complete in some countries where a substantial part of production comes from numerous small kilns, particularly vertical shaft kilns, for which data are difficult to obtain.

DEVELOPING A CONSISTENT TIME SERIES

It is *good practice* to calculate emissions from clinker production using the same method for every year in the time series. Where data are unavailable to support a more rigorous method for all years in the time series, *good practice* is to recalculate these gaps according to the guidance provided in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

If clinker data are available, the uncertainty of the emission factor is equal to the uncertainty of the CaO fraction and the assumption that it was all derived from $CaCO_3$. Since chemical analysis has an uncertainty of 1-2%, this is also the uncertainty of the emission factor. The uncertainty in clinker production data is about 1-2%. If clinker production must be estimated from cement production, the error is about 35%, Table 3.2, Example of Estimation of Uncertainties in CO_2 Emission Calculations Based on the Steps in Figure 3.1. As an example, an attempt has been made to estimate errors at individual steps during emissions estimates (see Figure 3.1, Decision Tree for Estimation of CO_2 Emissions from Cement Production, numbers (1)-(9)). The results are presented in Table 3.2 and give an indication as to how large an error is introduced when different tiers are used.

The component uncertainties in Table 3.2 below have been combined as though they were symmetric maximum-minimum errors. This approach was adopted because many of the uncertainties are non-Gaussian, and some may be systematic. The conclusion from the analysis is that estimation of emissions via cement production data results in an error not exceeding 20 to 40% (depending on the view taken about the values in Table 3.2 where ranges are quoted). Estimation via direct clinker production data decreases the error to about 10%. These ranges should be treated as systematic errors when applying the methods outlined in Chapter 6, Quantifying Uncertainties in Practice.

TABLE 3.2
EXAMPLE OF ESTIMATION OF UNCERTAINTIES IN CO_2 EMISSION CALCULATIONS OF CEMENT PRODUCTION BASED ON THE STEPS IN FIGURE 3.1

Step	Error[a]	Comment	Method
(1)	1-2%	Uncertainty of plant-level production data. Plants generally do not weigh clinker better than this. Assumes complete reporting.	Tier 2
(2)	1-3%	Error associated with assuming that all CaO in clinker is from calcium carbonate.	Tier 2
(3)	1-2%	Uncertainty of plant-level data on CaO content of clinker. This is the best case error of chemical analysis on a production basis.	Tier 2
(4)	4-8%	Error in assuming an average CaO in clinker of 65% (CaO usually 60-67%).	Tier 1, 2
(5)	5%	The best case error assuming that weight and composition of cement kiln dust (CKD) are known.	Tier 2
(6)	1-2%	Plants generally do not weigh cement production better than this. Assumes complete reporting.	Tier 1
(7)	20%	Error due to miss-reporting or non-unique blended cement formulations.	Tier 1
(8)	35%	‘Worst case’ assumes overall 70% blended cement of 50% non-clinker recipe.	Tier 1
(9)	5%	Reporting error, but more accurate than for cement (clinker tariff number is less encompassing).	Tier 1
Summary of resulting error estimates in emissions (see Chapter 6, Quantifying Uncertainties in Practice)			
	20-40%	**Tier 1 error** assuming that clinker production data were derived from cement production data (excluding additional errors for correction of international clinker trade stemming from any need to estimate national clinker production level from cement production).	
	5-10%	**Tier 2 error** assuming derivation from clinker production data.	

[a] Numbers refer to Figure 3.1 and are the ‘maximum’ error – i.e. the most likely rectangular distribution function is assumed. The estimated error at each step, and certain summations thereof, are based on experience in collecting and calculating data.

Source: van Oss (1998).

3.1.1.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. Some examples of specific documentation and reporting relevant to this source category are provided below:

Tier 2 Method

For Tier 2, this includes the following data:

(i) Clinker production and CaO content of clinker;

(ii) Data on non-carbonate feeds to kiln;

(iii) Cement kiln dust losses (indicate if default values were used).

Tier 1 Method

For Tier 1, this includes the following data:

(i) Cement production by type;

(ii) Clinker import/exports;

(iii) Clinker/cement ratio by type of cement (indicate if default values were used);

(iv) CaO content of clinker (indicate if default values were used);

(v) Cement kiln dust losses (indicate if default values were used).

In addition, for both tiers, inventory agencies should:

(i) Clearly specify which data have been used: IPCC defaults or country-specific data;

(ii) Provide all information needed to reproduce the estimate, and provide documentation of QA/QC procedures;

(iii) To preserve an internally consistent emission time series, whenever national methods change, recalculate the entire base-year emissions (from 1990 to the current year). This also calls for additional documentation and discussion of changes;

(iv) If confidentiality is an issue for any type of production, aggregate estimates to the minimum extent needed to maintain confidentiality.

Note: The calculation of CO_2 emissions from fuel combustion (*IPCC Guidelines*, Vol. 3, Chapter 1, Energy) should consider waste fuels in cement kilns (tyres, waste oils, paints etc.) that may not be included in the energy balance. These emissions are not to be mixed with the reporting of industrial process emissions.

3.1.1.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventories agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of emissions estimates using different approaches

If the bottom-up approach is used to collect activity data, then inventory agencies should compare the emissions estimates to the estimates calculated using national production data for the cement or clinker industry (top-down approach). The results of such comparisons should be recorded for internal documentation, including explanations for any discrepancies.

Review of emission factors

Inventory agencies should compare aggregated national emission factors with the IPCC default factors in order to determine if the national factor is reasonable relative to the IPCC default. Differences between national factors and default factors should be explained and documented, particularly if they are representative of different circumstances.

If the aggregated top-down approach is used, but limited plant-specific data are available, inventory agencies should compare the site or plant level factors with the aggregated factor used for the national estimate. This will provide an indication of the reasonableness and the representativeness.

Site-specific activity data check

For site-specific data, inventory agencies should review inconsistencies between sites to establish whether they reflect errors, different measurement techniques, or result from real differences in emissions, operational conditions or technology. For cement production, inventory agencies should compare plant data (content of CaO in clinker, content of clinker in cement) with other plants.

Inventory agencies should ensure that emission factors and activity data are developed in accordance with internationally recognised and proven measurement methods. If the measurement practices fail this criterion, then the use of these emissions or activity data should be carefully evaluated, uncertainty estimates reconsidered and qualifications documented. If there is a high standard of measurement and QA/QC is in place at most sites, then the uncertainty of the emissions estimates may be revised downwards.

Expert review[6]

Inventory agencies should include key industrial trade organisations associated with cement and clinker production in a review process. This process should begin early in the inventory development process to provide input to the development and review of methods and data acquisition. Expert review is particularly important for the content of CaO in clinker, sources of CaO, differences in cement composition, and irregularities in annual production.

Third party reviews are also useful for this source category, particularly related to initial data collection, measurement work, transcription, calculation and documentation.

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[6] The types of expert reviews are covered in Chapter 8, Quality Assurance and Quality Control, and include peer review and third party reviews and audits. In this chapter, the term *expert review* is used to cover all aspects of review, including auditing.

APPENDIX 3.1.1A.1 DEFINITIONS OF CEMENT TYPES

Data for cement commonly include all forms of hydraulic cement, and may include varieties such as slag cement that do not involve substantial amounts of clinker and the associated release of CO_2 from calcination. Blended cements and slag or pozzolan cements are produced and used in many countries. Tables 3.3A, Examples of Clinker Fraction of Blended Cement 'Recipes' (Based on US Standards) and 3.3B, Classification of Cement Types (Based on European Standards (DIN 1164, part 1)), present data on some of the most common types of cement in the US and European countries, respectively.

TABLE 3.3A
EXAMPLES OF CLINKER FRACTION OF BLENDED CEMENT 'RECIPES' (BASED ON US STANDARDS)

Cement Name	Symbol	Recipe	% of Clinker	Notes
Portland	'PC'	100% PC	95-97	
Masonry	'MC'	2/3 PC	64	recipe varies considerably
Slag-modified portland	I(SM)	slag < 25%	>70-93	
Portland blast furnace slag	IS	slag 25-70%	28-70	
Portland pozzolan	IP and P	pozz 15-40%	28-79/81	base is PC or IS
Pozzolan-modified portland	I(PM)	pozz < 15%	28-93/95	base is PC or IS
Slag cement	S	slag 70%	<28/29	can use lime instead of clinker

Source: van Oss (1998) based on ASTM (1996a).

TABLE 3.3B
CLASSIFICATION OF CEMENT TYPES (BASED ON EUROPEAN STANDARDS (DIN 1164, PART 1))

Cement Name	Symbol	Recipe	% of Clinker
Portland cement	CEM I	–	95-97
Slag modified portland	CEM II/A-S	slag 6-20%	77-90
	CEM II/B-S	slag 21-35%	62-76
Portland pozzolan	CEM II/A-P	pozzolan 6-20%	77-90
	CEM II/B-P	pozzolan 21-35%	62-76
Portland fly ash cement	CEM II/A-V	fly ash 6-20%	77-90
Portland oil shale cement	CEM II/A-T	oil shale 6-20%	77-90
	CEM II/B-T	oil shale 21-35%	62-76
Portland limestone cement	CEM II/A-L	limestone 6-20%	77-90
Portland fly ash slag cement	CEM II/A-SV	fly ash 10-20%	77-86
	CEM II/B-SV	slag 10-21%	76-86
Portland blast furnace slag	CEM III/A	blast furnace slag 36-65%	34-61
	CEM III/B	blast furnace slag 66-80%	19-33

Source: DIN (1994).

Cement types can be characterised as follows:

- **Hydraulic cement**: any cement that sets and hardens in water.
- **Portland cement** is a mixture of clinker and gypsum, with clinker comprising about 95-97% of the total weight of the cement (95% clinker is a common default value). Many countries may allow a small (1-5%) addition of inert or cementitious extenders. Some production data for 'portland cement' may include blended cements.

- **Blended cements** are a mix (sometimes interground) of portland cement or its clinker, with additives such as ground granulated blast furnace slag and pozzolans (e.g. fly ash, silica fume, burned shale). The additives make up a variable, non-unique percentage of the total cement, but generally are in the range of 15-40%, with clinker thus making up 57-81%.
- **Slag cements** contain high proportions (> 70%) of ground granulated blast furnace slag, with the remainder either portland cement (or clinker) or lime or both. Some slag cements contain no portland cement at all. Granulated blast furnace slag is itself a latent cement (as binding material), possessing moderate hydraulic properties, but develops improved cementitious properties when interacted with free lime (and water).
- **Masonry cement** recipes vary but typically are about 2/3 portland cement or its clinker, and 1/3 additives such as lime or limestone.
- **Aluminous cements** are hydraulic cements manufactured by burning a mix of limestone and bauxite. Typically, aluminous cements contain about 30-42% CaO, or about 45-65% of the CaO content of portland cement clinker.
- **Pozzolan cement** can refer to a blended cement containing a substantial quantity of pozzolans, but more properly refers to a cement made predominantly of pozzolans and an activator agent – such as lime – that supplies CaO but does not involve substantial amounts of portland cement or portland cement clinker.
- **Pozzolan** is a siliceous material that in itself is not cementitious, but which develops hydraulic cement properties when it reacts with free lime (CaO) and water. Common examples of pozzolans include natural pozzolans (e.g. certain volcanic ashes or tuffs, certain diatomaceous earths, burned clays and shales) and synthetic pozzolans (e.g. silica fume, fly ash).

3.1.2 Lime production

3.1.2.1 Methodological issues

Lime production[7] emits CO_2 through the thermal decomposition (calcination) of the calcium carbonate ($CaCO_3$) in limestone to produce quicklime (CaO), or through the decomposition of dolomite[8] ($CaCO_3 \cdot MgCO_3$) to produce dolomitic 'quick' lime ($CaO \cdot MgO$). *Good practice* to estimate emissions from lime production is to determine the complete production of CaO and $CaO \cdot MgO$ from data on lime production. The accuracy depends on obtaining complete lime production statistics and establishing the proportion of different types of lime. The *IPCC Guidelines* address both points briefly, presenting an upper limit emission factor as a default to avoid underestimating emissions.

CHOICE OF METHOD

The *IPCC Guidelines* provide the following equation for estimating emissions:

EQUATION 3.4

$$CO_2 \text{ Emissions} = \text{Emission Factor (EF)} \bullet \text{Lime Production}$$

Where:

EF = 785 kg CO_2 per tonne of high calcium quicklime, and
913 kg CO_2 per tonne of dolomitic quicklime

Equation 3.4 can be applied either to national statistics or at the producer level. It is *good practice* to assess the available national statistics for completeness, and for the ratio of limestone to dolomite used in lime production. Industries that use lime, and may produce it, are listed in the section on completeness. Data collection should cover both the amounts produced and average composition. The choice of *good practice* methods depends on national circumstances (as shown in Figure 3.2, Decision Tree for Lime Production).

CHOICE OF EMISSION FACTORS

The default emission factors in the *IPCC Guidelines* mentioned under Equation 3.4 correspond to 100% of CaO (or $CaO \cdot MgO$) in lime (stoichiometric ratio) and can lead to an overestimation of emissions since the CaO and (if present) MgO content may be less than 100%. It is *good practice* to apply Equation 3.5A or Equation 3.5B, or both, to adjust the emission factors and to account for the CaO or the $CaO \cdot MgO$ content (see Table 3.4, Basic Parameters for the Calculation of Emission Factors for Lime Production):

EQUATION 3.5A

$$EF_1 = \text{Stoichiometric Ratio } (CO_2 / CaO) \bullet \text{CaO Content}$$

Where: EF_1 = emission factor for quicklime

EQUATION 3.5B

$$EF_2 = \text{Stoichiometric Ratio } (CO_2 / CaO \cdot MgO) \bullet (CaO \cdot MgO) \text{ Content}$$

Where: EF_2 = emission factor for dolomitic quicklime

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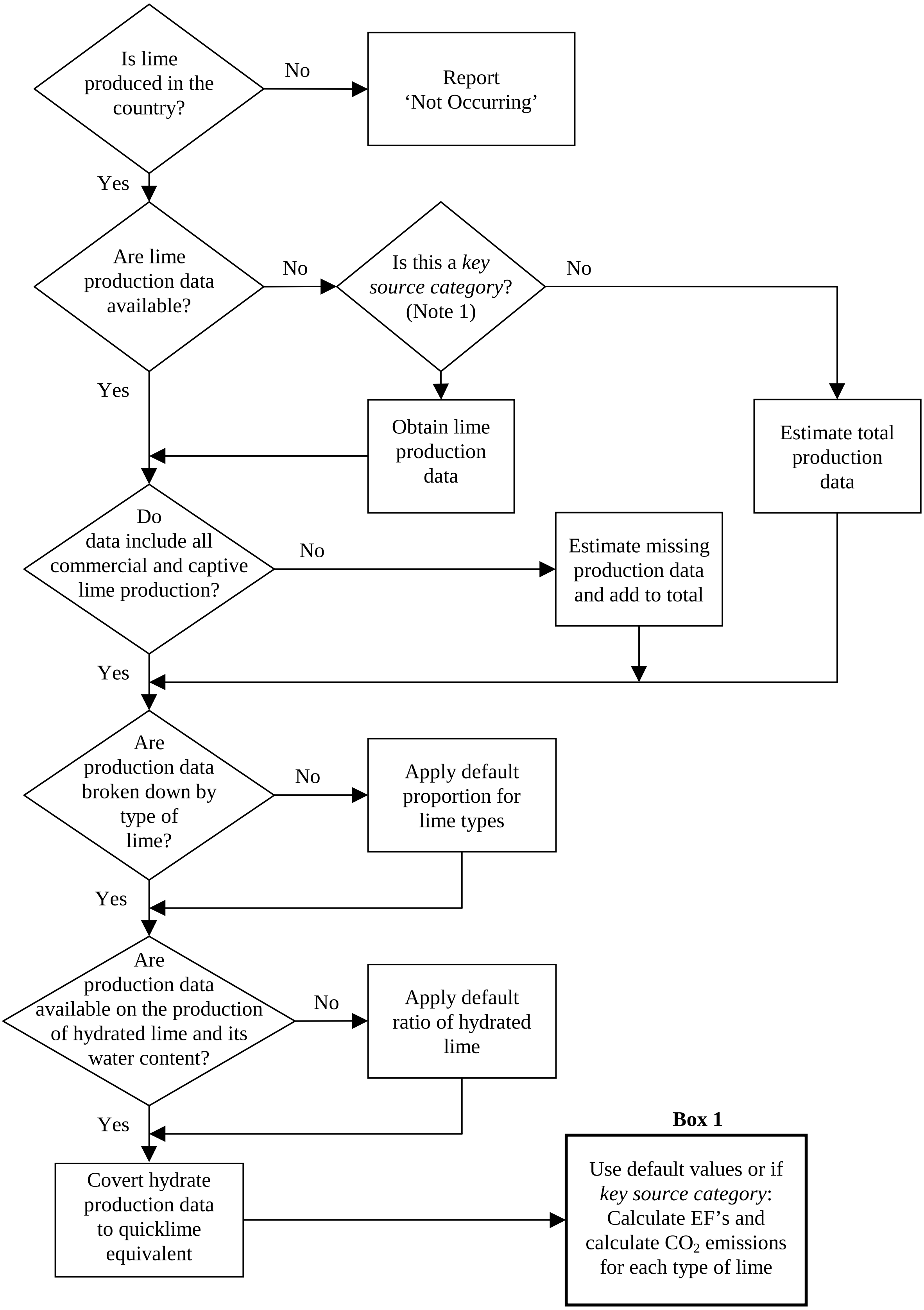
[7] Emissions from limestone use are also discussed separately in the *IPCC Guidelines*, but *good practice guidance* for this source category and some other related emission source categories are not presented in this report. *Good practice guidance* has not yet been developed because emissions from the source categories are assumed to be small and corresponding data are unavailable.

[8] Non-stoichiometric chemical compounds, such as the isomorphic crystal mixtures between Ca and Mg in its compounds as oxides and carbonates, are usually expressed by the chemical formula $CaO \cdot MgO$ and $CaCO_3 \cdot MgCO_3$, respectively.

Figure 3.2 Decision Tree for Lime Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Table 3.4, Basic Parameters for the Calculation of Emission Factors for Lime Production, provides data on stoichiometric ratio, the ranges of CaO and CaO·MgO contents and the resulting default emission factors, for the main lime types produced. There are three main types of lime:

- High-calcium lime (CaO + impurities);
- Dolomitic lime (CaO·MgO + impurities);
- Hydraulic lime (CaO + calcium silicates) that is a substance between lime and cement.

The main reason to distinguish these types is that the first two have different stoichiometric ratios, and the third has substantially lower CaO content. There is no exact chemical formula for each type of lime because the chemistry of the lime product is determined by the chemistry of the limestone or dolomite used to manufacture the lime.

Taking the types of lime into account will improve the emissions estimates. Consequently, when determining lime composition, *good practice* is to check the following two attributes: (1) the proportion of the three different types of lime, and (2) the proportion of hydrated lime in production.

When there are no disaggregated data for the breakdown of lime types, the default value for high-calcium/dolomitic lime is 85/15 (Miller, 1999) and the proportion of hydraulic lime should be assumed zero unless other information is available.

TABLE 3.4
BASIC PARAMETERS FOR THE CALCULATION OF EMISSION FACTORS FOR LIME PRODUCTION

Lime Type	**Stoichiometric Ratio (1)**	**Range of CaO Content [%]**	**Range of MgO Content [%]**	**Default Value for CaO/ CaO·MgO Content (2)**	**Default Emission Factor (1) • (2)**	**Uncertainty Estimate in Emissions Estimates**
High-calcium lime[a]	0.79	93-98	0.3-2.5	0.95	0.75	±2%
Dolomitic lime [b]	0.91	55-57	38-41	0.95 or 0.85[c]	0.86 or 0.77[c]	±2%
Hydraulic lime [b]	0.79	65-92		0.75	0.59	±15%

Source:
[a] Miller (1999b) based on ASTM (1996b) and Schwarzkopf (1995).
[b] Miller (1999a) based on Boynton (1980).
[c] This value depends on technology used for lime production. The higher value is suggested for developed countries, the lower for developing ones.

CHOICE OF ACTIVITY DATA

Complete activity data include both lime production data and data on lime structure (including types of lime and proportion of hydrated lime).

Correction for the proportion of hydrated lime: Both high-calcium and dolomitic limes can be slaked and converted to hydrated lime that is $Ca(OH)_2$ or $Ca(OH)_2 \cdot Mg(OH)_2$.[9]

If *x* is the proportion of hydrated lime and *y* is the water content in it, it is *good practice* to multiply the production by a correction factor 1 – (x • y). Table 3.5, Correction of Activity Data for Hydrated Lime, below provides ranges for the amount water (y) in different types of lime. Default values are x = 0.10, y = 0.28 resulting in a correction factor of 0.97 (Miller, 1999).

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[9] The term ‘slaked lime’ can mean dry hydrated lime, putty or an aqueous solution. Assuming complete hydration and 100% pure quicklime, the water of hydration for high-calcium lime is 24% and for dolomitic lime is 27%. In practice, an excess of water over the theoretical amount is required for complete hydration (Miller, 1999).

TABLE 3.5
CORRECTION OF ACTIVITY DATA FOR HYDRATED LIME

Lime Type	Theoretical Content of Water in Hydrated Lime [%]	Content of Water in Commercial Hydrated Lime [%]	Default Water Content Correction Factor
High-calcium lime	24.3	26-28	0.28
Dolomitic lime	27.2	17-31	0.28
Hydraulic lime	–	–	–

Source: Miller (1999b) based on ASTM (1996) and Schwarzkopf (1995).

COMPLETENESS

Completeness of the activity data (e.g. lime production) is a crucial attribute of *good practice*. Typically, reported production accounts for only a portion of the actual production, if lime production is considered to be that product that is sold on the market. Use or production of lime as a non-marketed intermediate is not well accounted for or reported. For example, many plants that produce steel, synthetic soda ash, calcium carbide[10], magnesia and magnesium metal, as well as copper smelters and sugar mills, produce lime but may not report it to national agencies. Also, industries that regenerate lime from waste calcium carbonates (e.g. wood pulp and paper plants) are unlikely to report their lime production. Omission of these data may lead to an underestimation of lime production for a country by a factor of two or more.

DEVELOPING A CONSISTENT TIME SERIES

It is *good practice* to calculate emissions from lime production using the same method for every year in the time series. Where data are unavailable to support a more rigorous method for all years in the time series, *good practice* is to recalculate these gaps according to the guidance provided in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

The stoichiometric ratio is an exact number and therefore the uncertainty of the emission factor is the uncertainty of lime composition, in particular of the share of hydraulic lime that has 15% uncertainty in the emission factor (2% uncertainty in the other types). Therefore, the total uncertainty is 15% at most (see Table 3.4, Basic Parameters for the Calculation of Emission Factors for Lime Production).

The uncertainty for the activity data is likely to be much higher than for the emission factors, based on experience in gathering lime data (see completeness section above). Omission of non-marketed lime production may lead to an error of +100% or more. The correction for hydrated lime typically adds about ±5% to the former uncertainty.

3.1.2.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

To preserve an internally consistent emission time series, whenever national methods change, *good practice* is to recalculate the entire time series. If confidentiality is an issue for any type of production, estimates may be aggregated to the minimum extent possible to maintain confidentiality.

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[10] Some carbide producers may also regenerate lime from their calcium hydroxide by-products, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2\ H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2 + \text{heat} \rightarrow CaO + H_2O$] and no CO_2 is released to the atmosphere.

3.1.2.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of the emissions estimates using different approaches

If the bottom-up approach is used, then inventory agencies should compare the emissions estimates to the estimate calculated using national lime production data (top-down approach). The results of such comparisons should be recorded for internal documentation, including explanations for any discrepancies.

Activity data check

Inventory agencies should confirm the correct definitions of the different types of lime produced in the country (i.e. CaO and MgO content, high-calcium quicklime (CaO), and dolomitic quicklime (CaO·MgO). They should check the completeness of national statistics for limestone, lime and dolomite use by comparing them with the default list of industries using limestone provided in the *IPCC Guidelines*, Vol. 3, p 2.9).

3.1.3 Iron and steel industry

3.1.3.1 Methodological issues

Crude iron is produced by the reduction of iron oxide ores mostly in blast furnaces, generally using the carbon in coke or charcoal (sometimes supplemented with coal or oil) as both the fuel and reductant. In most iron furnaces, the process is aided by the use of carbonate fluxes (limestone). Additional emissions occur as the limestone or dolomite flux gives off CO_2 during reduction of pig iron in the blast furnace, but this source category is covered as emissions from limestone use (see the *IPCC Guidelines*, Vol. 3, Section 2.5, Limestone and Dolomite Use). Except for a small amount of carbon retained in the crude iron, all the carbon in the coke and in the fluxes is emitted as the product of combustion and calcination. Emissions also occur to a much lesser extent during the production of steel that is essentially the process of removal (generally by oxidation) of most of the carbon in crude iron.

Carbon plays the dual role of fuel and reductant. It is important not to double-count the carbon from the consumption of coke or other reducing agents if this is already accounted for as fuel consumption in the Energy Sector. Since the primary purpose of carbon oxidation is to reduce iron oxide ore to crude or pig iron (carbon is used as a reducing agent), the emissions are considered to be industrial processes emissions, and they should be preferably reported as such. If this is not the case, it should be explicitly mentioned in the inventory. This source category should include CO_2 emissions from the use of blast furnace gas as a fuel if emissions are reported in the Industrial Processes Sector.

CHOICE OF METHOD

The *IPCC Guidelines* outline several approaches for calculating CO_2 emissions from iron and steel production. The choice of a *good practice* method depends on national circumstances as shown in the decision tree in Figure 3.3, Decision Tree for the Iron and Steel Industry. The Tier 1 method calculates emissions from the consumption of the reducing agent (e.g. coke from coal, coal, petroleum coke), using emission factors similar to those used to estimate combustion emissions. The Tier 1 method is rather simple and slightly overestimates emissions. The Tier 2 method is similar to Tier 1 but includes a correction for the carbon stored in the metals produced. In addition, a very simple approach that is mentioned in the *IPCC Guidelines,* is to multiply iron and steel production by a production-based emission factor. However, this method is not considered to be *good practice*.

CO_2 emissions from limestone used as 'flux' in the reduction process are not included here because they are accounted for in the *IPCC Guidelines*, Vol. 3, Section 2.5, Limestone and Dolomite Use.[11]

Tier 2 Method

The Tier 2 method is based on tracking carbon through the production process. It is more accurate than Tier 1, but also more data-intensive. Estimating the emissions on the basis of plant-specific data for both Tier 1 and Tier 2 will avoid double counting or missing emissions. With the Tier 2 method, emissions from iron production and steel production are calculated separately. To achieve the highest accuracy, *good practice* is to develop emissions estimates at the plant-level because plants can differ substantially in their technology. If plant-level data are not available, *good practice* is to use nationally compiled production data for iron/steel production that are to be subtracted from the fuel combustion sector. Thus, detailed knowledge of the conventions in the national energy statistics and the inventory are necessary to avoid double counting or omission.

Iron**:** *Good practice* is to use the following equation from the *IPCC Guidelines*:

EQUATION 3.6A

$$\text{Emissions}_{\text{pig iron}} = \text{Emission Factor}_{\text{reducing agent}} \bullet \text{Mass of Reducing Agent} + (\text{Mass of Carbon in the Ore} - \text{Mass of Carbon in the Crude Iron}) \bullet 44 / 12$$

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[11] Iron furnaces require limestone of higher purity than can be needed for clinker (cement) production. The *IPCC Guidelines* cite a USEPA reference that assumes 250 kg of lime is used for every tonne of iron. This value varies with the purity of ore and type of furnace, however.

Reducing agents can be coke, coal, charcoal and petroleum coke. In Table 3.6, CO_2 Emission Factors for Metal Production (tonne CO_2/tonne reducing agent), default emission factors from the *IPCC Guidelines* (Vol. 3, Table 2-12, CO_2 Emission Factors for Metal Production Generally (tonne CO_2/tonne reducing agent)) are presented for the most common reducing agents. In direct reduction techniques, other reducing agents such as CO, H_2 or natural gas are used. Plant-level or country-specific emission factors should be applied in these cases. According to the *IPCC Guidelines,* CO_2 emissions occurring from the limestone flux are reported as emissions from limestone and dolomite use (see the *IPCC Guidelines*, Vol. 3, Section 2.5, Limestone and Dolomite Use).

The amount of carbon in ore is almost zero and crude iron contains about 4% carbon.

***Steel*:** Emissions from steel production (e.g. using a basic oxygen furnace (BOF), open hearth furnace (OHF) or electric arc furnaces (EAF)) are based on the difference between the carbon contents of iron (3-5%) and steel (0.5-2%). In addition, for steel produced in electric arc furnaces it is *good practice* to add the carbon released from consumed electrodes to the emissions (roughly 1-1.5 kg carbon per tonne of steel):[12]

EQUATION 3.6B

$$\text{Emissions}_{\text{crude steel}} = (\text{Mass of Carbon in the Crude Iron used for Crude Steel Production} - \text{Mass of Carbon in the Crude Steel}) \bullet 44/12 + \text{Emission Factor}_{\text{EAF}} \bullet \text{Mass of Steel Produced in EAF}$$

The total emissions from iron and steel production are just the sum of the two Equations 3.6A and 3.6B above:

EQUATION 3.7

$$\text{Total emissions} = \text{Emissions}_{\text{pig iron}} + \text{Emissions}_{\text{crude steel}}$$

Tier 1 Method

Using the Tier 1 method, the carbon storage in pig iron and crude steel produced is not included as it is in the Tier 2 method. This simplifies the calculation in the sense that the carbon content information in the metals produced is not required. When using the Tier 1 method, it is *good practice* to calculate the emissions as follows:

EQUATION 3.8

$$\text{Emissions} = \text{Mass of Reducing Agent} \bullet \text{Emission Factor}_{\text{reducing agent}}$$

The coke and charcoal consumption in the iron and steel industry can be used to estimate the mass of reducing agents, if plant-specific information on the fuels used as reducing agent is not readily available (while subtracting the same amount from the fuel combustion sector). This step affects only the sectoral allocation of the CO_2 emissions, not the total amount. The error made in neglecting the carbon storage term of Tier 2 will be 1-5% if all pig iron produced is used for the production of crude steel and at maximum 10% if all pig iron is used for other purposes (e.g. in cast iron foundries). Thus, this method will result in a small overestimation of the source.

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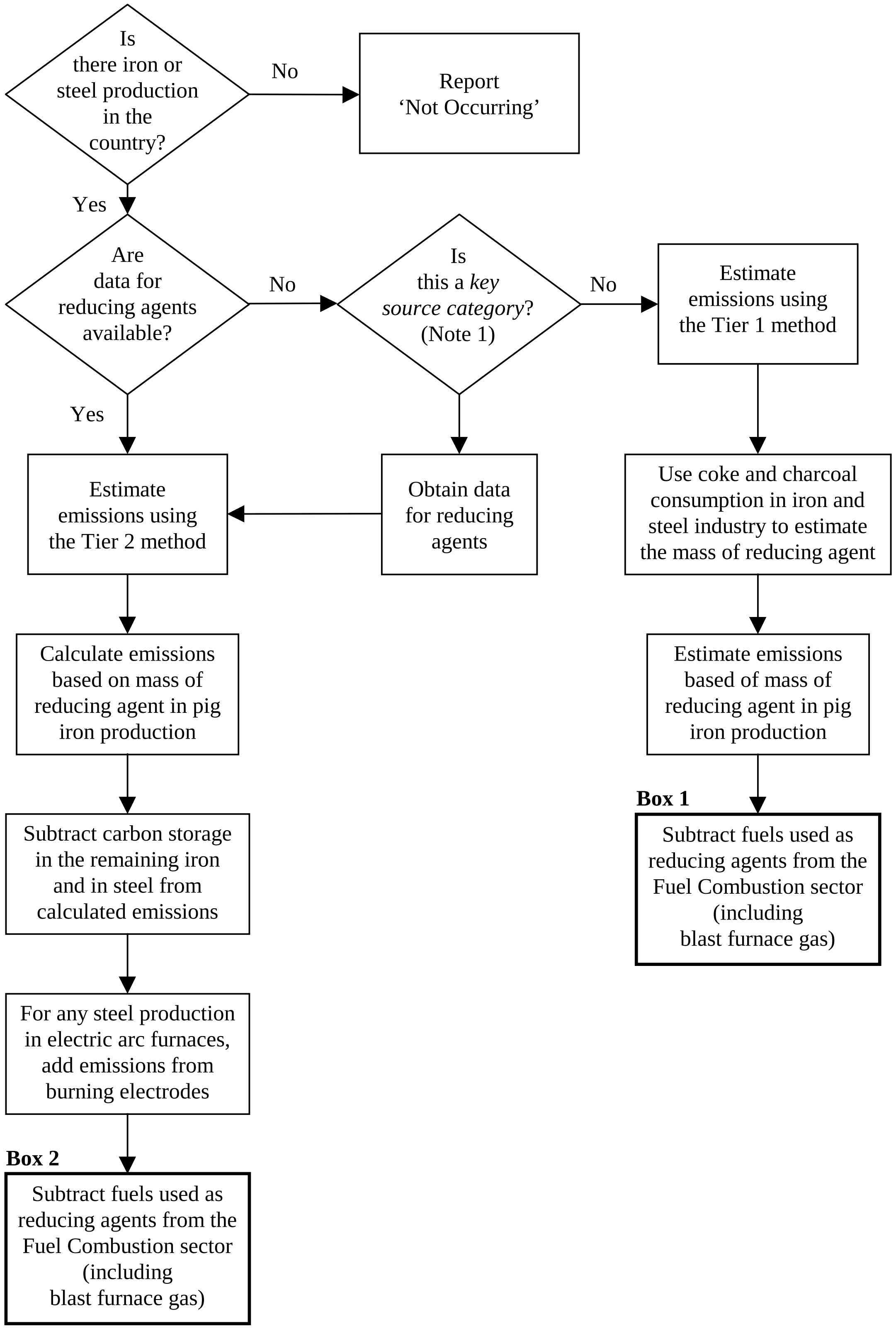
[12] Lime is added to electric arc furnaces (EAF) and its CO_2 emission should be accounted for in the lime use section (see the *IPCC Guidelines*, Vol. 3, Section 2.5). The carbon emissions factor is based on carbon loss from the electrode as an average value for the following process: In the EAF, the electrodes are made of carbon – either graphite or as Søderberg paste. Where the electrodes are kept above the steel melt (liquid), the electrical arc oxidises the carbon to CO or CO_2. The rate of gas production will vary with the electrode type and various other factors. Also, the heat causes oxidation of carbon in the melt, reducing it from around 4% for crude iron to 2% or less (usually less than 1%) in steel. Sometimes, the electrode is immersed in the melt to increase the carbon content of the steel, should too much carbon have been burned out of the melt. In this case, carbon is removed from the electrode, but may or may not result in CO_2 production. If the EAF is adjusted correctly, just enough electrode erosion is allowed to restore the steel's carbon content to the desired level. If the EAF is not efficient, excess working electrode erosion happens to excess, the electrode is retracted to above the melt, and excess carbon in the melt is burned off.

Figure 3.3 Decision Tree for the Iron and Steel Industry



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: CO_2 emissions from limestone used as 'flux' in the reduction process are not included here since they are accounted for in the *IPCC Guidelines*, Vol. 3, section 2.5, on CO_2 emissions from limestone and dolomite use.

CHOICE OF EMISSION FACTORS

If country-specific data at the plant level are not available, the default emission factors for reducing agents in the pig iron production can be taken from the *IPCC Guidelines*, Vol. 3, Table 2-12 (see Table 3.6, CO_2 Emission Factors for Metal Production (tonne CO_2/tonne reducing agent)).

TABLE 3.6
CO_2 EMISSION FACTORS FOR METAL PRODUCTION (TONNE CO_2/TONNE REDUCING AGENT)

Reducing Agent	Emission Factor[a]
Coal[b]	2.5
Coke from coal[b]	3.1
Petrol coke	3.6

[a] If better information on actual carbon content is not available nationally or cannot be calculated from data in the *IPCC Guidelines*, Vol. 3, Chapter 1.
[b] Derived from data in the *IPCC Guidelines*, Vol. 3, Chapter 1.

Source: *IPCC Guidelines*, Reference Manual, Table 2-12.

In direct reduction techniques, other reducing agents such as CO, H_2 or natural gas are used, each with a specific emission factor. It is *good practice* to use plant specific emission factors for steel produced in an EAF. If plant-level data are not available, a default emission factor for the electrode oxidation should be used. For the Tier 2 method, a default emission factor of 5 kg CO_2 per tonne of steel produced in EAFs should be used for the electrode consumption from the steel produced in electric arc furnaces (emission factor_{EAF}) (Tichy, 1999).

CHOICE OF ACTIVITY DATA

Tier 2 Method

Activity data should be collected at the plant-level. The most important datum is the amount of reducing agent used for iron production. If this is not a *key source category* and plant-specific data are not available, the mass of reducing agent can be estimated using the Tier 1 approach (see below). In addition, the amount of pig iron produced as well as the amounts used for crude steel production, and their carbon contents, should be collected along with data on the amount of crude steel produced in EAFs and the amount of iron in ore and its carbon content.

Tier 1 Method

The Tier 1 method requires only the amount of reducing agent used for iron production. If plant-specific data on the mass of reducing agent are not available, they can be estimated by subtracting the amount of fuel used in the iron and steel industry (ISIC 1990) for the iron ore reduction from the fuel use and reported in the Energy Sector. The amount of fuel used for the reduction can be calculated from the mass balance of the chemical formula to reduce iron ore. This rough estimation affects only the allocation of the CO_2 emissions between the Industrial Processes and the Energy Sector.

COMPLETENESS

In estimating emissions from this source category, there is a risk of double-counting or omission in either the Industrial Processes or the Energy Sector. Since the primary use of coke oxidation is to produce pig iron, the emissions are considered to be industrial processes, and it should be reported as such. If this is not the case it should be explicitly mentioned in the inventory. Inventory agencies should perform a double counting/completeness check. This will require good knowledge of the inventory in that source category.

DEVELOPING A CONSISTENT TIME SERIES

Emissions from iron and steel production should be calculated using the same method for every year in the time series. Where data are unavailable to support a more rigorous method for all years in the time series, these gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

For both Tier 1 and 2 the most important type of activity data is the amount of reducing agent used for iron production. According to Chapter 2, Energy, energy data have a typical uncertainty of about 5% (about 10% for countries with less developed energy statistics). For calculating the carbon storage term Tier 2 requires additional activity data on amounts of pig iron and net crude steel production that have a typical uncertainty of a few percent. In addition, Tier 2 requires information on the carbon content of pig iron, crude steel, and of iron ore that may have an uncertainty of 5% when plant-specific data are available. Otherwise the uncertainty in the carbon content could be of the order of 25 to 50%. Finally, the uncertainty in the emission factors for the reducing agent (e.g. coke) are generally within 5% (see Section 2.1.1.6, CO_2 Emissions from Stationary Combustion, Uncertainty Assessment).

The systematic error made in emissions estimated in Tier 1 by neglecting the carbon storage term of Tier 2 will be 1-5% if all pig iron produced is used for the production of crude steel and at maximum 10% if all pig iron should be used for other purposes, i.e. in cast iron foundries. Thus, this method will result in a small overestimation of the source.

3.1.3.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

Tier 2 Method

Good practice is to document the emissions, all activity data (reducing agents, carbon stored, steel produced in EAFs, electrodes), in addition to corresponding emission factors and assumptions used to derive them. There should be an explanation of the linkage with the Fuel Combustion Sub-sector estimate to demonstrate that double counting or missing emissions have not occurred.

Tier 1 Method

Besides the emissions, *good practice* is to report the amount of reducing agents and their emission factors. In the corresponding table, reported emissions are only part of total emissions and the rest are reported elsewhere (Fuel Combustion Section).

In addition, inventory agencies should for both tiers, document all information needed to reproduce the estimate, as well as the QA/QC procedures.

3.1.3.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Activity data check

For the Tier 2 method, inventory agencies should check with Fuel Combustion as mentioned in Section 2.1.1.4 to ensure that emissions from heating/reducing agents (coal, coke, natural gas, etc.) are not double counted or omitted.

Inventory agencies should examine any inconsistency between data from different plants to establish whether these reflect errors, different measurement techniques or result from real differences in emissions, operational conditions or technology. This is particularly relevant to the plant-specific estimates of the mass of the reducing agent.

Inventory agencies should compare aggregated plant-level estimates to industry totals for carbon and limestone consumption where such trade data are available.

3.2 N_2O EMISSIONS FROM ADIPIC ACID AND NITRIC ACID PRODUCTION

3.2.1 Methodological issues

Nitrous oxide (N_2O) is generated as an unintended by-product during the production of adipic acid and nitric acid (HNO_3), and in many industrial processes that use nitrogen oxides or nitric acids as feedstocks (e.g. the manufacture of caprolactam, glyoxal, and nuclear fuel reprocessing). Adipic acid and nitric acid are large sources of atmospheric N_2O if not abated.[13] Emissions of N_2O from these processes depend on the amount generated in the specific production process and the amount destroyed in any subsequent abatement process. Abatement of N_2O can be intentional, through installation of equipment specifically designed to destroy N_2O in adipic acid plants, or unintentional in systems designed to abate other emissions such as nitrogen oxides (NO_x). For further discussion, see Reference Manual of the *IPCC Guidelines* (Sections 2.9 and 2.10, Nitric Acid Production and Adipic Acid Production).

CHOICE OF METHOD

The choice of *good practice* methods depends on national circumstances. The decision tree in Figure 3.4, Decision Tree for N_2O Emissions from Adipic Acid and Nitric Acid Production describes *good practice* in adapting the methods in the *IPCC Guidelines* to these national circumstances. The decision tree should be applied separately to adipic and nitric acid production.

The *IPCC Guidelines* present a basic equation for estimating N_2O emissions in which production data is multiplied by an emission factor. Given the current and potential future use of N_2O abatement technologies, particularly in adipic acid plants, it is *good practice* to include an additional term in this equation as follows:

EQUATION 3.9

$$N_2O \text{ Emissions} = \text{Specific Emission Factor} \bullet \text{Production Level} \bullet [1 - (N_2O \text{ Destruction Factor} \bullet \text{Abatement System Utilisation Factor})]$$

The N_2O destruction factor has to be multiplied by an abatement system utility factor in order to account for any down time of the emission abatement equipment (i.e. time the equipment is not operating).

To achieve the highest accuracy, *good practice* is to apply this equation at the plant-level using N_2O generation and destruction factors developed from plant-specific measurement data. In this case, the national total is equal to the sum of plant totals. Where plant-level information is not available, *good practice* provides default N_2O generation factors and destruction factors as shown in Tables 3.7, Default Factors for Adipic Acid Production, and 3.8, Default Factors for Nitric Acid Production, based on the plant types and abatement technologies implemented.

Given the relatively small number of adipic acid plants (about 23 globally, Choe *et al.*, 1993), obtaining plant-specific information requires few additional resources. However, there are more nitric acid plants (estimates range from 255 to 600 plants according to Choe *et al.*, 1993,, Bockman and Granli, 1994) with a much greater variation in the N_2O generation factors among plant types. Thus, default factors may be needed more often for nitric acid N_2O emissions estimates. Where default values are used to estimate emissions from nitric acid production, it is *good practice* to categorise plants according to type and to use an appropriate N_2O generation factor used to the extent possible.

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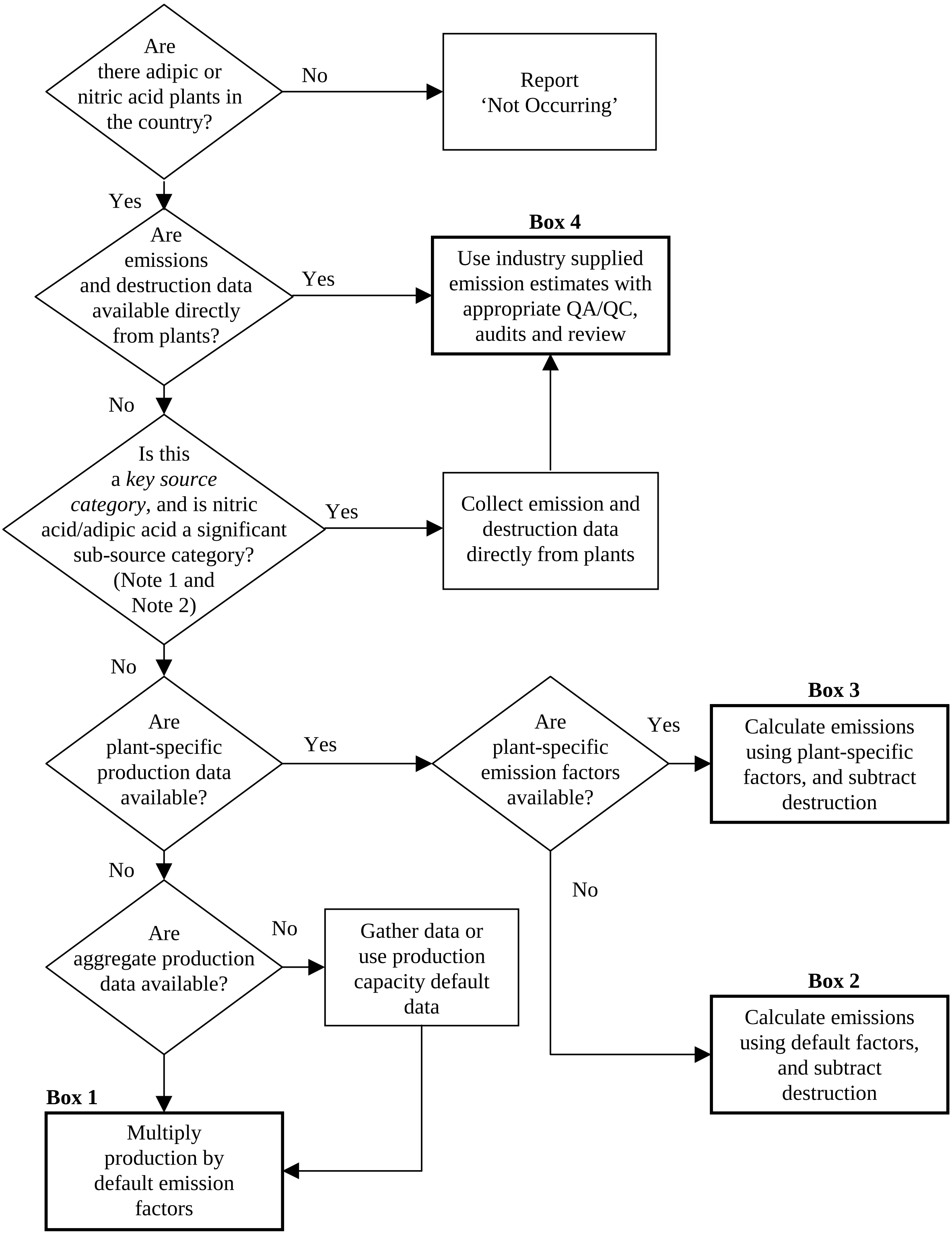
[13] The chemical and other industries included in this section are generally unrelated except for the fact that nitric acid is used in the manufacture of adipic acid. The manufacturing technologies and the applicable technologies for abating N_2O are very different for each industry.

Figure 3.4 Decision Tree for N_2O Emissions from Adipic Acid and Nitric Acid Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: As a rule of thumb, a sub-source category would be significant if it accounts for 25-30% of emissions from the source category.

CHOICE OF EMISSION FACTORS

Plant measurements provide the most rigorous data for calculating net emissions (i.e. N_2O generation and destruction factors). Monitoring N_2O emissions from both adipic acid and nitric acid production is practical because these are point sources and there are a finite number of production plants. Given currently available technology, instrumentation for sampling and monitoring emission rates do not limit precision or accuracy of the overall measurement. Usually sampling frequency and timing is sufficient to avoid systematic errors and to achieve the desired level of accuracy. As a general rule, it is *good practice* to conduct sampling and analysis whenever a plant makes any significant process changes that would affect the generation rate of N_2O, and sufficiently often otherwise to ensure that operating conditions are constant. In addition, plant operators should be consulted annually to determine the specific destruction technologies employed and confirm their use, since technologies may change over time. Precise measurement of the emissions rate and abatement efficiencies requires measurement of both the exit stream and the uncontrolled stream. Where measurement data are available only on the exit stream, *good practice* is to base emissions on these data. In this case, any available estimates of abatement efficiency should be provided only for information purposes and not used to calculate emissions.

If plant-level factors are not available, it is *good practice* to use default factors. These default values often represent midpoint or mean values of data sets (as determined by expert analysis). The extent to which they represent a specific plant's emission rate is unknown. Default factors should be used only in cases where plant-specific measurements are not available.

Table 3.7, Default Factors for Adipic Acid Production, presents default emission factors for adipic acid production, and default N_2O destruction factors for commonly used abatement technologies, and associated uncertainties. This table supplements the *IPCC Guidelines* default values by providing information about N_2O abatement technologies. Failure to determine if abatement technologies are being used can result in overestimation of emissions.

Table 3.8, Default Factors for Nitric Acid Production, supplements the emission factors for nitric acid production provided in the *IPCC Guidelines* (Vol. 3, Section 2.9, Table 2-7, Emission Factors for N_2O from Nitric Acid Production). It also includes additional emission and destruction factors for NO_x abatement technologies, and associated uncertainties. The generation factors listed in Table 3.8 for plants using non-selective catalytic reduction (NSCR) already incorporate the effect of abatement measures. The N_2O destruction factor for NSCR in Table 3.8 is provided for information purposes only and should not be applied to an emissions estimate using the NSCR default generation factor because this would double-count the destruction.

TABLE 3.7
DEFAULT FACTORS FOR ADIPIC ACID PRODUCTION

Production Process	**N_2O Generation Factor**[a,d]	**Uncertainty Estimate**
Nitric Acid Oxidation	300 kg/tonne adipic acid	± 10% (based on expert judgement). The range of 300 kg ± 10% encompasses the variability from pure ketone to pure alcohol feedstocks, with most manufacturers somewhere in the middle.[a]
Abatement Technology	**N_2O Destruction Factor**[b]	**Uncertainty Estimates (distinct from destruction factor ranges)**
Catalytic Destruction	90-95%	± 5% (based on expert judgement). Manufacturers known to employ this technology include: BASF (Scott, 1998), and DuPont (Reimer, 1999b).
Thermal Destruction	98-99%	± 5% (based on expert judgement). Manufacturers known to employ this technology include: Asahi, DuPont, Bayer, and Solutia (Scott, 1998).
Recycle to feedstock for Phenol	98-99%	± 5% (based on expert judgement). Manufacturers known to employ this technology include: Alsachemie (Scott, 1998).
Recycle to feedstock for Adipic Acid	90-98%	± 5% (based on expert judgement). Solutia will be implementing this technology around 2002 (Scott, 1998).
Abatement System	**Utilisation Factor**[e]	
Catalytic Destruction	80-98%	See Note c
Thermal Destruction	95-99%	See Note c
Recycle to Nitric Acid	90-98%	See Note c
Recycle to Adipic Acid	80-98%	See Note c

[a] With regard to the Japan Environment Agency value (264 kg N_2O/tonne adipic acid) provided in the *IPCC Guidelines*, it is believed that this manufacturer uses oxidation of pure cyclohexanol (alcohol), instead of a ketone-alcohol mixture (Reimer, 1999). This is the only plant known to use this method.

[b] The destruction factor (that represents the technology abatement efficiency) should be multiplied by an abatement system utility factor. Note that this range is not an uncertainty estimate.

[c] Note that these default values are based on expert judgement and not industry-supplied data or plant-specific measurements. In the first 1-5 years of the abatement technology implementation, the utilisation factor tends to be at the lower end of the range. Lower utility of the equipment typically results because of the need to learn how to operate the abatement system and because more maintenance problems occur during the initial phase. After 1-5 years, the operating experience improves and the utilisation factor would tend to be at the high end of the range.

Source:
[d] Thiemans and Trogler, 1991.
[e] Reimer, 1999b.

TABLE 3.8
DEFAULT FACTORS FOR NITRIC ACID PRODUCTION

Production Process	**N_2O Generation Factor (kg N_2O/tonne nitric acid)**	**Special Considerations**
Canada - plants without NSCR[a]	8.5	Based on an average emissions rate for plants of European design (Collis, 1999)
- plants using NSCR	<2	The N_2O generation factor accounts for N_2O destruction by NSCR. Uncertainty = ± 10% (based on expert judgement – Collis, 1999).
USA - plants without NSCR	9.5	An estimated 80% of nitric acid (HNO_3) plants do not use NSCR systems (Choe *et al.*, 1993).
- plants using NSCR	2	The N_2O generation factor accounts for N_2O destruction by NSCR. Industry indicates a range of 1.12 to 2.5 kg N_2O/tonne HNO_3, field experts have indicated that the lower end of the range is more accurate (Choe *et al.*, 1993,, Collis, 1999). A factor of 2 was selected as a conservative default. An estimated 20% of HNO_3 plants use NSCR systems (Choe *et al.*, 1993). Uncertainty = ± 10% (based on expert judgement).
Norway - process-integrated N_2O destruction	<2	Norsk Hydro developed a state-of-the-art reactor design in which emissions of N_2O are reduced in a process-integrated manner (Norsk Hydro, 1996). There is only one installation operational of this type (Oonk, 1999).
- atmospheric pressure plant (low pressure)	4-5	(Norsk Hydro, 1996)
- medium pressure plant	6-7.5	(Norsk Hydro, 1996)
Japan	2.2-5.7	(Japan Environment Agency, 1995)
Other Countries - European designed, dual pressure, double absorption plants	8-10	
- Older (pre - 1975), plants without NSCR	10-19	Emission factors up to 19 kg N_2O/tonne nitric acid have been reported for plants not equipped with NSCR technology (Choe *et al.*, 1993, EFMA, 1995). Such a high emissions rate would most likely apply to outdated plants (Choe 1993, Cook (1999).
NO_x Abatement Technology	**N_2O Destruction Factor (%)**	**Notes**
Non-Selective Catalytic Reduction (NSCR)	80-90	Uncertainty = ± 10% (based on expert judgement). NSCR is a typical tail gas treatment in the USA and Canada with less application in other parts of the world.
Selective Catalytic Reduction (SCR)	0	SCR with ammonia does not reduce N_2O.
Extended Absorption	0	

[a] Non-Selective Catalytic Reduction (NSCR).

CHOICE OF ACTIVITY DATA

It is *good practice* to gather activity (production) data at a level of detail consistent with that of the generation and destruction data. Where plant-level emission factors are used, *good practice* is to collect plant-level production data. Typical plant-level production data is accurate to ±2% due to the economic value of having accurate information . If plant-level data are not available, nationally compiled production data may be used. However, for the nitric acid source category, these statistics may miss an average of one-half of a national total (see details in Completeness Section).

If neither plant-level nor national-level activity data are available, information on production capacity can be used. It is *good practice* to multiply the total national production capacity by a capacity utilisation factor of 80% ± 20% (i.e. range of 60-100%).

COMPLETENESS

Complete coverage for the adipic acid source category is straightforward, but nationally compiled nitric acid production statistics may miss an average of one-half of the total. Studies that compare global statistics compiled from national data on nitric acid production with industry estimates of global production suggest that the national statistics account for only 50 to 70% of the total (Bouwman *et al.*, 1995, Olivier, 1999). This is probably due to nitric acid production that is integrated as part of larger production processes, where the nitric acid never enters into commerce and is not counted in the national statistics. For example, in the manufacture of caprolactam, nitrogen oxides produced via ammonia oxidation are used directly in the process without prior conversion to nitric acid. Accounting for these sources by methods such as identifying them through national registries of NO_x emissions, another unintended by-product of nitric acid production, will improve completeness.

DEVELOPING A CONSISTENT TIME SERIES

N_2O emissions should be recalculated for all years whenever emission calculation methods are changed (e.g. if the inventory agency changes from the use of default values to actual values determined at the plant level). If plant-specific data are not available for all years in the time series, it will be necessary to consider how current plant measurements can be used to recalculate emissions for previous years. It may be possible to apply current plant-specific emission factors to production data from previous years, provided that plant operations have not changed substantially. Such a recalculation is required to ensure that any changes in emissions trends are real and not an artefact of changes in procedure. It is *good practice* to recalculate the time series according to the guidance provided in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

Uncertainties for the default values are estimates based on expert judgement. In general, adipic acid default emission factors are more certain than nitric acid default emission factors because they are derived from the stoichiometry of an intended chemical reaction (nitric acid oxidation) and N_2O-specific abatement systems. The uncertainty in the emission factor for adipic acid represents a variability in N_2O generation due to differences in the composition of the cyclohexanone and cyclohexanol feedstock (i.e. ketone and alcohol) that are used by different manufacturers. Higher ketone content results in increased N_2O generation, whereas higher alcohol content results in less N_2O generation (Reimer, 1999a). An individual plant should be able to determine the production of N_2O (based on HNO_3 consumption) within 1%. In contrast, the default values for nitric acid production are much more uncertain. First, N_2O may be generated in the gauze reactor section of nitric acid production as an unintended by-product reaction (Cook, 1999). Second, the exhaust gas may or may not be treated for NO_x control, and the NO_x abatement system may or may not reduce (or may even increase) the N_2O concentration of the treated gas. [14]

Although there is greater uncertainty associated with nitric acid values than those for adipic acid, potential N_2O emissions per metric ton produced are far greater for adipic acid production. Thus, the uncertainty associated with adipic acid production may be more significant when converted into N_2O emissions. A properly maintained and calibrated monitoring system can determine emissions using Equation 3.9 above to within ±5% at the 95% confidence level.

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[14] In some cases, processes designed to reduce NO_x emissions may result in additional N_2O generation. Increased N_2O concentrations due to NO_x abatement technology have been measured at various power plants that employ non-catalytic reduction for NO_x (Cook, 1999). From at least one nitric acid plant, it is known that NO_x control resulted in increased N_2O emissions (Burtscher, 1999).

3.2.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving.

Some examples of specific documentation and reporting relevant to this source category are provided below:

- Description of the method used;
- Number of adipic acid and nitric acid plants, respectively;
- Emission factors;
- Production data;
- Production capacity;
- Number of plants using abatement technology;
- Type of abatement technology, destruction efficiency, and utilisation;
- Any other assumptions.

BOX 3.1
OTHER POTENTIAL INDUSTRIAL N_2O SOURCES

The Reference Manual of the *IPCC Guidelines* identifies several other potential N_2O source categories of unknown magnitude, but which are believed to be small. Potential N_2O non-combustion industrial source categories include: caprolactam production, urea production, petrochemical production, propellant and foaming agents, fumes from explosives, dodecanedioic acid production (DDDA or 3DA), and fume sweep from adipic acid and nitric acid tanks. Inventory agencies that quantify such source categories should report the data in their inventory and provide documentation of their method. This information could provide a basis for subsequent revisions of the *IPCC Guidelines.*

Plant operators should supply this information to the inventory agency for compilation, and also archive the information at the site. Plant operators should also log and archive the measurement frequencies and instrumental calibration records where actual plant measurements are made.

Where there are only one or two producers in a country, as could often be the case for adipic acid production, activity data may be considered confidential. In this case, operators and the inventory agency should determine the level of aggregation at which information can be reported while still protecting confidentiality. Detailed information including instrumentation records should still be archived at the plant level.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

3.2.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of emissions estimates using different approaches

If emissions are calculated using data from individual adipic acid and nitric acid plants (bottom-up approach), inventory agencies should compare the estimate to emissions calculated using national production data (top-down approach). They should record the results and investigate any unexplained discrepancies.

Since industrial N_2O source categories are relatively small compared to other anthropogenic and natural sources, it is not feasible to compare emissions with measured trends in atmospheric N_2O concentrations.

Plant-level data

Inventory agencies should archive sufficient information to allow an independent review of the time series of emissions beginning in the base year, and to explain trends in emissions when making historical comparisons. This is particularly important in cases where recalculations are necessary, for example, when an inventory agency changes from using default values to actual values determined at the plant level.

Revision of direct emission measurements

If plant-level N_2O measurements are available, inventory agencies should confirm that internationally recognised, standard methods were used. If the measurement practices fail this criterion, then they should evaluate the use of these emissions data. In addition, they should reconsider the uncertainty estimates in light of the QA/QC results.

Inventory agencies should compare plant-based factors to the IPCC defaults to ensure that the plant-specific factors are reasonable. They should explain and document any differences between plant-specific factors and default factors, particularly any differences in plant characteristics that might lead to these differences.

3.3 PFC EMISSIONS FROM ALUMINIUM PRODUCTION

3.3.1 Methodological issues

Two PFCs, tetrafluoromethane (CF_4), and hexafluoroethane (C_2F_6) are known to be emitted from the process of primary aluminium smelting. These PFCs are formed during the phenomenon known as the anode effect (AE), when the aluminium oxide concentration in the reduction cell electrolyte is low.

CHOICE OF METHOD

The choice of a *good practice* method will depend on national circumstances. The decision tree in Figure 3.5, Decision Tree for PFC Emissions from Aluminium Production describes *good practice* in adapting the methods in the *IPCC Guidelines* to these country-specific circumstances. The decision tree should be applied separately for CF_4 and C_2F_6 emissions estimation.

The *IPCC Guidelines* describe three general methods for estimating PFC emissions from aluminium production (Vol.3, Section 2.13.6, PFCs from Aluminium Production). These three methods correspond to tiers, but are not identified as such. To be consistent with other sections of the *IPCC Guidelines* and the *good practice guidance*, the methods presented in the *IPCC Guidelines* are referred to as tiers in this section.

The most accurate method is either to monitor smelter emissions continuously (Tier 3a) or to develop a smelter-specific long term relationship between measured emissions and operating parameters and to apply this relationship using activity data (Tier 3b). The Tier 3b method requires comprehensive measurements to develop the smelter-specific relationship and on-going collection of operating parameter data (e.g. frequency and duration of anode effects and the Anode Effect Overvoltage[15]) and production data. Where a smelter-specific relationship has not been developed but information on operating parameters and production is available, default technology-specific slope and overvoltage coefficients may be used (Tier 2). Where the only information available is the annual quantity of aluminium produced, default emission factors by technology type may be used (Tier 1). The level of uncertainty in the Tier 1 method will be much greater than for estimations produced using Tier 3 or Tier 2 methods.

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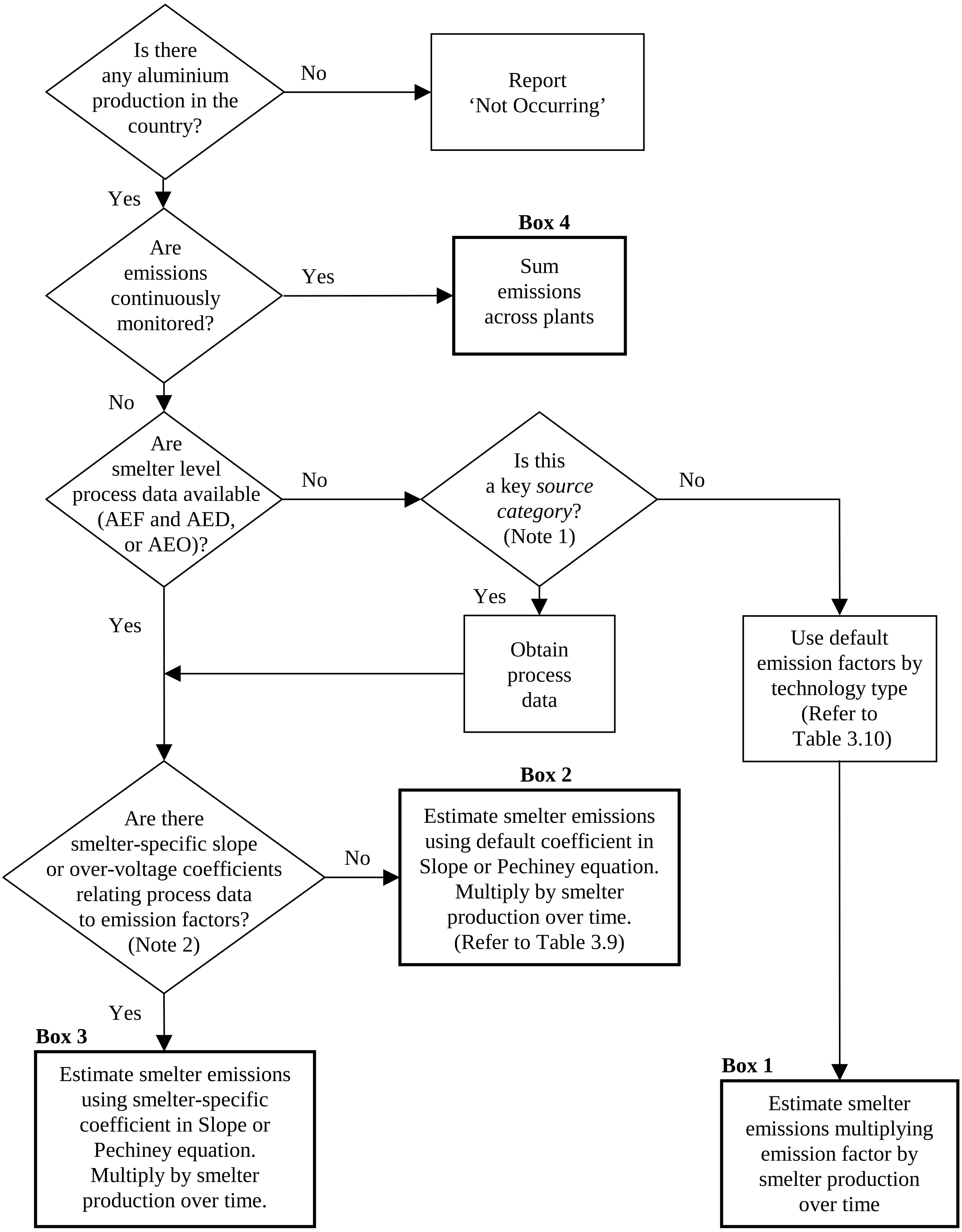
[15] The Anode Effect Overvoltage indicates the fluctuation in voltage occurring during the anode effect.

Figure 3.5 Decision Tree for PFC Emissions from Aluminium Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: In cases where a smelter has more than one distinct cell technology, a smelter must measure/use specific emission coefficients for each technology.

Tier 3a Method – Continuous emission monitoring

Continuous monitoring of emissions is possible and is the most accurate means of determining emissions. Given likely cost and other resource considerations, however, it is not regarded as necessary for *good practice*. For details on direct measurement techniques, see Box 3.2, Direct Measurement Techniques, below.

BOX 3.2
DIRECT MEASUREMENT TECHNIQUES

Sampling and measurement must be performed to a *good practice* standard to ensure the accuracy of the data, which means that:

- Measurements of PFCs at smelters should account for both emissions captured by the reduction cell hooding and extracted by the fume exhaust duct, and also fugitive emissions released into the potroom[16] atmosphere. Ideally, these data can be obtained by direct measurement of PFCs in duct and fugitive emissions. Otherwise, direct measurement of PFCs in duct emissions can be conducted along with careful measurement of the cell hooding capture efficiency, allowing fugitive emissions to be calculated.
- The analytical technology used should be capable of measuring both CF_4 and C_2F_6 gases simultaneously. Several suitable analytical technologies are available. The technology chosen must have a suitable dynamic range for the measurement of expected concentrations of duct emissions and fugitive emissions. The sensitivity of the detection should be capable of reliable measurement at the lowest levels expected in electrolysis cell exhaust ducts and for fugitive emissions where fugitive emissions account for 5% or more of total PFC emissions. The dynamic range of the measurement device should be capable of reliable measurement to the highest concentration to be measured. For duct emissions, this means a concentration measurement range of 0 to 1000 ppmv (parts per million by volume). Measurements should be normalised for temperature and pressure and these measurement conditions must be reported and recorded with the concentration measurements that will be used when calculating mass emissions.
- Duct volumetric gas flow measurements should be performed according to nationally or internationally recognised standards. Gas flow measurements should be performed during the course of the concentration measurement program at sufficient intervals to ensure accurate representation of the volumetric gas flow. Measurements should be normalised for temperature and pressure and these measurement conditions must be reported and recorded with the flow measurements that will be used when calculating mass emissions.
- Calibration of analytical instruments should be performed at regular intervals during the measurement campaign. The required schedule for calibrations will vary according to the type and known stability of the analytical instrumentation used but must be sufficient to minimise the effect of instrument calibration drift. The results of all calibrations should be reported and recorded with the concentration measurement. Measurements affected by drift should be omitted from emission estimations. Calibration gases should be traceable to recognised national or international standards. The calibration method should be thoroughly documented and recorded with the emission measurements. Chapter 8, Quality Assurance and Quality Control, provides general advice on sampling representativeness.

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[16] The potroom is the standard industry term for the large room in which the reduction cells or 'pots' are housed. The smelting cells have hooding which, depending on the smelter design, age etc., will have varying fume collection efficiency. The collected fume is transported via ducts to a fume scrubbing facility where other pollutants are removed. Fume that escapes from the hooding may either be collected in a fume manifold and also transported to the fume scrubbing facility or exhausted to atmosphere through the potroom roof. Since the potrooms may be up to a kilometre long and 20 metres or more in width, accurate measurements of fugitive emissions may not be feasible. Therefore, measurements of PFCs in collected fume and fugitive fume are required or else measurements of collected fume along with a comprehensive understanding of the fume collection efficiency is required to ensure that PFCs captured by the scrubbing system along with fugitive emissions are included in estimations.

Tier 3b Method – Smelter-specific relationship between emissions and operating parameters based on field measurements

This method uses periodic measurements to establish a smelter-specific relationship between operating parameters (i.e. frequency and duration of anode effects or Anode Effect Overvoltage) and emissions of CF_4 and C_2F_6. Once established, the relationship can be used along with process data collected on an on-going basis, to estimate emissions factors over time. These emission factors are multiplied by smelter-specific production (tonnes) to estimate smelter emissions. Emissions estimates will be aggregated across smelters to estimate national emissions.

The following estimation relationships can be used:

Slope Method: This method uses a linear least squares relationship between anode effect (AE) minutes per cellday[17] and emissions, expressed as an emission factor (EF):

EQUATION 3.10

$$\text{EF (kg } CF_4 \text{ or } C_2F_6 \text{ per tonne of Al)} = \text{Slope} \bullet \text{AE min / cellday}$$

To develop an accurate estimate of the slope, simultaneous measurements of emissions and collection of anode effect data over an appropriate period of time are required. The Slope Method is a variant of the **Tabereaux approach** described in the *IPCC Guidelines*:

BOX 3.3
TABEREAUX APPROACH

$$\text{Slope} = 1.698 \bullet (p / CE) \quad \text{and} \quad \text{AE min / cellday} = AEF \bullet AED$$

Where:

p = Average fraction of CF_4 in the cell gas during anode effects for the CF_4 slope
or
Average fraction of C_2F_6 in the cell gas during anode effects for the C_2F_6 slope

CE = Current Efficiency for the aluminium production process, expressed as a fraction rather than as a percentage

AEF = Number of anode effects per cellday

AED = Anode effect duration in minutes

Pechiney Overvoltage Method: This method uses the Anode Effect Overvoltage as the relevant process parameter. The Anode Effect Overvoltage is the extra cell voltage, above 8V, caused by anode effects, when averaged over a 24-hour period (mV/day). The correlation formula was derived from measurements of PFC generation at smelters with Pechiney technology, expressed as an emission factor (EF):

EQUATION 3.11

$$\text{EF (kg } CF_4 \text{ or } C_2F_6 \text{ per tonne of Al)} = \text{Over-Voltage Coefficient} \bullet AEO / CE$$

Where:

AEO = Anode effect over-voltage in mV/cellday

CE = Aluminium production process current efficiency expressed in percent

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[17] The 'cellday' term really means 'the number of cells operating multiplied by the number of days of operation'. At a smelter this would more usually be calculated (for a certain period of time, e.g. a month or a year) using 'the average number of cells operating across the smelter over a certain period of days multiplied by the number of days in the period'.

Tier 2 Method – smelter-specific relationship between emissions & operating parameters based on default technology-based slope and over-voltage coefficients

If measurement data are not available to determine smelter-specific Slope or Overvoltage coefficients, default coefficients may be used together with smelter-specific operating parameters. *Good practice* default coefficients are listed in Table 3.9, Default Coefficients for the Calculation of PFC Emissions from Aluminium Production (Tier 2 Methods).

Tier 1 Method – Production-based emission factors

The simplest estimation method is to multiply default emission factors by aluminium production. When the only smelter-specific activity data available are metal production statistics, it is *good practice* to use default emission factors (see Choice of Emission Factors).

Default slope coefficients (Tier 2 method) and emission factors (Tier 1 method) were developed using available data from International Primary Aluminum Institute (IPAI) surveys and other field measurement data (Bouzat e*t al.*, 1996, Leber *et al.*, 1998, Marks, 1998, Roberts *et al.*, 1994a and 1994b, Kimmerle *et al.*, 1998, Marks *et al.*, 2000). The limited information available for some data required expert judgement regarding the suitability of some measurement sets. As an example, the Tier 1 Method Horizontal Stud Søderberg (HSS) default emission factors were calculated using 1991 data, rather than 1990 data.

When possible, the consistency of available measurement data surveyed over different time periods and at different smelters should be used to confirm a significant degree of confidence about the magnitude and trend of the emission factors and coefficients.

CHOICE OF EMISSION FACTORS

Tier 3b Method

For this method, it is *good practice* to determine the coefficients of the models by using *smelter-specific measurements.* The smelter-specific coefficients should be based on comprehensive measurements of CF_4 and C_2F_6 emissions with simultaneous collection of process data. This means that emission factors should reflect the specific conditions of a plant and the technologies involved. Emission factors are to be measured over a period of time that reflects the variability of the process and accounts for both emissions captured by the fume collection system and fugitive emissions (if this sub-source category is significant, compared with emissions captured by the fume control system). Box 3.2, Direct Measurement Techniques, gives guidance on some aspects of direct measurement techniques. It is *good practice* to follow these approaches in implementing a sampling and measurement program.[18]

Tier 2 Method

If smelter-specific measurements are unavailable, default coefficients may be used. Default coefficients are provided by technology type in Table 3.9, Default Coefficients for the Calculation of PFC Emissions from Aluminium Production (Tier 2 Methods).[19] The default coefficients must be applied by technology type within each smelter. If more than one technology type is being used at a smelter, the appropriate default coefficients must be applied separately for each technology segment.

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[18] Other methods may incorporate an explicit factor representing a contribution from newly started cells. The smelter-specific slope coefficients developed under Tier 3b will incorporate these emissions.

[19] Current measurement programs are improving the quantity and quality of available data. These data should be available by early 2000, and may supersede the values provided in Table 3.9.

TABLE 3.9
DEFAULT COEFFICIENTS FOR THE CALCULATION OF PFC EMISSIONS FROM ALUMINIUM PRODUCTION
(TIER 2 METHODS)

Technology[a]	**Slope**[b,d] **[(kg $_{PFC}$/t$_{Al}$) / (AE-Minutes/cellday)]**				**Overvoltage coefficient**[b] **[(kg $_{PFC}$/t$_{Al}$) / (mV/cellday)]**	
	CF_4	**Uncertainty**	**C_2F_6**	**Uncertainty**	**CF_4**	**C_2F_6**
CWPB	0.14	±0.009	0.018	±0.004	1.9	NA
SWPB	0.29	±0.02	0.029 [c]	±0.01	1.9	NA
VSS	0.068 [g]	±0.02	0.003 [g]	±0.001	See note e	–
HSS	0.18 [f]		0.018		–	–

[a] Centre Worked Prebaked (CWPB), Side Worked Prebaked (SWPB), Vertical Stud Søderberg (VSS), Horizontal Stud Søderberg (HSS).
[b] Source: IPAI, EPA field measurements, and other company measurement data.
[c] There is inadequate data for establishing a slope coefficient for C_2F_6 emissions from SWPB cells based on measurement data; therefore a default of one-tenth of the CF_4 coefficient is *good practice*, consistent with the *IPCC Guidelines*.
[d] Embedded in each Slope coefficient is an assumed emissions collection efficiency as follows: CWPB 95%, SWPB 90%, VSS 85%, HSS 90%. These collection efficiencies have been assumed based on expert opinion. While collection efficiency for HSS cells may vary, the company measurement data used for calculation of these coefficients are consistent with a collection efficiency of at least 90%.
[e] Overvoltage coefficients are not relevant to VSS and HSS technologies.
[f] The HSS Slope coefficients are based on 1991 IPAI survey data.
[g] Further work on emission measurement and uncertainty analysis should be pursued for VSS. These default coefficients are based on a small number of data, and it is expected that the uncertainty might be higher than for other coefficients (Bjerke, 1999a, and Bjerke *et al*., 1999b).
NA = not available.

Tier 1 Method

The simplest method is to multiply default emission factors by aluminium production. Default emission factors by technology-type are available in the *IPCC Guidelines*. It is *good practice* to base these factors on recently updated measurements, and revised default emission factors and associated uncertainty ranges are presented in Table 3.10, Default Emission Factors and Uncertainty Ranges for the Calculation of PFC Emissions from Aluminium Production (by Technology Type), below. As the Tier 1 method is the most uncertain of the three approaches, it is *good practice* to use default emission factors as a method of last resort, when only metal production statistics are available.

TABLE 3.10
DEFAULT EMISSION FACTORS AND UNCERTAINTY RANGES FOR THE CALCULATION OF PFC EMISSIONS
FROM ALUMINIUM PRODUCTION (BY TECHNOLOGY TYPE)

Technology	**CF_4**		**C_2F_6**	
	kg/tonne Al[e]	**Uncertainty Range**[a]	**kg/tonne Al**[e]	**Uncertainty Range**[a]
CWPB	0.31	0.0003-1.3	0.04	0.00004-0.2
SWPB	1.7	0.8-3.8	0.17 [b]	0.08-0.4
VSS	0.61 [c]	0.4-1.1	0.061 [c]	0.04-0.1
HSS	0.6 [d]	0.0006-1.4	0.06 [d]	0.00006-0.13

[a] Uncertainty was estimated by the IPCC Washington expert meeting group to a 95% confidence interval on the basis of the variance of anode effect minute data from IPAI Survey Data for 1990 (or 1991 for HSS) for each technology type.
[b] There are inadequate data for establishing an emission factor for C_2F_6 emissions from SWPB cells based on measurement data; therefore a default of one-tenth of the CF_4 coefficient is *good practice*, consistent with the *IPCC Guidelines*.
[c] The VSS default emission factors are based on IPAI, EPA field measurements, and other 1990 company measurement data. These default factors are based on a small number of data, and it is expected that the uncertainty might be higher than for other factors (Bjerke, 1999a, and Bjerke *et al*., 1999b).
[d] The HSS default emission factors are based on 1991 IPAI survey data.
[e] Source: IPAI, EPA field measurements, and other 1990 company measurement data, except for HSS that is based on 1991 data (Bjerke, 1999a, and Bjerke *et al*., 1999b).

It is *good practice* to apply the default emission factors that are based on 1990 (or 1991 for HSS) median anode effect frequency and duration data, for all years for which there are no process (anode effect) data unless it can be demonstrated otherwise.

It is *good practice* to apply the default emission factors that are based on 1990 (or 1991 for HSS) median anode effect frequency and duration data, for all years for which there are no process (anode effect) data unless it can be demonstrated otherwise.

CHOICE OF ACTIVITY DATA

It is *good practice* to record the information requested for Tier 3b and Tier 2 methods concerning frequency and duration of anode effects and Anode Effect Overvoltage and production data at the plant level. Individual companies or industry groups should be consulted to ensure that the data are available and in a useable format for inventory estimation. For the Tier 1 method, activity data consist of production statistics that should be available from companies at the plant level. Uncertainty in production data (tonnes of aluminium) is likely to be low in most countries. Given the expected universal availability of production data, production capacity data should only be used as a check on production statistics.

COMPLETENESS

In principle, production statistics should be available for all smelters. It is *good practice* to aggregate emissions estimates from each smelter to estimate total national emissions. All members of the IPAI, who represent 60% of 1999 world capacity, report production data. If smelter-level production data are unavailable, smelter capacity data may be used along with aggregate national production to estimate smelter production. All inventory agencies should be able to implement at a minimum level the Tier 1 method and ensure completeness of reporting. There is no reason to report the terms NA (not available) and NE (not estimated) for this source category. When emissions are being measured by continuous monitoring or for the purposes of calculating emission coefficients or emission factors, complete coverage of emissions at the smelter level for this source category requires estimation of emissions of CF_4 and C_2F_6 from the exhaust duct and potroom roof or a good understanding of the collection efficiency.

DEVELOPING A CONSISTENT TIME SERIES

If all the necessary historical data (e.g. production statistics, AED and AEF or AEO) are available, emissions over the entire time period can be estimated using the appropriate *good practice* method.

Where some historical data are missing, it is *good practice* to use available plant-specific measurements to establish an acceptable relationship between emissions and activity data in the base year. Implementing any relationship retroactively requires that records of process data be available. Most smelters should have records of process data, with perhaps some regional exceptions. In addition to having historical data, each smelter must be able to demonstrate that the relationship to be retroactively implemented is applicable to its historical operating conditions (i.e. there have been no significant technological or operational changes).[20] To ensure consistency over time, if the estimation method for a smelter changes it is *good practice* to recalculate emissions estimates using both the past and current methodologies to ensure that any trends in emissions are real and not caused by the change in estimation methodologies. These recalculations should be carried out according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques, and all assumptions should be documented clearly.

UNCERTAINTY ASSESSMENT

It is possible to apply classical statistical quantitative approaches to estimate uncertainty ranges for the Tier 1, Tier 2 and Tier 3 methods. Tables 3.9, Default Coefficients for the Calculation of PFC Emissions from Aluminium Production (Tier 2 Methods), and 3.10, Default Emission Factors and Uncertainty Ranges for the Calculation of PFC Emissions from Aluminium Production (by Technology Type), provide estimates of uncertainty associated with emission factors for Tier 1 and Tier 2 methods. The method used to derive these values was a combination of classical statistics (two-sigma estimates) and expert judgement. Uncertainty for the Tier 1 method default factors is significantly higher than the Tier 3 and Tier 2 methods because smelter-specific operating conditions are not reflected in these estimates.

The uncertainty associated with AEF and AED or AEO, when measured, is expected to be low but will depend on computer scan rates (e.g. long scan rates will yield higher uncertainties) and data collection systems at each site.

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[20] If the Tier 3b method is being used, expert judgement should be used to determine when a significant change in operations or technology at a smelter will require development of a new smelter-specific slope coefficient.

3.3.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving.

Some examples of specific documentation and reporting relevant to this source category are provided below.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

To improve transparency, it is *good practice* to report emissions estimates for PFCs from aluminium production separately from other source categories. Additionally, it is *good practice* that CF_4 and C_2F_6 emissions are reported separately on a *mass basis*, as well as in CO_2-equivalent. [21]

Good practice methods require accurate anode effect frequency (AEF) and anode effect duration (AED) data for all cell types except Pechiney technology that requires instead accurate overvoltage (AEO) data. Statistical error estimates for AEF and AED or AEO should be reported.

It is *good practice* to archive at the company level the following information on the computer control system that will be included in statistical error estimates:

(i) AE trigger voltage; the voltage that defines the start of an AE;

(ii) AE termination voltage; the voltage that defines the end of an AE;

(iii) Scan rate; the frequency with which the cell voltage is measured;

(iv) Voltage averaging period; the period of time used to calculate the average voltage that is compared to the trigger and termination voltages.

The supporting information necessary to ensure transparency in reported emissions estimates is shown in Table 3.11, Good Practice Reporting Information for PFC Emissions from Aluminium Production by Tier, below.

Much of the production and process data are considered proprietary by operators, especially where there is only one smelter in a country. It is *good practice* to exercise appropriate techniques, including aggregation of data, to ensure protection of confidential data.

TABLE 3.11
GOOD PRACTICE REPORTING INFORMATION FOR PFC EMISSIONS FROM ALUMINIUM PRODUCTION BY TIER

Data	Tier 3	Tier 2	Tier 1
Annual production by smelter (by technology)	x	x	x
Anode Effect minutes per pot day (non Pechiney cells)	x	x	
Anode Effect Overvoltage (mV/cellday) (Pechiney cells)	x	x	
Emission coefficients	x	x	
Emission factor	x	x	x
GWPs	x	x	x
Supporting documentation	x	x	x

3.3.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC

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[21] According to *good practice* the GWPs used should be consistent with the *Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, Part I: UNFCCC reporting guidelines on annual inventories* (*UNFCCC Guidelines*).

Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Additional procedures specific to aluminium production are outlined below:

Comparison of emission factors

Inventory agencies should check if the estimated emission factors are within the range of default emission factors provided for the Tier 1 method. If the emission factors are outside of this range, they should assess and document the smelter-specific conditions that account for the differences. It may be necessary to repeat measurements for validation purposes.

Plant-specific data check

The following plant-specific data is required for adequate auditing of emissions estimates:

- Production data;
- Process data records;
- Calculations and estimation method;
- List of assumptions;
- Documentation of sampling, measurement method, and measurement results.

If emission measurements from individual plants are collected, inventory agencies should ensure that the measurements were made according to recognised national or international standards. QC procedures in use at the site should be directly referenced and included in the QC plan. If the measurement practices were not consistent with QC standards, the inventory agency should reconsider the use of these data.

Verification of emissions estimates

Global atmospheric measurements of CF_4 and C_2F_6 concentrations can provide an upper limit on the total global emissions of PFCs from all source categories (Harnisch *et al.*, 1998). This can be used to check emissions estimates across the international aluminium production source category and potentially to evaluate the consistency of emission factors and coefficients. While it may be feasible to cross check emissions estimates from this source category by external measurements of plumes from smelters, the procedures for doing this are impractical, given the current state of technology, and are not required under *good practice*.

3.4 SF_6 EMISSIONS FROM MAGNESIUM PRODUCTION

3.4.1 Methodological issues[22]

In the magnesium industry, SF_6 is used as a cover gas in foundries to prevent oxidation of molten magnesium. It is assumed that all SF_6 used as cover gas is emitted to the atmosphere. It is *good practice* in inventory preparation in estimating emissions of SF_6 from use in the magnesium industry to consider, in a disaggregated way if possible, all segments of the industry using SF_6. These segments include primary magnesium production, die casting, gravity casting, and reprocessing (secondary production). It is *good practice* to assess other magnesium production processes that use and emit SF_6.

CHOICE OF METHOD

The choice of a *good practice* method will depend on national circumstances. The decision tree (see Figure 3.6, Decision Tree for SF_6 Emissions from Magnesium Production) describes *good practice* in adapting the methods in the *IPCC Guidelines* (Vol. 3, Section 2.13.8, SF_6 Used in Aluminium and Magnesium Foundries) to these country-specific circumstances. The *IPCC Guidelines* describe a general equation for calculating SF_6 emissions from magnesium that is the basis for all the methods described:

EQUATION 3.12

$$\text{Emissions of } SF_6 = \text{Consumption of } SF_6 \text{ in Magnesium Smelters and Foundries}$$

The most accurate application of this equation requires collecting direct data on SF_6 consumption from all individual users of the gas in the magnesium industry because these figures reflect apparent consumption rather than emissions. Consumption is defined as the use of SF_6 as a cover gas. In the absence of direct data, it is *good practice* to obtain estimates through a top-down method using production data and emission factors relevant to the various manufacturing processes. In cases where the data on direct use are incomplete, it is *good practice* to use a hybrid method that uses direct data where available, and production-based emission factors to complete the estimate. A hybrid approach is preferable to relying solely on the top-down approach.

If no direct data are available, an alternative but a less accurate method is to estimate the share of annual national SF_6 consumption attributable to the magnesium industry. This requires collecting annual data on national SF_6 sales and assumes that all SF_6 gas sold to the magnesium industry is emitted within the year.

CHOICE OF EMISSION FACTORS

Since the direct reporting method assumes that all SF_6 consumption is emitted, there is no need to use emission factors or coefficients when SF_6 consumption data are available. When complete reported data are not available it is *good practice* to obtain emission factors for each segment of the industry consistent with the decision tree in Figure 3.6, Decision Tree for SF_6 Emissions from Magnesium Production. These emission factors should relate SF_6 emissions to magnesium production at the same disaggregated level as the available activity data (e.g. national, sub-national). National emission factors based on plant measurements are preferable to international default factors because they reflect conditions specific to the country. Such information may be accessible through industry associations, surveys or studies.

The *IPCC Guidelines* do not provide default emission factors for SF_6 from magnesium. Under recommended conditions for die-casting, the consumption rates are about 1 kg SF_6 per tonne magnesium produced or smelted (Gjestland, 1996). It is *good practice* to use this value in the absence of better information. This default value is quite uncertain, however. For example, one diecasting industry survey showed a wide range of SF_6 consumption rates, from 0.1 to 10 kg SF_6 per tonne magnesium produced (Palmer, 1999).

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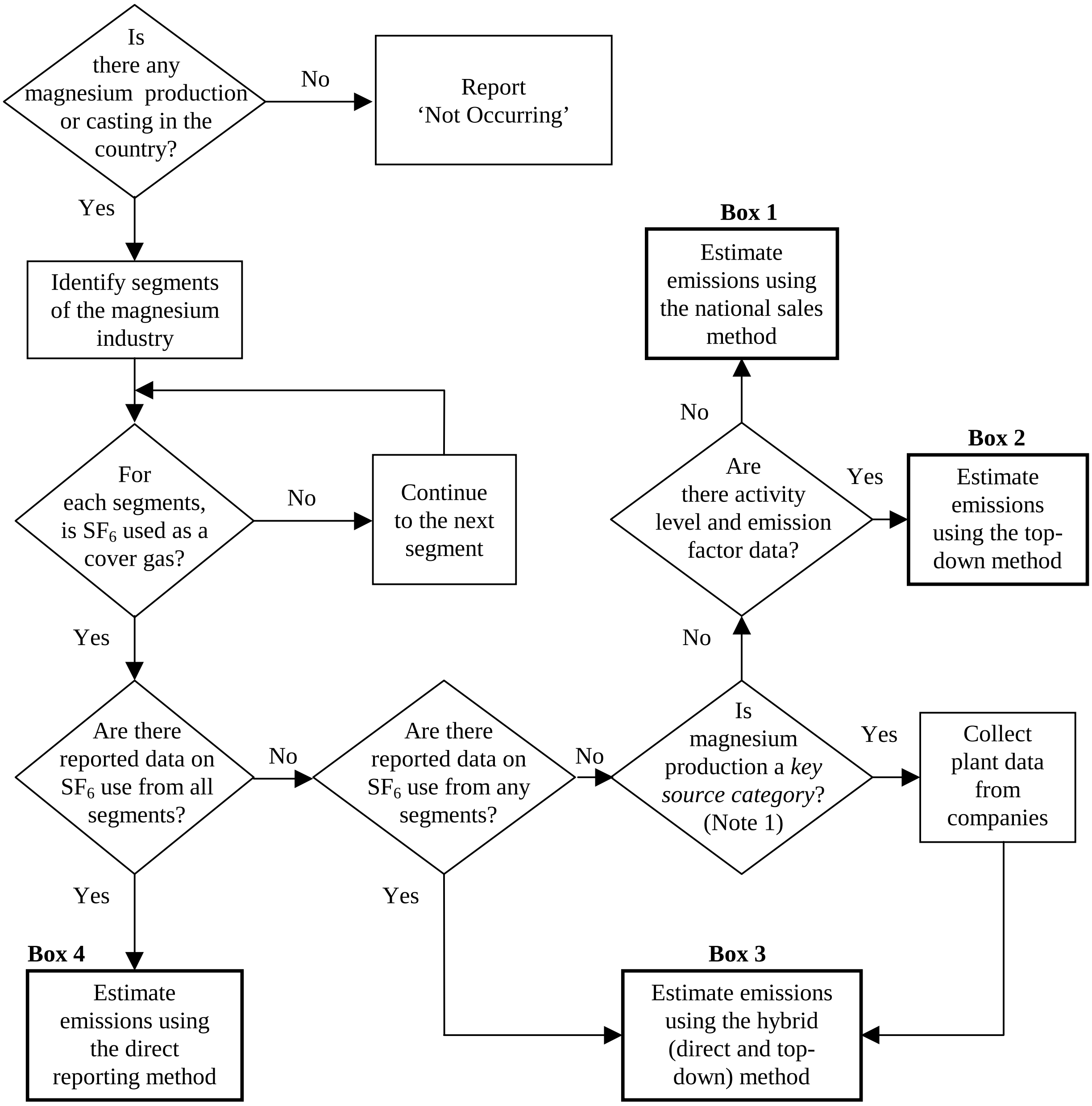
[22] SF_6 is sometimes used in the aluminium industry as a cover gas or for other purposes, and is assumed to be inert. The emissions of SF_6 are therefore assumed to be equal to consumption, and can be estimated using a consumption-based approach similar to the consumption-based method for magnesium production. The emission factors and the national sales method as discussed for magnesium production are not applicable to SF_6 used in aluminium production.

Figure 3.6 Decision Tree for SF_6 Emissions from Magnesium Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

CHOICE OF ACTIVITY DATA

With the direct-reporting method, the activity data are SF_6 consumption totals from each plant. Magnesium production data are necessary for those plants that do not report SF_6 consumption data. Where there is some direct reporting of SF_6 use, it is *good practice* to assess the share of the total segment's magnesium production that is represented by the plants that are directly reporting SF_6 data. For the other plants, it is *good practice* to use production-based estimates of emissions.

To the maximum possible extent, it is *good practice* to disaggregate production data into segments (e.g. primary production, die casting, gravity casting) using SF_6 within the magnesium industry to make full use of segment-specific emission factors. Where disaggregated data are not available, more aggregated production data, possibly combining output from several different processes, may be used to provide an estimate. In the absence of SF_6 consumption data or magnesium production data, the alternative is to collect annual national data on SF_6 sales to the magnesium industry. This data could come directly from SF_6 producers or from national statistics. It is *good practice* to consider data on consumption by other industries that use SF_6 (e.g. electrical equipment) when estimating the share consumed by the magnesium industry.

COMPLETENESS

Incomplete direct reporting or activity data should not be a significant issue for primary production. There is a small number of primary magnesium producers that are generally well known and keep good records. Completeness issues generally arise in the casting segments, where facilities are more widely distributed, and have a wide range of capacities and technologies. Some plants may supply to niche markets that are not captured by national data sets. The inventory agency should confirm the absence of estimates for these smaller industry segments rather than simply assuming they do not occur. It is also *good practice* to undertake periodic surveys of the industry and establish close links with the local industry associations to check completeness of estimates.

DEVELOPING A CONSISTENT TIME SERIES

There may be issues of data availability associated with establishing historical emissions, particularly when implementing a direct reporting approach. It is *good practice* to use historical SF_6 data where available, but SF_6 purchase records for previous years may not be archived by magnesium manufacturers.

In the absence of such data, a default approach of multiplying activity data by an assumed emission factor may be used. In some cases, emission factors may decrease over time due to environmental awareness, economic factors, and improved technologies and practices. *Good practice* is to assess the appropriate historical emission factors following the guidance in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques. In some cases, historical production data may not be available due to lack of initial records or changes in the structure of the industry in the intervening period. In this case, international production data may be used or, if this too is unavailable, a general relationship between national economic activity and magnesium production. To ensure consistency over time, it is *good practice* to recalculate emissions estimates using previously used and new methods to ensure that any trends in emissions are real and not caused by changes in the estimation methodologies. *Good practice* is to document assumptions in all cases and archive them at the inventory agency.

UNCERTAINTY ASSESSMENT

At the plant level, there is a very low uncertainty associated with plant SF_6 use data, since SF_6 use is measured easily and accurately from purchase data. (An uncertainty estimate of less than 5% is usually appropriate for directly reported data.) There is some uncertainty associated with the assumption that 100% of the SF_6 used is emitted. Anecdotal evidence suggests that, under certain extreme conditions, a minor portion of SF_6 applied may react or decompose in the process. For inventory purposes, however, until further peer-reviewed research work clarifies this effect, the assumption is that all SF_6 used as a cover gas is emitted. Uncertainties are much higher where plant data are not available and emissions could be much higher or lower than indicated by use of the IPCC defaults, as already indicated

At the national inventory level, the accuracy of magnesium production activity data is comparable to that of other national production statistics (i.e. ±5%). Additional uncertainty is introduced through estimating the share of production not reporting directly. Aggregating production from different segments and using aggregated emission factors also introduces uncertainty. For example, national data from casting operations may not be segregated into die-casting and gravity casting segments despite their potentially different SF_6 emission rates. Estimating SF_6 emissions on the basis of sales to the magnesium industry each year is highly uncertain, because SF_6 may be purchased in bulk quantities and not used until later years. The uncertainty in this case will be bounded by the total sales data.

3.4.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal

Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

To improve transparency, it is *good practice* to report emissions estimates from this source category separately by industry segment.

The following additional information can provide a reasonable degree of transparency in reporting:

Direct Reporting

- Number of plants reporting;
- Magnesium and magnesium products production;
- SF_6 emissions;
- Emission factor data (and reference).

National SF_6 sales-based estimate of potential emissions

- National SF_6 consumption (and reference);
- Assumptions for allocating SF_6 used to magnesium;
- Estimate of percentage of national SF_6 used in magnesium (and reference);
- Any other assumptions made.

In most countries, the magnesium industry will be represented by a small number of plants. In this industry, the activity level data and SF_6 emissions (that are directly related to activity levels) may be considered confidential business information and public reporting may be subject to confidentiality considerations.

3.4.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1 Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks, as outlined in Chapter 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from *this source category*. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Additional procedures specific to magnesium production are outlined below:

Comparison of emissions estimates using different approaches

If emissions were calculated using data from individual plants (bottom-up approach), inventory agencies should compare the estimate to emissions calculated using national magnesium production data or national SF_6 consumption (top-down approach). The results of the comparison should be recorded and any discrepancies should be investigated.

Review of plant-level data

The following plant-specific information should be archived to facilitate independent review:

- SF_6 consumption or magnesium production (where factors are used);
- Plant-level QA/QC results (including documentation of sampling, measurement method, and measurement results for plant level data);
- Results of QA/QC conducted by any integrating body (e.g. industry association);
- Calculations and estimation method;
- Where applicable, a list of assumptions in allocating national SF_6 usage or production to plant level.

Inventory agencies should determine if national or international measurement standards were used for SF_6 consumption or magnesium production data at the individual plants. If standard methods and QA/QC were not followed, then they should reconsider the use of these activity data.

Review of national activity data

QA/QC activities associated with the reference to magnesium production data should be evaluated and referenced. Inventory agencies should check if the trade association or agency that compiled the national production data used acceptable QA/QC procedures. If the QA/QC procedures are deemed acceptable, inventory agencies should reference the QC activity as part of the QA/QC documentation.

Assessment of emission factors

Where country-specific SF_6 factors are used, inventory agencies should review the level of QC associated with the underlying data. Although there is no IPCC default emission factor, *good practice* is that the inventory agency cross-check national level default factors against plant-level factors to determine their representativeness.

Peer review

Inventory agencies should involve magnesium industry experts in a thorough review of the inventory estimate, giving consideration to potential confidentiality issues. Historical production data may be less sensitive to public disclosure than current data and could be utilised for an external peer review of plant level emissions.

Verification of SF_6 emissions data

Inventory agencies should sum the amount of SF_6 used by different industrial sectors (e.g. magnesium, electrical equipment) and compare this value with the total usage of SF_6 in the country, obtained from import/export and production data. This provides an upper bound on the potential emissions.[23]

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[23] It may not always be the case that such aggregated consumption data will provide an upper limit on emissions. It is possible, depending on the national characteristics of the SF_6 consuming industry that in some years actual emissions of SF_6 may be greater than consumption of SF_6. For instance, consumption in die casting of magnesium may be very low, there may not be much semiconductor manufacturing, but a considerable bank of SF_6 in electrical equipment may have evolved through the years. In this case, leakage from bank combined with emissions resulting from decommissioning of equipment may lead to actual emissions that exceed consumption of SF_6 (potential emissions). See also Table 3.12, Default Emission Factors for SF_6 Emissions from Electrical Equipment – Tier 2 (fraction of SF_6/yr).

3.5 EMISSIONS OF SF_6 FROM ELECTRICAL EQUIPMENT AND OTHER SOURCES

3.5.1 Electrical equipment

3.5.1.1 Methodological issues

Sulfur hexafluoride (SF_6) is used for electrical insulation, arc quenching, and current interruption in equipment used in the transmission and distribution of electricity. Most of the SF_6 used in electrical equipment is used in gas insulated switchgear (GIS) and circuit breakers, though some SF_6 is used in high voltage gas-insulated transmission lines and other equipment. SF_6 emissions from electrical equipment are the largest global source category of SF_6 emissions.

CHOICE OF METHOD

The choice of *good practice* method will depend on national circumstances. The decision tree, Figure 3.7, Decision Tree for SF_6 from Electrical Equipment, describes *good practice* in adapting the methods in the *IPCC Guidelines* to these country-specific circumstances.

The *IPCC Guidelines* include methods for estimating both potential (Tier 1 method) and actual (Tier 2 method) emissions of SF_6 from electrical equipment. This section describes *good practice* for using the Tier 1 method and two variants of the current Tier 2 method. Three variants of a more accurate approach (termed Tier 3 method) are also described. Emissions estimates developed using the Tier 3 method will be the most accurate. Estimates developed using the Tier 1 method will be the least accurate because these figures reflect apparent consumption rather than emissions.

Tier 3 Method – Mass-balance approach

The Tier 3 method is the most accurate approach for estimating actual emissions of SF_6 from electrical equipment. It is a mass-balance approach that tracks the amount of new SF_6 introduced into the industry each year. Industry uses some of this newly purchased SF_6 to replace leaked gas that escaped to the atmosphere the previous year. The remainder of the new SF_6 is used to fill an increase in total equipment capacity, and thus does not replace leaked gas. To develop an accurate estimate, therefore, this approach distinguishes between the SF_6 used to replace emitted gas and SF_6 used to increase total equipment capacity or replace destroyed gas.[24]

The main advantages of this approach are: (i) equipment manufacturers and facilities can readily track the required information, and (ii) it does not depend on global default emissions factors that are subject to considerable uncertainty. This tier can be implemented at different levels of aggregation depending on data and resource availability. The most accurate approach is to estimate emissions from each lifecycle stage of the equipment at the facility level (Tier 3a method). Alternatively, the life cycle calculation may be bypassed and emissions can be estimated at the aggregate facility level (Tier 3b method) or at the country level (Tier 3c method). Inventory agencies are encouraged to use the most detailed approach that is practical, and to use alternative estimation methods to check the results.

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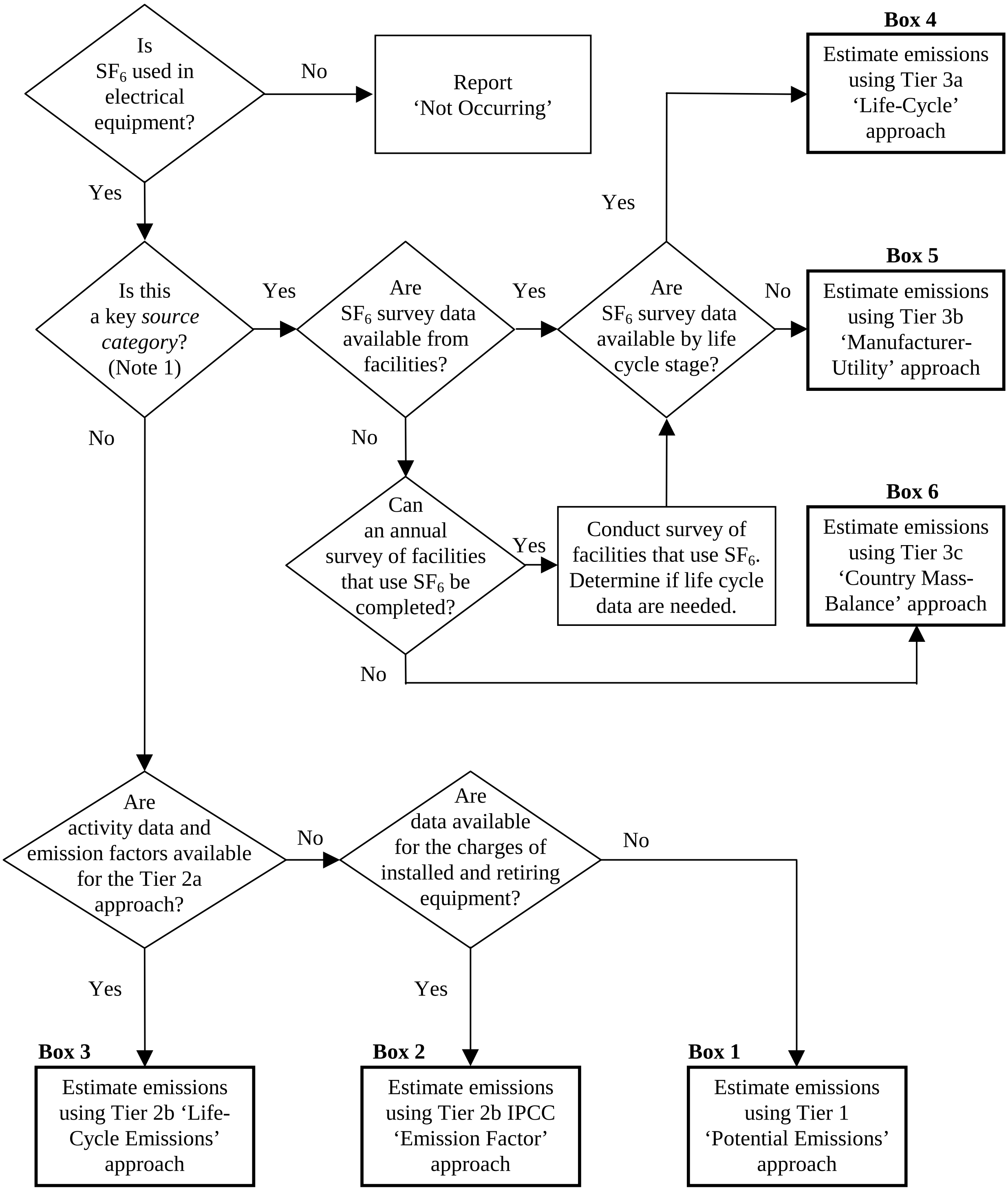
[24] For example, suppose that 100 circuit breakers are retired in a country in a certain year, and 150 new circuit breakers (with the same average charge size as the retiring breakers) are installed. In this case, the manufacturers or users of the circuit breakers in that country must purchase at least enough gas to charge 50 circuit breakers, even if they recover all of the gas from the retiring 100 circuit breakers and use it to fill 100 of the breakers that replace them. The gas used to charge the 50 ‘extra’ circuit breakers is used to fill an increase in equipment capacity, and does not replace emitted gas. Some gas that is contaminated during inspection is destroyed using thermal destruction methods.

Figure 3.7 Decision Tree for SF_6 from Electrical Equipment



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Tier 3a Method – Emissions by life cycle stage of equipment

This approach is useful for inventory agencies or facilities that, in addition to estimating their total emissions of SF_6 from electrical equipment, wish to determine how and when such emissions occur during the lifecycle of the equipment. Information on how and when emissions occur is important for focusing mitigation efforts where they will be most effective. The method includes separate equations for each phase of the lifecycle of equipment, including equipment manufacture, installation, usage, and disposal. Ideally, data are obtained for every equipment manufacturer and utility in the country, and the emissions of all manufacturers and utilities are summed to develop the national estimate. The basic equation is:

EQUATION 3.13

$$\text{Total Emissions} = \Sigma \text{ Manufacturing Emissions} + \Sigma \text{ Installation Emissions} + \Sigma \text{ Use Emissions} + \Sigma \text{ Disposal Emissions}$$

In the above equation, national emissions for each phase are equal to the sum of all equipment manufacturers' emissions for each phase.

Each *equipment manufacturer's* emissions can be calculated in three steps:

(i) Collect the data on the net decrease in their annual SF_6 inventory on hand. (Note that if the inventory increases, this will be a negative number);

(ii) Add the amount of SF_6 obtained during the year (including any SF_6 purchased from producers or distributors, any SF_6 returned from equipment users, and any SF_6 returned by users after recycling);

(iii) Subtract the amount of SF_6 transferred to others during the year (including the amount of SF_6 in new equipment delivered to customers, the amount delivered to equipment users in containers, and the amount returned to SF_6 producers, sent to recycling firms, or destroyed).

Equipment installation emissions can be estimated by subtracting the nameplate capacity[25] of all new equipment filled from the actual amount of SF_6 used to fill new equipment.

Equipment use emissions are determined by the amount of SF_6 used to service equipment. If SF_6 is being recovered from equipment before servicing and returned after servicing, it is important that this amount not be included in the estimate.

Emissions from *equipment disposal* are estimated by subtracting the amount of SF_6 recovered from retired equipment from the nameplate capacity of the retired equipment and also subtracting the amount of SF_6 destroyed.

Tier 3b Method – Manufacturer and utility-level mass-balance method

If data for estimating emissions from lifecycle stages are unavailable, emissions can be estimated by tracking overall consumption and disposal of SF_6 for all utilities and manufacturers. Beginning with the equation for Tier 3a method, installation, use, and disposal emissions are aggregated into the category of *utility emissions*. The equation presented in Tier 3a method is thus simplified to:

EQUATION 3.14

$$\text{Total Emissions} = \Sigma \text{ Manufacturer Emissions} + \Sigma \text{ Utility Emissions}$$

Using this approach, *equipment manufacturer* emissions are estimated as for the Tier 3a method.

Utility emissions are equal to the sum of emissions from all utilities. Each utility's emissions can be calculated through the following seven steps:

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[25] Nameplate capacity – The 'nameplate capacity' is the quantity of SF_6 required to fill a piece of equipment so that it will function properly. It may also be referred to as the 'charge' and is generally indicated by the nameplate of the equipment. The 'total nameplate capacity' of all the equipment in a country or facility is the sum of the proper, full charges of all the equipment in use in that country or facility.

(i) Determine the net decrease in the amount of SF_6 stored in containers over the reporting year;

(ii) Add the amount of SF_6 purchased from producers/distributors and equipment manufacturers, including the amount of SF_6 contained in purchased equipment;

(iii) Subtract the amount of SF_6 returned to suppliers;

(iv) Add SF_6 returned after recycling;

(v) Subtract any SF_6 sent to recycling firms, sold to other entities, or destroyed by the utility or installation;

(vi) Add the nameplate capacity of retired equipment;

(vii) Subtract the nameplate capacity of new equipment.

Tier 3c Method – Country-level mass-balance method

In some cases, it may be impractical for inventory agencies to obtain emissions data from all equipment manufacturers and utilities, or such data may be incomplete. In this case, a national level estimate can be developed based on annual national sales of SF_6 into the electrical sector (current and historical), equipment imports and exports, SF_6 destruction, and, if possible, country-specific equipment lifetime assumptions. The basic equation is:

EQUATION 3.15

$$\text{Emissions} = \text{Annual Sales} - (\text{Net Increase in Nameplate Capacity}) - (SF_6 \text{ Destroyed})$$

Annual sales are equal to new SF_6 for filling or refilling electrical equipment, both in bulk and in equipment itself.

Net increase in nameplate capacity can be calculated through the following steps:

(i) Collect data on the nameplate capacity of new equipment, including both equipment that is filled in the factory before shipment and equipment that is filled after installation;

(ii) Subtract the nameplate capacity of all retiring equipment.

It is *good practice* to include the quantity of SF_6 destroyed from all electrical equipment in *SF_6 destroyed.*

Tier 2a Method – Life-cycle emission factor approach

If only limited data are available on annual sales of SF_6 to equipment manufacturers and utilities, emissions can be estimated for each stage of the lifecycle of the equipment, using emission factors that are unique to each stage. *Good practice* is to use the following equation:

EQUATION 3.16

$$\text{Total Emissions} = \text{Manufacturing Emissions} + \text{Installation Emissions} + \text{Use Emissions} + \text{Disposal Emissions}$$

Manufacturing emissions are estimated by using emission factors based on the amount of SF_6 purchased by equipment manufacturers, or the nameplate capacity of new equipment charged.

Similarly, *equipment installation* emissions are estimated using either purchase-based or nameplate-based emission factors. This will require data on either the amount of SF_6 purchased by utilities for new equipment or the nameplate capacity of new equipment charged by utilities (not equipment manufacturers). In some cases, the nameplate capacity of new equipment may be known, but not the fractions of this capacity filled by manufacturers versus utilities. Under these circumstances, a single ‘Manufacturing/Installation Emission Factor’ can be multiplied by the total nameplate capacity of new equipment.

Equipment use emissions are estimated by multiplying the total nameplate capacity of installed equipment by a ‘Use Emission Factor’. The ‘use emission factor’ includes emissions due to leakage, and servicing and maintenance that are typically carried out every 12 years.

Finally, *equipment disposal* emissions are estimated by multiplying the nameplate capacity of retiring equipment by the assumed fraction of SF_6 left in equipment at the end of its life. If SF_6 is being recovered, *good practice* is to adjust the resulting estimate to reflect recovery, by multiplying by (1 – the recovery factor). The default recovery factor is zero. Other factors should be country-specific and determined at the site-level.

Tier 2b Method – IPCC default emission factors

If inventory agencies only have information on the total charges of installed and retiring equipment, the emission factors can be applied at a national level, as described in the *IPCC Guidelines***:**

EQUATION 3.17

Emissions of SF_6 in year t = (2% of the Total Charge of SF_6 Contained in the Existing Stock of Equipment of Operation in year t) + (95% of the Nameplate Capacity of SF_6 in Retiring Equipment)

The first term of the equation estimates leakage and maintenance losses as a fixed percentage of the total charge (e.g. 2%). The existing stock of equipment in each year includes all equipment installed in that year in addition to previously installed equipment that is still in use. The second term calculates emissions from retiring equipment (e.g. after a lifetime of 30 years) and assumes that the minimum charge is 90%. Recent experience indicates that the default assumption of 70% in the *IPCC Guidelines* underestimates retiring emissions, because equipment does not function below 90% capacity and will be refilled during its lifetime (Bitsch, 1999b). Thus, inventory agencies using this approach are encouraged to review the applicability of the emissions factors in the equation and use country-specific emission factors if appropriate – especially with respect to implemented recycling procedures.

Tier 1 Method – Potential approach

The simplest estimation method in the *IPCC Guidelines* estimates potential emissions of SF_6 from all uses by equating emissions to total consumption of SF_6:

EQUATION 3.18

Potential SF_6 Emission = Production + (Imports – Exports) – Destruction

Inventory agencies will need to determine how much of the total SF_6 is sold to utilities and equipment manufacturers. This can be done directly (by obtaining data on such sales) or indirectly (by obtaining data on sales for other uses). The direct approach uses the following equation:

EQUATION 3.19

SF_6 Emissions from Electrical Equipment = Sales of SF_6 to Equipment Manufacturers + Sales of SF_6 to Utilities + (SF_6 in Imported Equipment – SF_6 in Exported Equipment)

The indirect approach is as follows:

EQUATION 3.20

SF_6 Emissions = Production + (Imports – Exports) – Destruction
– Consumption by Other SF_6 Uses (i.e. Mg Smelting, Semiconductor Manufacturing, Other Uses)

Both equations implicitly assume that all SF_6 sold into the electrical sector replaces released gas, when in fact some of that SF_6 may be used to fill a net increase in the nameplate capacity of installed equipment or to replace destroyed gas. *Good practice* considers estimates developed using the Tier 1 method an upper bound.

CHOICE OF EMISSION FACTORS

As of the variability of emissions rates from region to region, inventory agencies using the Tier 2 method are encouraged to develop and use their own emissions factors. Surveying a representative sample of equipment manufacturers and utilities within the country is an effective way to develop such factors.

Tier 2a Method

Emission factors for the Tier 2a method are developed based on data collected from representative manufacturers and utilities that track emissions by life cycle stage, essentially using the Tier 3a method at their facilities for one year. Total emissions from the survey of manufacturers are summed and then divided by the surveyed facilities' new equipment capacity. This emission factor can then be applied to the manufacturing sector as a whole, using national new equipment capacity.

Tier 2b Method

For developing emission factors for the Tier 2b method, it is *good practice* for surveyed utilities to track their total consumption of SF_6 for refilling of equipment, the total nameplate capacity of their equipment, the quantity of SF_6 recovered from retiring equipment, and the nameplate capacity of their retiring equipment. It is *good practice* to sum emissions from the servicing and disposal of equipment across surveyed utilities. The resulting total emissions estimates for servicing and disposal are then divided by the surveyed utilities' total installed equipment capacity or by their total retiring equipment capacity, respectively, to calculate emission factors for use and for disposal.

The *IPCC Guidelines* do not provide default emission factors for each lifecycle stage, but suggested factors have been developed for some regions based on recent research. These factors are shown in Table 3.12, Default Emission Factors for SF_6 Emissions from Electrical Equipment – Tier 2 (fraction of SF_6/yr).

TABLE 3.12
DEFAULT EMISSION FACTORS FOR SF_6 EMISSIONS FROM ELECTRICAL EQUIPMENT – TIER 2 (FRACTION OF SF_6/YR)

Phase	**Manufacturing**		**Installation**		**Use**		**Retired Equipment**		
Region	**before 1996**	**Since 1996**	**before 1996**	**Since 1996**	**before 1996**	**Since 1996**	**Lifetime**	**Remaining**	**Recovery**
Europe[b]	0.15	0.06	NA	0.06	NA	NA	NA	NA	NA
Japan[a]	0.3	0.3	NA	NA	0.001	0.001	NA	NA	NA
Global[c]	NA	NA	0.15	0.15	0.05	0.02	30 years	0.95	NA

[a] Emission factors of use phase are only for natural emissions (Denki Kyodo Kenkyu, 1998 and Chemical Products Council, 1999).
Sources:
[b] Bitsch, 1999a.
[c] Olivier and Bakker, 2000.
NA = not available.

CHOICE OF ACTIVITY DATA

The guidance given below for the Tier 3 methods applies to the same parameters when they are used in the Tier 2 and Tier 1 methods. The only unique requirement for the Tier 2 method is the *total nameplate capacity* of equipment. Nameplate capacity may be estimated either by surveying utilities directly, or by surveying equipment manufacturers regarding their sales of equipment over the lifetime of the equipment (e.g. for the last 30 years).

Tier 3a Method – Emissions by life cycle stage

Since Tier 3a method does not rely on emissions factors, the quality of the estimate depends on the accuracy and completeness of surveyed activity data. The data should be available directly from individual manufacturers, or through manufacturer associations.

***Equipment manufacturing*: ** A complete survey of all equipment manufacturers includes, at a minimum, data on the movement of SF_6 through the production and assembly phase, and data on handling emissions of the gas after delivery to manufacturing sites. The survey should request enough information to provide a full accounting of SF_6 consumption and losses during the production phase. Annual *mass balance tables* can be used to estimate how much SF_6 gas is lost due to emission releases and what fraction this is of nominal SF_6 content of total electrical equipment produced.

If survey data are not available for all manufacturers, alternative methods can be considered (e.g. based on extrapolation of production capacity). *Good practice* is to use survey data as far as possible and only supplement them with extrapolative approaches where survey data is not available. For guidance on extrapolating when data are not available, see Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

***Equipment installation*:** All utilities and other users of electrical equipment should track and record the nameplate capacity of the equipment that is filled. Utilities should also track the amount of SF_6 that is used to fill equipment by weighing cylinders before and after filling operations, and tracking any SF_6 that is already in the shipped equipment (e.g. to maintain a slight positive pressure during shipment). If filling is performed by the equipment manufacturer rather than by the utility, then the manufacturer may provide this information to the utility.[26] Where there are gaps and omissions in the survey, it is possible to use estimates of SF_6 stock additions and default emission rates for installation and set-up procedures.

***Equipment use*:** It is *good practice* to calculate the quantity of SF_6 used to refill equipment by weighing cylinders before and after filling operations.

***Equipment disposal*:** The quantity of SF_6 recovered from equipment may be calculated by weighing recovery cylinders before and after recovery operations. Data on disposal should include all equipment, including imported equipment.

Tier 3b Method – Manufacturer and utility-level mass-balance method

***Equipment manufacturers*:** Same as for Tier 3a, above.

***Utilities*:** To collect the information necessary to use the Tier 3b method, a survey of all utilities is required. *Good practice* is to survey industrial sites, military installations, and other non-utility sites that use significant amounts of SF_6 in electrical equipment. Some, but not all, of the above information may also be obtained from equipment manufacturers.

If the utility does not perform all of its own installation, maintenance, and disposal of equipment, persons who provide these services should provide data to the utility (e.g. the quantity of gas used to refill equipment, if this gas did not come from the utility's own inventory). A full accounting of SF_6 emissions associated with handling and filling losses needs to be collected. This accounting can be based on annual mass balance tables that include the amount of SF_6 already contained in the equipment when shipped to the site. The party responsible for tracking SF_6 handling and filling operations needs to be identified, since this can vary from site to site.

Tier 3c Method – Country-level mass-balance method

***Annual sales*:** Chemical manufacturers or importers or both should be able to supply the most complete data. If information from chemical manufacturers is not available, it is *good practice* to contact both equipment manufacturers and utilities to ensure complete data on SF_6 used to fill both new and existing equipment.

***Nameplate capacity of new and retiring equipment*:** Nameplate capacity can be estimated using one of the following data sources: (1) information from equipment manufacturers/importers on the total nameplate capacity of the equipment they manufacture or import and export, (2) information from utilities on the total nameplate capacity of the equipment they purchase and install each year, or (3) information from chemical manufacturers/importers on their sales of SF_6 to equipment manufacturers. The first two data sources are preferable to the third, because gas sales to new equipment manufacturers will differ to some extent from the nameplate capacity of new equipment. In estimating the nameplate capacities of new and retiring equipment, inventory agencies should include the nameplate capacity of imported equipment and exclude the nameplate capacity of exported equipment. (See Section 3.7.4, Stationary Refrigeration Sub-source Category, Box 3.4, Accounting for Imports and Exports of Refrigerant and Equipment, for a full discussion of how to treat imports and exports in estimating these quantities.)

In the case of retiring equipment, capacity or sales information should be historical, starting in the year when the current year's retiring equipment was built. The default value for the lifetime of electrical equipment is 30 years. If information on the total nameplate capacity of retiring equipment is not available, it can be estimated from new nameplate capacity, using the estimated annual growth rate of equipment capacity. In estimating the growth rate,

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[26] The quantity already in shipped equipment may be calculated by multiplying the internal volume of the equipment by the density of SF_6 at the shipment pressure, or by multiplying the nameplate capacity of the equipment by the ratio of the shipping pressure to the nameplate pressure, in absolute terms (e.g. Pa or psi). In theory, equipment that arrives at the utility already completely filled does not need to be included in this calculation, because the quantity of SF_6 inside the equipment will be identical to the nameplate capacity, and the two will simply cancel. However, utilities are encouraged to track the total nameplate capacity of the equipment they install, because this quantity is useful for calculating emissions using the Tier 3 and Tier 2 methods and for understanding emissions during equipment use.

it is *good practice* to consider both the number of pieces of equipment sold each year and the average nameplate capacity of the equipment.[27]

The following equation can be used to estimate retiring nameplate capacity, if this information is not available directly:

EQUATION 3.21

$$\text{Retiring Nameplate Capacity} = \text{New Nameplate Capacity} \;/\; (1 + g)^{L}$$

Where:

L = equipment lifetime

g = rate of growth

According to a 1997 survey, the average annual growth rate of SF_6 sales to equipment manufacturers between 1991 and 1996 was 6.7%, while the average rate of growth between 1986 and 1996 was 5.3% (Science and Policy Associates, 1997). In the absence of country-specific information, it is *good practice* to use a default factor of 6%.

Quantity destroyed**:** The amount of SF_6 destroyed can be estimated using information from electrical equipment manufacturers, utilities, chemical manufacturers, or destruction facilities. It is necessary to ensure that the quantities of SF_6 reported as destroyed do not include quantities from sources other than electrical equipment.

COMPLETENESS

Completeness for this source category requires accounting for emissions both at utility facilities and during the manufacture of electrical equipment. Where Tier 3 methods are used, completeness requires that all SF_6 users (manufacturers and utilities) be identified.

In the manufacturing sector, this requires assessing emissions from:

- GIS and circuit breaker manufacturers;
- Manufacturers of high voltage gas-insulated transmission lines, substations (mini-stations) and transformers;
- Minor SF_6 users, including medium voltage equipment manufacturers and equipment remake manufacturers;
- SF_6 moving from producers and distributors to manufacturing facilities.

In the utility sector, this requires accounting for all SF_6 losses associated with:

- New electrical equipment installations;
- Leakage, refill and maintenance;
- Disposal of discarded electrical equipment.

It is *good practice* to identify and include industrial, military and small-utility applications if these are believed to contribute substantially to total emissions from this source category.

DEVELOPING A CONSISTENT TIME SERIES

When estimating emissions over a time series, it is necessary to consider SF_6 emissions associated with manufacturing and all installed equipment at utilities for the years of interest. Developing an accurate historical estimate for installed equipment thus requires information on the capacity and performance of equipment installed for 20 to 30 years preceding the years of interest.

On the manufacturing side, if historical data for developing base year emissions for 1990/1995 are not available, the top-down method calibrated to more accurate account balances for current years may be applied. Since SF_6 handling practices of equipment manufacturers may have changed substantially since 1995 (e.g. more gas is recovered), it is *not good practice* to apply current loss rates to historical estimates. Aggregate loss rates determined from global and regional sales and emission analyses may assist in providing an unbiased estimate for earlier years. It is *good practice* to recalculate emissions according to the guidance provided in Chapter 7,

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[27] While the number of pieces of equipment sold each year has generally grown, the average nameplate capacity has generally declined.

Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques, with all assumptions clearly documented.

In the utility sector, if historical data for the period 1970-1995 are unavailable, *good practice* is to develop estimates using the top-down method, and then calibrate as discussed above. Average leakage rates for new equipment, and the frequency of refill and routine maintenance all decreased from 1970 to 1995.[28] It is *good practice* not to apply current (post-1995) overall loss rates to historical years. Aggregate loss rates can be used in this case as well.

UNCERTAINTY ASSESMENT

When using Tier 3 methods, the resulting emissions estimates are likely to be more accurate than Tier 2 or Tier 1 methods, of the order of ±10%. If surveys are incomplete or only top-down consumption data are available, the associated uncertainty will be greater. Particular sources of uncertainty in the Tier 3 methods estimates may include:

- SF_6 exported by equipment manufacturers (either in equipment or separately in containers);
- SF_6 imported by foreign equipment manufacturers (either in equipment or in containers);
- SF_6 returned to foreign recycling facilities;
- Time lag between emissions and servicing;[29]
- Lifetime of the equipment.

The uncertainties in the default emission factors recommended for the Tier 2 method are shown in Table 3.13, Uncertainties for Default Emission Factors for SF_6 Emissions from Electrical Equipment. As the Tier 1 method estimates potential rather than actual emissions, Tier 1 estimates will have an uncertainty of the order of 100% or more in representing an estimate of actual emissions.

TABLE 3.13
UNCERTAINTIES FOR DEFAULT EMISSION FACTORS FOR SF_6 EMISSIONS FROM ELECTRICAL EQUIPMENT

Phase	**Manufacturing**		**Installation**		**Use**		**Retired Equipment**		
Region	**<1996**	**1996-**	**<1996**	**1996-**	**<1996**	**1996-**	**Lifetime**	**Remaining**	**Recovery**
Europe	±30%	±30%	NA	±30%	NA	NA	NA	NA	NA
Japan	±30%	±30%	NA	NA	NA	NA	NA	NA	NA
Global	Larger	Larger	±30%	±30%	±40%	±50%	±30%	±5%	NA

NA= not available.

Source: Olivier and Bakker (2000).

3.5.1.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

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[28] Standards for leakage from GIS are now 1%, but were as much as 3% prior to 1980. In addition, maintenance intervals have increased, from 3-5 years to 8 years for circuit breakers and about 12 years for GIS.

[29] The sales-based method is designed to yield a good estimate of the quantity of chemicals used to replace emitted chemicals in a given year. However, because some equipment may leak but nevertheless continue to run with less than a full charge, emitted chemicals are not always replaced during the year that it leaks. Thus, under some circumstances, the sales-based method may slightly either over or underestimate actual emissions. (The net effect of the time lag is to make emissions appear to occur later in the life of equipment than they actually do.) The frequency of servicing and the growth rate of the equipment stock should be investigated to ascertain the size of any error.

Some examples of specific documentation and reporting relevant to this source category ensuring transparency in reported emissions estimates are provided in Table 3.14, Good Practice Reporting Information for SF_6 Emissions from Electrical Equipment by Tier.

Confidentiality issues may arise where there are limited numbers of manufacturers or utilities. In these cases, aggregated reporting for the total electrical equipment sector, or even total national SF_6 applications, may be necessary. If survey responses cannot be released as public information, third party review of survey data may be necessary to support data verification efforts.

TABLE 3.14
GOOD PRACTICE REPORTING INFORMATION FOR SF_6 EMISSIONS FROM ELECTRICAL EQUIPMENT BY TIER

Data	Tier 3a	Tier 3b	Tier 3c	Tier 2a	Tier 2b	Tier 1
Annual sales of SF_6 to equipment manufacturers and utilities			X			X
Nameplate capacity of new equipment	X	X	X	X		
Nameplate capacity of existing equipment				X	X	
Nameplate capacity of retiring equipment	X	X	X	X	X	
SF_6 destroyed	X	X	X			X
SF_6 in inventory at beginning of year	X	X				
SF_6 in inventory at end of year	X	X				
SF_6 purchased by facility	X	X				
SF_6 sold or returned by facility	X	X				
SF_6 sent off-site for recycling	X	X				
SF_6 returned to site after recycling	X	X				
SF_6 used to fill new equipment	X					
SF_6 used to service equipment	X					
SF_6 recovered from retiring equipment	X					
Emission/recovery factors				X	X	
Documentation for factors, if country-specific				X	X	
Production of SF_6						X
Consumption of SF_6 by other uses						X
Imports of SF_6						X
Exports of SF_6						X

3.5.1.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Additional procedures specific to electrical equipment are outlined below:

Comparison of emissions estimates using different approaches

Inventory agencies should sum the facility-level data used as part of a bottom-up method and cross-check the data against national level emissions calculated using the IPCC defaults (Tier 2b method) or potential emissions estimated using national apparent consumption data (Tier 1 method). The Tier 1 method can set an upper bound on the emissions that could be expected from the sum of the individual plants if the annual use of SF_6 containing equipment in these sources is increasing or stable. Tier 1 will underestimate the annual emissions if the trend of filling of new equipment is decreasing.

Review of facility-level activity data

In all instances where site-specific activity data are obtained through surveys, inventory agencies should compare the activity data between sites (adjusting for relative size or capacity) to identify significant outliers. They should investigate any outliers to determine if the differences can be explained or if there is an error in the reported activity.

Inventory agencies should compare national SF_6 production, adjusted for imports and exports, to the aggregated national SF_6 activity data for this source. This total national usage can be considered an upper bound on SF_6 emissions.

Verification of emissions estimates

For large countries, it may be possible to conduct an independent cross-check of national total SF_6 emissions estimates with top-down estimates derived from local atmospheric concentration measurements, provided that the inverse model calculation of emissions can be done with reasonable precision.

Inventory agencies should compare effective emission factors (loss rates) with values reported by other countries in the region, or with defaults published in the scientific literature that are calibrated to global total atmospheric concentrations. Transparent reporting, as outlined above, is essential for making international comparisons.

3.5.2 Other sources of SF_6

The *IPCC Guidelines* (Vol. 3, Section 2.17.4.7, Estimation of Emissions of HFCs and PFCs from Other Applications) describe other uses of SF_6 that lead to emissions. This source category excludes the following source categories that are reported elsewhere:

- Production and use in electrical equipment;
- Magnesium and aluminium production;
- Semiconductor manufacturing;
- Substituting in applications of Ozone Depleting Substances such as CFCs and halons (e.g. aerosol, fire extinguishing).

Identified remaining applications in this source category include:

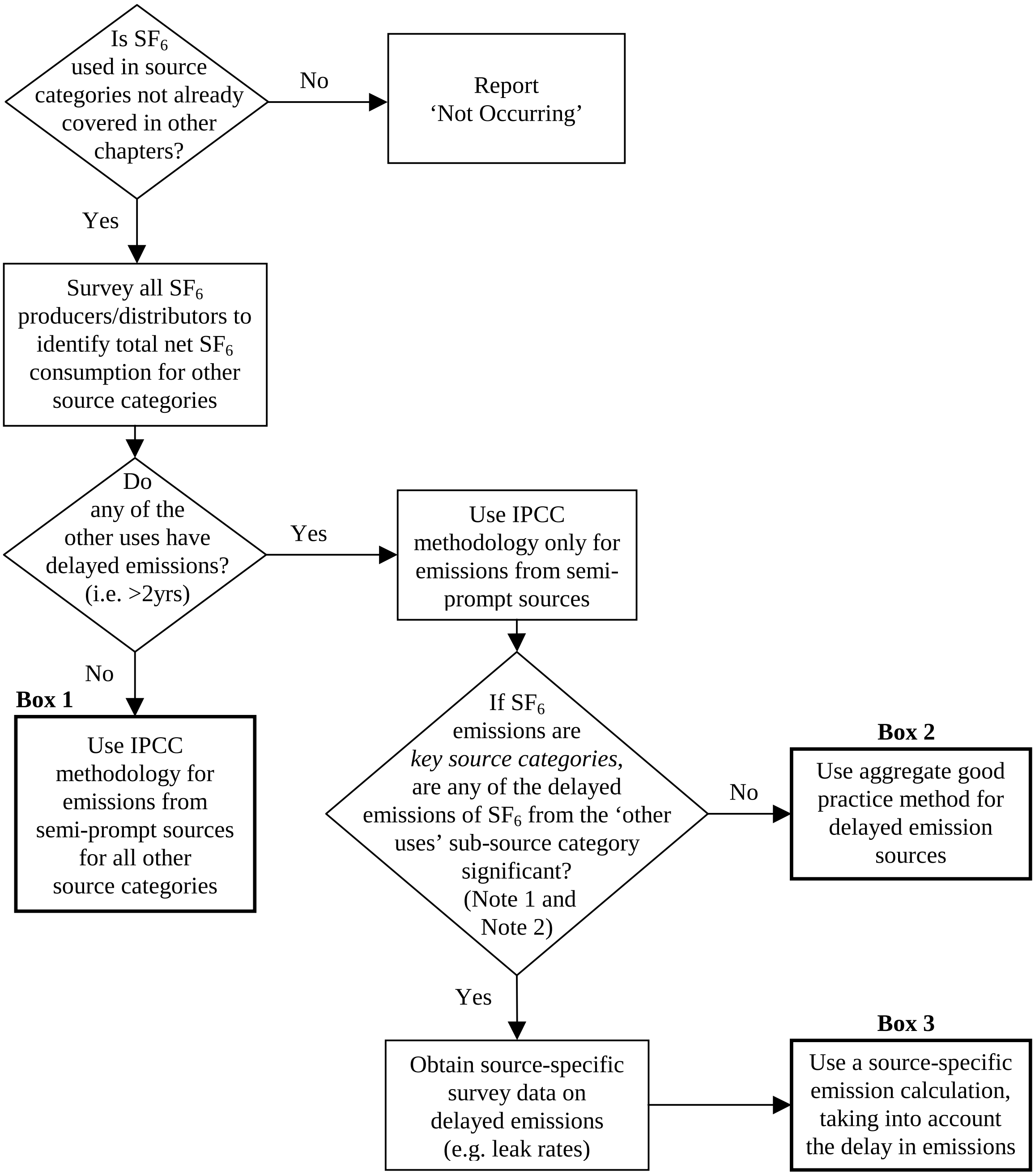
- Gas-air tracer in research and leak detectors;
- Medical purposes;
- Equipment used in accelerators, lasers and night vision goggles;
- Military applications;
- Sound-proof windows;
- Applications utilising its adiabatic property, e.g. car tires and sport attributes like tennis balls or shoe soles (i.e. using its low permeability through rubber).

3.5.2.1 Methodological issues

CHOICE OF METHOD

The *good practice* method is to use top-down import, export and consumption data from national SF_6 producers and distributors, disaggregated by major type of SF_6 application (see Figure 3.8, Decision Tree for Other Uses of SF_6). Acquiring this data will entail a survey of all SF_6 producers and distributors to identify total net SF_6 consumption. Once the data are obtained, the amount of SF_6 consumed by application in this source category should be estimated.

Figure 3.8 Decision Tree for Other Uses of SF_6



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: As a rule of thumb, a sub-source category would be significant if it accounts for 25-30% of emissions from the source category.

In many of the miscellaneous applications identified above, SF_6 is emitted within two years of consumption (e.g. tracers and in medical applications). *Good practice* in calculating SF_6 emissions from these 'semi-prompt' emissive applications is to use the following formula, as outlined in the *IPCC Guidelines*:

EQUATION 3.22

$$\text{Emissions in year t} = (0.5 \bullet \text{Amount Sold in year t}) + (0.5 \bullet \text{Amount Sold in year t} - 1)$$

This equation is similar to the equation for halocarbon emissions where an average delay of one year is assumed.

If, as a result of an initial survey, applications with distinctive delayed emissions appear significant, then *good practice* is to use a source category-specific emission calculation, taking into account the delay in emissions. For two delayed emission applications the following formulas can be used (based on experience in Germany):

- *Adiabatic property applications*: For car tires, a delay in emissions of 3 years is assumed (Schwarz *et al.*, 1996). For other applications such as shoes and tennis balls, the same delay time may be used:

EQUATION 3.23

$$\text{Emissions in year t} = \text{Sales in year t} - 3$$

- *Double-glazed soundproof windows*: Approximately 33% of the total amount of SF_6 purchased is released during assembly (i.e. filling of the double glass window). Of the remaining stock contained inside the window, an annual leakage rate of 1% is assumed (including glass breakage). Thus, about 78% of initial stock is left at the end of its 25-year lifetime. The application of SF_6 in windows began in 1975, so disposal is only beginning to occur. Emissions from this source sub-category should be calculated using Equations 3.24 to 3.26:

EQUATION 3.24

$$\text{Assembly Emissions} = 0.33 \bullet \text{Window Capacity}$$

EQUATION 3.25

$$\text{Leakage Emissions in year t} = 0.01 \bullet \text{Existing Stock in the Window}$$

EQUATION 3.26

$$\text{Disposal Emissions} = \text{Amount Left in Window at End of Lifetime} \bullet (1 - \text{Recovery Factor})$$

Unless country-specific data are available, a default recovery factor value of zero should be assumed in Equation 3.26. Use in military applications and for particle accelerators could also lead to delayed emissions. If no specific information is available for these sub-source categories, *good practice* is to treat them as semi-prompt emissions.

CHOICE OF EMISSION FACTORS

The emission factors required for these estimates can be found in the *IPCC Guidelines*. If inventory agencies use regional or country-specific data, it is *good practice* to clearly document them.

CHOICE OF ACTIVITY DATA

The activity data for these sub-source categories should be consistent with the data used in the calculation of SF_6 emissions from other source categories (e.g. electrical equipment) to ensure that the estimate is complete and there is no double counting.

COMPLETENESS

Data per application on import, export and consumption from national SF_6 producers and distributors will suffice, provided that (i) all SF_6 producers and distributors are identified, (ii) domestic consumers only purchase SF_6 from national suppliers, and (iii) imports and exports in products (e.g. sport attributes) are negligible. It is *good practice* to check regularly for additional distributors to ensure that no SF_6 is imported directly (in bulk) by end-users and that identified products containing SF_6 are not imported in sizeable amounts.

DEVELOPING A CONSISTENT TIME SERIES

For base year estimates, data may be needed for a few years prior to the base year; one year for semi-prompt emissions and more years for delayed emission applications. It is *good practice* to calculate emissions of SF_6 using the same method for every year in the time series. Where data are unavailable to support a more rigorous method for all years in the time series, it is *good practice* to recalculate according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7 3.2.2, Alternative Recalculation Techniques.

UNCERTAINTY ASSESSMENT

If the survey of domestic sales per application by national SF_6 producers and distributors is complete, then the accuracy of annual apparent consumption data will be high. The uncertainty in emissions estimates will be similarly small when the uses are all semi-prompt emissions. In case of delayed emission applications the uncertainties are:

- Default delay times in adiabatic property applications: 3±1 year;
- Defaults for soundproof windows: 50±10% filling emissions and 1±0.5% leakage/breach emissions.

3.5.2.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

For transparency, it is *good practice* to report both actual and potential emissions from the source category ‘other uses’ separately from other SF_6 emissions. In addition, providing information on the specific applications that are included in this source category is useful for comparing (estimates of) national practices with other countries, regionally, or globally. In addition, the methods applied and references should be documented. For delayed emission sub-source categories, annual emissions, delay times and emission factors per type of sub-source category should be reported.

3.5.2.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Additional procedures specific to other sources of SF_6 are outlined below:

Comparison of emissions estimates using different approaches

Inventory agencies should compare total national potential SF_6 emissions (minus the amount allocated to the electrical equipment use category, the semiconductor manufacturing use category, the metal production category and the SF_6 production category) to the estimated SF_6 emissions from other uses. The potential national emissions can be used as an upper bound on emissions.

Activity data check

Inventory agencies should compare the activity data submitted by different producers and distributors, and, adjusting for relative size or capacity of the companies, to identify significant outliers. Any outliers should be investigated to determine if the differences can be explained or if there is an error in the reported activity.

Comparison of emissions with other countries

Inventory agencies should compare the emissions from other SF_6 end-uses included in the national inventory with information submitted by other similar countries. For each source, emissions per capita or per unit of GDP with other countries should be compared. If national figures appear to be relatively very high or very small, a justification should be provided.

3.5.3 Production of SF_6

3.5.3.1 Methodological issues

The *IPCC Guidelines* do not provide a default emission factor for inadvertent losses during production and handling of SF_6. Although these emissions are likely to be small, emissions may be significant in some countries. For example, experience in Japan indicates an emission factor of 8% of the gas produced, including handling losses during disposal of residual gas in returned cylinders (Suizu, 1999). This is because there is a large demand for highly purified SF_6 gas, and impure gas may be released.

CHOICE OF METHOD

It is *good practice* to choose the method according to the decision tree in Figure 3.9, Decision Tree for SF_6 Production. The number of major SF_6 producers is quite small: globally about 6 companies produce SF_6 with about 10 production facilities world-wide (Preisegger, 1999). The number of smaller producers may grow in the near future, particularly in the Economies in Transition and in China. However, a survey of national producers should not be difficult to compile. These producers should provide an estimate of their total emissions.

Emissions of SF_6 may occur during production as well as handling of new gas at the site. Based on German experience, a default emission factor of 0.2% of the total quantity of SF_6 produced is suggested for those countries in which the predominant end use does not require highly purified SF_6 gas (e.g. electrical equipment, insulated windows) (Preisegger, 1999). As discussed above, in countries where the major uses require highly purified SF_6 gas (e.g. semiconductor manufacturing), the default value should be 8%. If national data are available, these should be used.

Recycling of used gas may be done by the producers of new gas or by other recycling firms. Emissions may occur during handling and purification of old gas and handling of recycled gas. Specific emission factors are not available. Thus, *good practice* is to use the default factor for new production (0.2%).

UNCERTAINTY ASSESSMENT

Production emissions can be negligible (e.g. when scrubbers capture the SF_6 gas released). The estimated uncertainty range for the default emission factor is therefore 0.2±0.2 (%). Relative uncertainty of the default 8% emission factor is of the same order.

COMPLETENESS

For some inventory agencies, identifying smaller producers and, in particular, recycling firms may be a difficult task. However, initial estimates based on the national mass balance of SF_6 should identify if such entities provide a sizeable contribution to total national emissions.

3.5.3.2 Reporting and documentation

Confidentiality issues may arise where there are limited numbers of manufacturers. In these cases more aggregate reporting of total national SF_6 applications may be necessary. If survey responses cannot be released as public information, third-party review of survey data may be necessary to support data verification efforts.

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

3.5.3.3 Inventory quality assurance/quality control (QA/QC)

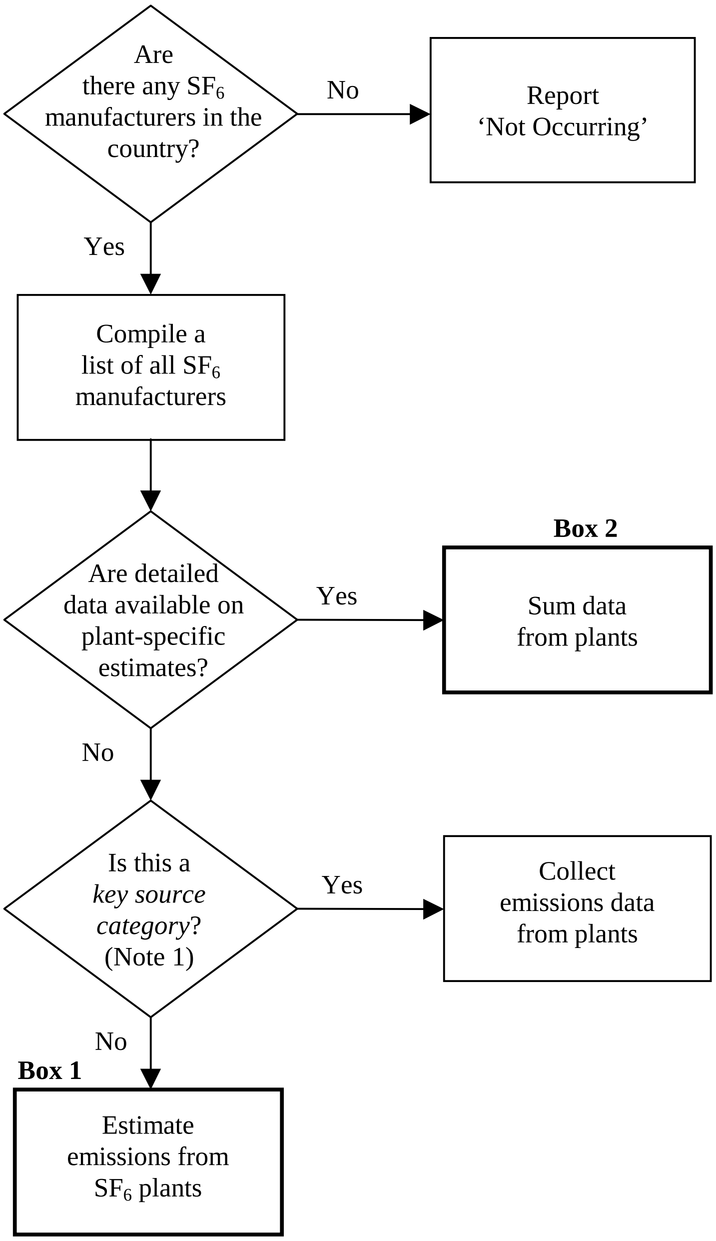
It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category.

Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Comparison of emissions estimates using different approaches

Inventory agencies should compare the estimate based on aggregated producer-level data to an estimate based on national production data and the suggested default emission factor of 0.2%. They should investigate significant discrepancies in cooperation with the producers to determine if there are unexplained differences.

Figure 3.9 Decision Tree for SF_6 Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

3.6 PFC, HFC, SF_6 EMISSIONS FROM SEMICONDUCTOR MANUFACTURING

3.6.1 Methodological issues

The semiconductor industry currently emits fluorocarbons (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6) from its manufacturing process.[30] These gases, collectively referred to as fluorinated compounds (FCs), are used in two important steps of semiconductor manufacturing: (i) plasma etching thin films and (ii) cleaning chemical vapour deposition (CVD) tool chambers. In addition, a fraction of the fluorocarbons used in the production process are converted into CF_4.

CHOICE OF METHOD

Emissions vary according to the gases used in manufacturing different types of semiconductors, the process (or more roughly, process type (CVD or etch)) used, the brand of process tool used, and the implementation of atmospheric emission reduction technology.

The *IPCC Guidelines* do not provide specific guidance on how to estimate greenhouse gas emissions from semiconductor manufacturing. However, using the basic methodological principles outlined in the *IPCC Guidelines* for other source categories, four alternative methods for estimating FC emissions are described below. The use of the 'Tier' terminology in this section corresponds to increasing data requirements and sophistication of the emission estimation process. The choice of methods will depend on data availability and is outlined in the decision tree, see Figure 3.10, Decision Tree for FC Emissions from Semiconductor Manufacturing.

Continuous emissions monitoring is currently viewed as neither a technically nor economically viable means to estimate emissions from this industry. Thus, all four methods are based on gas sales/purchases data and a series of parameters that affect emissions. The most rigorous method, Tier 2a method, requires company-specific values for the parameters rather than defaults. The Tier 2b method uses company-specific data on the share of gas used in *etching* versus *cleaning* and the share of gas used in processes with emission control technology, but relies on default values for some or all of the other parameters. The Tier 2c method uses company-specific data on the share of gas used in processes with emission control technology, but does not distinguish between etching and cleaning, and uses default values for the other parameters. The Tier 1 method uses default values for all parameters and does not account for the use of emission control technology.

Tier 2a Method – Process-specific parameters

This method is appropriate where company-specific or plant-specific values are available for the following parameters: the amount of gas fed into each process or tool (or into small subsets of processes or tools), the fraction of purchased gas remaining in the shipping container after use (heel), the fraction of the gas 'used' (destroyed or transformed) in the semiconductor manufacturing process, the fraction of the gas converted to CF_4 during semiconductor manufacture, the fraction of the gas fed into processes with emission control technologies, and the fraction of the gas destroyed by those emission control technologies. For purposes of transparency and comparability, the values used for these emission parameters should be well documented (see Choice of Emission Factors).

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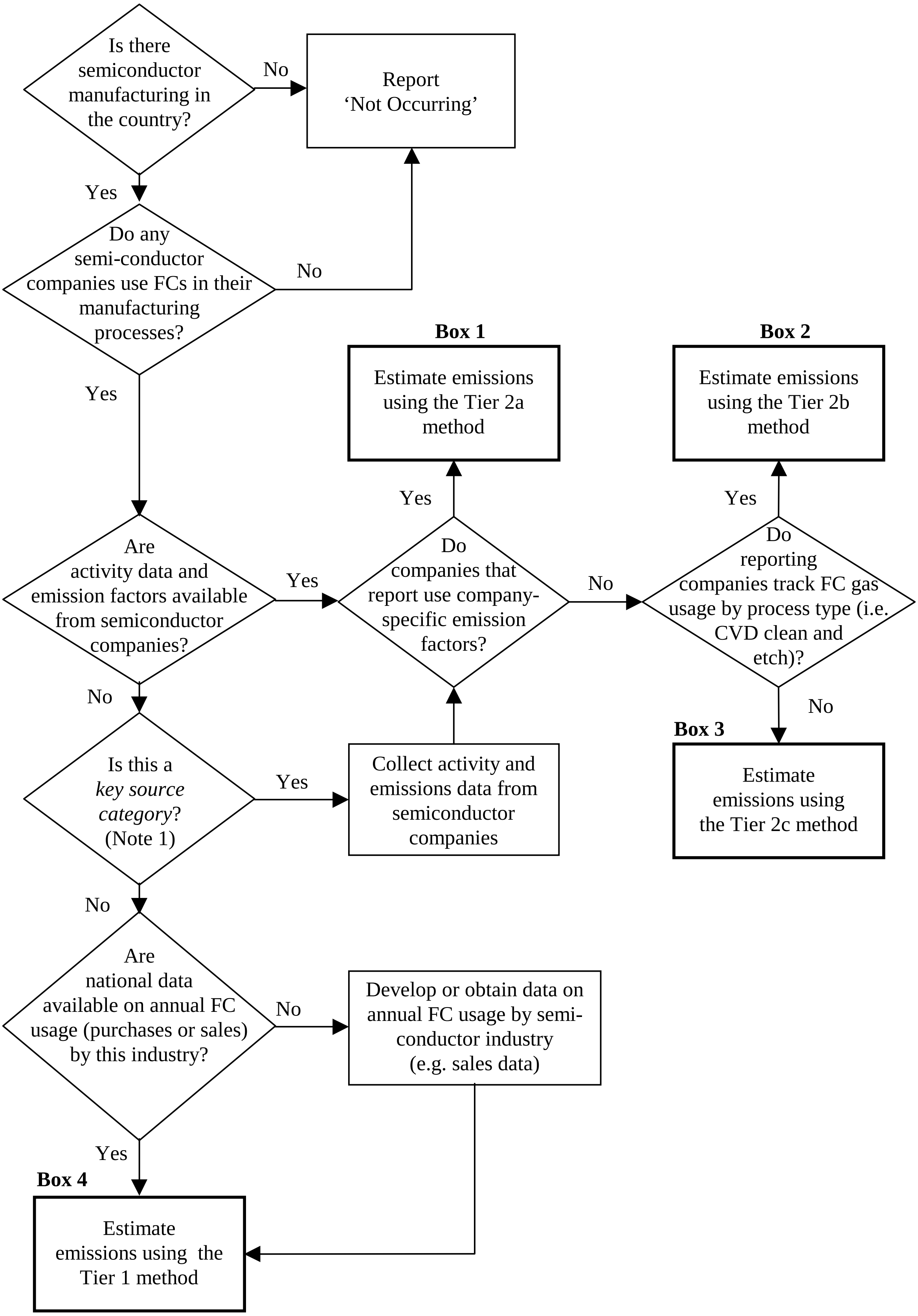
[30] Although NF_3 does not currently have a global warming potential (GWP) recognized by the IPCC, NF_3 emissions are discussed in this chapter. Molina *et al.* have estimated a GWP-100 of 8,000 and an atmospheric lifetime of 740 years (Molina, 1995).

Figure 3.10 Decision Tree for FC Emissions from Semiconductor Manufacturing



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Emissions resulting from the use of a specific FC (FC_i) consist of emissions of FC_i itself *plus* emissions of CF_4 created as a by-product during the use of FC_i . The following calculation should be repeated for each gas for each process type:

EQUATION 3.27

$$\text{Emissions of } FC_i = (1 - h) \bullet \sum_p \left[FC_{i,p} \bullet (1 - C_{i,p}) \bullet (1 - a_{i,p} \bullet d_{i,p})\right]$$

Where:

p = Process or process type (etching or CVD chamber cleaning)

$FC_{i,p}$ = kg of gas i fed into process/process type p (CF_4, C_2F_6, C_3F_8, C_4F_8, CHF_3, NF_3, SF_6)

h = Fraction of gas remaining in shipping container (heel) after use

$C_{i,p}$ = Use rate (fraction destroyed or transformed) for each gas i and process/process type p (in kgs)

$a_{i,p}$ = Fraction of gas volume fed into in processes with emission control technologies (company-or plant-specific)

$d_{i,p}$ = Fraction of gas i destroyed by the emission control technology (If more than one emission control technology is used in process/process type p, this is the average of the fraction destroyed by those emission control technologies, where each fraction is weighted by the quantity of gas fed into tools using that technology)

EQUATION 3.28

$$\text{By-product Emissions of } CF_4 \text{ for } FC_{i,p} = (1 - h) \bullet \sum_p \left[B_{i,p} \bullet FC_{i,p} \bullet (1 - a_{i,p} \bullet d_{CF4,p})\right]$$

Where:

$B_{i,p}$ = Fraction of gas i transformed into CF_4 for each process/process type

$d_{CF4,p}$ = Fraction of CF_4 by-product destroyed by the emission control technology (e.g. control technology type listed in Table 3.15, Default Emission Factors for HFC, PFC, and SF_6 Emissions from Semiconductor Manufacturing)

After estimating CF_4 emissions for each gas, inventory agencies or companies should sum these emissions across all gases to arrive at an estimate of aggregate CF_4 emissions.

Tier 2b Method – Process type-specific parameters

The Tier 2b method also uses the Equations 3.27 and 3.28. However, instead of distinguishing among processes or small sets of processes, it distinguishes only between process types (etching vs. CVD chamber cleaning). Consequently, the Tier 2b method requires data on the aggregate quantities of each gas fed into all etching processes and all cleaning processes ($FC_{i,p}$), as opposed to the quantities of each gas fed into each individual process. Industry-wide generic default values are used for any or all of the following: the fraction of the gas remaining in the shipping container (h), the fraction of the gas 'used' (destroyed or transformed) per process type ($C_{i,p}$), and the fraction of the gas converted into CF_4 in the process type (B_i). Defaults are also presented for the fraction of the gas destroyed by the emissions control technology ($d_{i,p}$ and $d_{CF4,p}$). Company or plant-specific emission factors may be substituted for default values when available. The equations account for the plant-specific use of emission-control devices, but do not account for differences among individual processes or tools or among manufacturing plants in their mix of processes and tools. Thus, Tier 2b estimates will be less accurate than Tier 2a estimates.

Tier 2c Method – FC-specific parameters

This method calculates emissions for each FC used on the basis of company-specific data on gas sales or purchases and on emission control technologies. It uses industry-wide generic default values for the fraction of the purchased gas remaining in the shipping container after use (h), the fraction of the gas 'used' (destroyed or transformed) in the semiconductor manufacturing process, and the fraction of the gas converted into CF_4 in semiconductor manufacture. As is the case with the Tier 2a and 2b methods, total emissions are equal to the sum of emissions from the gas FC_i used in the production process plus the emissions of by-product CF_4 resulting from use of the gas $FC_{i.}$, as shown in Equations 3.29 and 3.30. Unlike Tier the 2a and 2b methods, the Tier 2c method does not distinguish between processes or process types.

As discussed below in the section on emission factors, the Tier 2c method uses the emission factor for the process type (CVD or etch) in which the individual FC is most frequently used in the semiconductor industry. This method reflects a current trend where individual FCs tend to be used predominantly in particular process types (CVD or etch) throughout the semiconductor industry. However, in countries with companies or plants that depart significantly from the industry-wide pattern of usage (e.g. by using a gas primarily in etch while others primarily use it in CVD), inventory agencies should evaluate the potential to introduce error by using the Tier 2c method rather than the Tier 2b method.

EQUATION 3.29

$$\text{Emissions of } FC_i = (1 - h) \bullet [FC_i \bullet (1 - C_i) \bullet (1 - a_i \bullet d_i)]$$

Where:

FC_i = Sales/purchases of gas i in kg (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3, NF_3, SF_6)

h = Fraction of gas remaining in shipping container (heel) after use

C_i = Use rate of gas (fraction destroyed or transformed in process)

a_i = Fraction of gas i volume used in processes with emission control technologies (company- or plant-specific)

d_i = Fraction of gas i destroyed by the emission control technology

EQUATION 3.30

$$\text{By-product Emissions of } CF_4 \text{ for } FC_i = (1 - h) \bullet [(B_i \bullet FC_i) \bullet (1 - a_i \bullet d_{CF_4})]$$

Where:

B_i = kg CF_4 created per kg of gas i used

d_{CF4} = Fraction of CF_4 by-product destroyed by the emission control technology

After estimating CF_4 emissions for each gas, inventory agencies or companies should sum these emissions across all gases to arrive at an estimate of aggregate CF_4 emissions.

This method does not account for differences among process types (etching versus cleaning), individual processes, or tools.

Tier 1 Method – Default

The Tier 1 method is the least accurate estimation method. It should be used only in cases where company-specific data are not available. This method calculates emissions for each FC used on the basis of national gas sales or purchase data. It uses industry-wide generic default values for: the fraction of the purchased gas remaining in the shipping container after use, the fraction of the gas 'used' (transformed or destroyed) in the semiconductor manufacturing process, and the fraction of the gas transformed into CF_4 in semiconductor manufacture. As is the case with the Tier 2 method, emissions are equal to the sum of emissions from the gas FC_i used in the production process plus the emissions of by-product emissions of CF_4 resulting from use of the gas $FC_{i.}$, as shown in Equations 3.31 and 3.32.

EQUATION 3.31

$$\text{Emissions of } FC_i = (1 - h) \bullet [FC_i \bullet (1 - C_i)]$$

Where:

FC_i = Sales/purchases of gas i in kg (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3, NF_3, SF_6)

h = Fraction of gas remaining in shipping container (heel) after use

C_i = Use rate of gas (fraction destroyed or transformed in process)

EQUATION 3.32

$$\text{Emissions of } CF_4 \text{ for } FC_i = (1 - h) \bullet (B_i \bullet FC_i)$$

Where:

B_i = kg CF_4 created per kg of gas i

After estimating CF_4 emissions for each gas, inventory agencies or companies should sum them across all gases to arrive at an estimate of aggregate CF_4 emissions.

This method does not account for differences among process types (etching versus cleaning), individual processes, or tools. It also does not account for the possible use of atmospheric emission-control devices.

CHOICE OF EMISSION FACTORS

As discussed above, emissions factors based on simple semiconductor production variables are not adequate to account for all of the factors that influence emissions. Data for each of the following parameters are necessary to prepare a rigorous estimate:

- The gases used;
- The process type (CVD or etch) used;
- The brand of process tool used;
- Atmospheric emission reduction technology.

Default values have been developed for the parameters used in Tier 1, Tier 2b and 2c methods that reflect the literature and expert judgement (see Table 3.15, Default Emission Factors for HFC, PFC and SF_6 Emissions from Semiconductor Manufacturing). Given the difficulty in representing the diverse production conditions within the semiconductor industry, default emission parameters are inherently uncertain. Accuracy can be improved with larger sets of measured data and where factors are applied to similar processes using similar or identical chemical recipes. Emission factors for destruction (abatement) technologies are acknowledged as currently having greater uncertainty and variability than those for the manufacturing processes. Rapid technical innovation by chemical and equipment suppliers, and semiconductor manufacturers is expected to result in major emission reductions within this industry over the next 10 years. These innovations are also likely to affect emission factors. The semiconductor industry has established a mechanism through the World Semiconductor Council to evaluate global emission factors. Inventory agencies may wish to periodically consult with the industry to better understand global and national circumstances.

The default value for the fraction of gas remaining in the shipping container (heel) is 0.10.

TABLE 3.15
DEFAULT EMISSION FACTORS FOR HFC, PFC AND SF_6 EMISSIONS FROM SEMICONDUCTOR MANUFACTURING

	CF_4	**C_2F_6**	**CHF_3**	**C_3F_8**	**c-C_4F_8**	**NF_3**	**SF_6**
Tier 1							
$1 - C_i$	0.8	0.7	0.3	0.4	0.3	0.2	0.5
B	NA	0.1	NA	0.2	NA	NA	NA
Tier 2c							
$1 - C_i$	0.8	0.7	0.3	0.4	0.3	0.2	0.5
B	NA	0.1	NA	0.2	NA	NA	NA
Tier 2b							
Etch $1 - C_i$	0.7	0.4	0.3	0.4	0.3	0.3[a]	0.5
CVD $1 - C_i$	0.8	0.7	NA	0.4	ND	0.2	0.2
Etch B	NA	0.1	NA	ND	NA	NA	NA
CVD B	NA	0.1	NA	0.2	NA	NA	NA
Emission Control Technology (d)	**CF_4**	**C_2F_6**	**CHF_3**	**C_3F_8**	**c-C_4F_8**	**NF_3**	**SF_6**
Tier 2c[b]	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Tier 2b							
Hot Tube[c]	0.1	0.3	NT	NT	NT	0.5	0.1
Fueled combustion[d]	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Plasma (with additive H_20 vapour)[e]	0.9	NT	0.9	NT	0.9	0.9	0.9
Plasma (with additive O_2)	0.9	NT	0.9	NT	0.9	0.8	0.8
Catalytic[f]	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Cryogenic absorption	0.7	0.9	0.9	NT	NT	NT	0.9
Membrane Separation	0.8	0.9	NT	NT	NT	NT	0.9

[a] Use of NF_3 in the etch process is typically small compared to CVD. The aggregate emissions of NF_3 from etch and CVD under Tier 2b will usually not be greater than estimates made with Tier 2c or Tier 1 methods.

[b] Tier 2c emission control technology factors are applicable only to fueled combustion, plasma, and catalytic devices that are specifically designed to abate FCs. Under the Tier 2c approach, other technologies, such as hot tubes, are assumed to have a destruction efficiency of 0%.

Sources:

[c] SEMATECH Technology Transfer Report, SEMATECH, 1994.

[d] Vendor data verified by semiconductor manufacturers.

[e] Draft SEMATECH Technology Transfer Report, SEMATECH, 1999.

[f] Data for catalytic, cryogenic absorption and membrane separation as presented at *Semicon SW 1999*, Austin, Texas, USA.

NA = not applicable, ND = no data, NT = not tested.

PROCESS TOOL EMISSION FACTORS

The procedures for calculating process tool emission factors for Tier 1, Tier 2c and Tier 2b methods are identical. Process tool emission factors are defined as the amount of greenhouse gas emitted divided by the amount of greenhouse gas used in the process. The emission factors correspond to the '$(1 – C_i)$' term in the Tier 1 and Tier 2 formulas. For example, the emission factor of 0.8 for CF_4 (see Table 3.15 above, Tier 1 value) means that 80% of the CF_4 used in the process is emitted as CF_4. By-product emission factors were also calculated. The expert group determined that the only by-product emission of significance was that of CF_4. It was further determined that the only gases that emit significant amounts of CF_4 as a by-product are C_2F_6 and C_3F_8. As a result of this discussion, CF_4 by-product emission factors were calculated only for C_2F_6 and C_3F_8. For example, a value of 0.2 for C_3F_8 (taken from Table 3.15 above, Tier 1 value) means that 20% of the C_3F_8 used is converted into CF_4.

In order to calculate the Tier 2b process tool emission factors, data were collected from the process equipment manufacturers and semiconductor manufacturers. The data were collected according to process type (either Chemical Vapor Deposition (CVD) or etch) and also by type of gas (e.g. C_2F_6, CF_4). The methods used to conduct the emissions testing were real time Quadrupole Mass Spectrometry (QMS) and Fourier Transform Infrared Spectroscopy (FTIR). Calibration standards (usually 1% mixtures with a balance of N_2) were used to quantify the results. The quality analysis and quality control requirements that were followed are outlined in the 'Equipment Environmental Characterisation Guidelines' Revision 3. The emission factors for Tier 2b (see Table 3.15 above) are the simple average of the data collected for each gas for etch and CVD, rounded to one significant figure.

In order to determine the Tier 1 and Tier 2c process tool emission factors, some knowledge of the amounts of gas used in typical semiconductor manufacturing processes is required. The Tier 1 and Tier 2c emission factors were obtained by determining for each of the gases which process type (CVD or etch) uses the most gas. For example, the Tier 2b emission factors for SF_6 are 0.5 (etch) and 0.2 (CVD). Since the predominant use of SF_6 in the semiconductor industry is in the etch processes, the Tier 2b etch emission factor was used for the Tier 1 SF_6 emission factor.

For Tier 2a emission factors, semiconductor manufacturers use company or fab-specific values rather than using default values as listed in Table 3.15 above.[31] In order to assure the quality of emission factors, emission testing should be conducted in accordance with accredited methods.[32] If a third-party supplier conducts the emissions testing, the semiconductor manufacturer should make sure that the third-party supplier is capable of meeting all of the requirements outlined in Revision 3.0 of the Equipment Environmental Characterisation Guidelines. Semiconductor manufacturers who use emission factors provided by the process tool equipment supplier should make sure that the emission factors are applicable to their specific manufacturing process. Manufacturing methods with process parameters (e.g. pressure, flow rate) that deviate from centreline conditions may have different emission factors than those provided by the tool manufacturer.[33]

EMISSION CONTROL TECHNOLOGY FACTORS

Tier 2b Emission Factors

Assumptions for the emissions control technology emission factors for the Tier 2b methods include:

(i) Results listed are for actual fab emissions testing, no lab results were included;

(ii) Plasma abatement is applicable to etch tools only (less than or equal to 200mm);

(iii) Capture/Recovery (cryogenic absorption and membrane separation) emission factors are for the capture portion of process only, recovery efficacy must be further characterised;

(iv) Cost of ownership and applicability of various technologies vary widely;

(v) Applicability of various technologies to emission from >200 mm wafer processes was not characterised.

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[31] 'Fab-specific' means specific to a fabrication plant.

[32] One example of an internationally accredited testing method can be found in the latest version of the Semiconductor Industry Association (2000) 'Equipment Environmental Characterisation Guidelines' (Revision 3.0 as of February 2000)'.

[33] Centreline conditions refer to the conditions under which equipment manufacturers standardise their equipment for sale. It is common for semiconductor manufacturers to modify these conditions to optimise for particular needs.

The values presented in Table 3.15, Default Emission Factors for HFC, PFC and SF_6 Emissions from Semiconductor Manufacturing, are the average of all of the data received for each type of technology and input gas, rounded down to the next 10% (e.g. an average of 98% would be rounded down to 0.9). The averages were rounded down to reflect that (i) emissions control devices vary in their efficacy depending upon what gas they are optimised to destroy, and (ii) the efficacy of emission control devices on new tools processing larger wafers (>200 mm) is not well characterised. An emission control device that can destroy 99% of a FC when it is optimised to destroy that FC on a certain tool may destroy less than 95% of that FC when it is optimised to destroy something else or when it is used on a tool for which it was not designed.

Emissions control technologies, while currently not widely deployed in the industry, are developing at a rapid pace. Default control technology emission factors in Table 3.15, Default Emission Factors for HFC, PFC and SF_6 Emissions from Semiconductor Manufacturing, are based on limited testing of control devices in a small subset of processes and tools. Results are expected to vary across tools and gas flow rates. In addition, individual abatement technologies are not applicable to all tools or processes in semiconductor manufacturing facilities.

Tier 2c Emission Factors

The emission control technology factors listed for Tier 2c were calculated from data received from equipment suppliers, abatement suppliers and semiconductor manufacturers. Again, the values are the average of all of the data received for each type of input gas, rounded down to the next 10% It should be noted that only data from abatement devices that were specifically designed to abate FCs were used in the average calculation. Data were received from combustion abatement devices (all of which used some type of fuel), plasma abatement devices, and catalytic abatement devices. Default control technology emission factors for Tier 2c should be used only for emissions control technologies specifically designed and installed to reduce FC emissions. If companies use any other type of abatement device, such as a hot tube, they should assume that its destruction efficiency is 0% under the Tier 2c method. Emissions control technologies are expected to evolve over time and emission factors should be re-evaluated periodically.

CHOICE OF ACTIVITY DATA

Activity data for this industry consists of data on gas sales, purchases, or use. For the more data-intensive Tier 2 methods, gas purchase data at the company or plant-level are necessary. For the Tier 1 method, it is preferable that company-level gas purchase data are used. Where purchase data are not available, sales data may be available from the gas manufacturers or distributors. Sales data should include only the share of each gas that is sold to the semiconductor industry. It may be necessary to make assumptions about this share if the data are not available from gas manufacturers or distributors.

UNCERTAINTY ASSESSMENT

Use of the Tier 2a method will result in the least uncertain inventory and the Tier 1 method is the most uncertain. Given the limited number of plants and the close monitoring of production processes at the plant level, collection of data for use in Tier 2b or Tier 2a methods should be technically feasible. The Tier 1 method has the greatest level of uncertainty. Inventory agencies should seek the advice of the industry on uncertainties, using the approaches to obtaining expert judgement outlined in Chapter 6, Quantifying Uncertainties in Practice.

COMPLETENESS

Complete accounting of emissions from the semiconductor industry should be achievable in most countries because there are a limited number of companies and plants. There are four issues related to completeness that should be addressed:

- **Other by-products:** A number of transformation by-products are generated as a result of FC use for chamber cleaning and etching. With the exception of CF_4, however, FC by-product concentrations are assumed to be negligible. Inventory agencies should re-evaluate this assumption if new gases are adopted by the industry.
- **New chemicals:** Completeness will be an issue in the future as the industry evaluates and adopts new chemical processes to improve its products. Industry-wide efforts to reduce FC emissions are also accelerating the review of new chemicals. Consequently, *good practice* for this industry is to incorporate a mechanism that accounts for greenhouse gases not listed in the IPCC Second Assessment Report (e.g. NF_3, C_5F_8, HFEs). These new gases may also produce high GWP by-products.

- **Other sources:** A small amount of FCs may be released during gas handling (e.g. distribution) and by sources such as research and development (e.g. university) scale plants and tool suppliers. These emissions are not believed to be significant (e.g. less than 1% of this industry's total emissions).

- **Other products or processes:** FC use has been identified in the electronics industry in emissive applications including: manufacture of flat panel displays[34] and hard disk drives reliability testing (inert liquids), coolants[35] (direct evaporative cooling for electric and electronic apparatuses and indirect coolants in closed circuit of electric and electronic apparatuses), vapour phase reflow soldering, and precision cleaning.[36]

DEVELOPING A CONSISTENT TIME SERIES

Use of FCs by the semiconductor industry began in the late 1970s and accelerated significantly beginning in the early 1990s. Determining a base year emissions level may present difficulties because few data are available for emissions occurring before 1995. If historical emissions estimates were based on simple assumptions (e.g. use equals emissions), then these estimates could be improved by applying the methods described above. If historical data are not available to permit use of a Tier 2 method, then the Tier 1 method using default emission parameters can be used retrospectively. Both Tier 1 and Tier 2 could then be applied simultaneously for the years in which more data become available to provide a comparison or benchmark. This should be done according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

In order to ensure a consistent emissions record over time, an inventory agency should recalculate FC emissions for all years reported whenever emissions calculation procedures are changed (e.g. if an inventory agency changes from the use of default values to actual values determined at the plant level). If plant-specific data are not available for all years in the time series, the inventory agency will need to consider how current plant data can be used to recalculate emissions for these years. It may be possible to apply current plant-specific emission parameters to sales data from previous years, provided that plant operations have not changed substantially. Such a recalculation is required to ensure that any changes in emission trends are real and not an artefact of changes in procedure.

3.6.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

Explicit reporting on emissions in this industry would improve the transparency and comparability of emissions. For example, under Table 2F of the IPCC reporting tables an additional line should be added for semiconductor manufacturing emissions. As a number of FCs gases are emitted by this industry, reporting by individual gas species rather than by chemical type would also improve the transparency and usefulness of this data. Efforts to increase transparency should take into account the protection of confidential business information related to specific gas use. Country-level aggregation of gas-specific emissions data should protect this information in countries with three or more manufacturers. Table 3.16, Information Necessary for Full Transparency of Estimates of Emissions from Semiconductor Manufacturing, shows the supporting information necessary for full transparency in reported emissions estimates.

Good practice for Tier 2a is to document the development of company-specific emission factors, and to explain the deviation from the generic default values. Given confidentiality concerns, inventory agencies may wish to aggregate this information across manufacturers. In cases where manufacturers in a country have reported

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[34] Emissions from flat panel display (thin film transistor (TFT) liquid crystal) manufacturing may be estimated using methods similar to those used for semiconductor manufacturing. Company-specific emission and abatement factors are required. Very small amounts are also used in microelectronic machine (MEM) manufacturing and research and development laboratories/facilities.

[35] Emissions from 'hard disc drives reliability testing' and 'coolants' are to be accounted for in Section 3.7.6, Other Applications Sub-source Category.

[36] Emissions from precision cleaning are to be accounted for in Section 3.7.2, Solvents Sub-source Category.

different emission or conversion factors for a given FC and process or process type, inventory agencies may provide the range of factors reported and used.

Until handling of NF_3, C_5F_8, HFEs, and other FC gases is decided upon, emissions should be reported separately and not included in total emissions calculations.

TABLE 3.16
INFORMATION NECESSARY FOR FULL TRANSPARENCY OF ESTIMATES OF EMISSIONS FROM SEMICONDUCTOR MANUFACTURING

Data	Tier 1	Tier 2c	Tier 2b	Tier 2a
Emissions of each FC (rather than aggregated for all FCs)	X	X	X	X
Sales/purchases of each FC	X	X		
Mass of each FC used in each process or process type			X	X
Fraction of each FC used in processes with emission control technologies		X	X	X
Use rate for each FC for each process or process type (This and following information is necessary only if default value is not used)				X
Fraction of each FC transformed into CF_4 for each process or process type				X
Fraction of gas remaining in shipping container				X
Fraction of each FC destroyed by emission control technology				X
Fraction of CF_4 by-product destroyed by emission control technology				X

3.6.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Additional general guidance for higher tier QA/QC procedures is also included in Chapter 8. Due to the highly competitive nature of the semiconductor industry, provisions for handling confidential business information should be incorporated into the verification process. Methods used should be documented, and a periodic audit of the measurement and calculation of data should be considered. A QA audit of the processes and procedures should also be considered.

3.7 EMISSIONS OF SUBSTITUTES FOR OZONE DEPLETING SUSBSTANCES (ODS SUBSTITUTES)

Overview (3.7.1 to 3.7.7)

This chapter provides *good practice guidance* on seven sources of emissions of substitutes for ozone depleting substances (ODS). Each of the following uses is discussed in a separate section:

- Aerosols and metered dose inhalers;
- Solvent uses;
- Foam;
- Stationary refrigeration;
- Mobile air conditioning;
- Fire protection;
- Other applications.

General methodological issues for all ODS substitutes sub-source categories

CHOICE OF METHOD

The *IPCC Guidelines* describe two tiers for estimating emissions from the use of ODS substitutes: the advanced or actual method (Tier 2), and the 'basic' or 'potential' method (Tier 1).[37] The actual method (Tier 2) accounts for the time lag between consumption and emissions of ODS substitutes, whereas the potential method assumes that emissions occur during the year in which the chemical is produced or sold into a particular end-use sector.

While the Tier 1 method requires less data, it may produce very inaccurate estimates over the short term because, for many long-lived sources such as refrigerators, chemicals are emitted over a period of several years. The greater the length of time over which the chemical is released, the greater the possible inaccuracy of the 'potential' method. If, as is the case in most countries, equipment sales are increasing each year, the total amount of chemical stored in end-use equipment must also be increasing. Therefore, the potential method is likely to overstate emissions

Good practice is to use the Tier 2 actual method for all sub-source categories within this source category. Consistency requires that inventory agencies make every attempt to apply actual methodologies across the whole spectrum of ODS substitute emission sources. If an inventory agency is unable to implement actual methods for all sub-source categories, it is *good practice* to calculate and report potential estimates for all sub-source categories to allow the summation of total emissions. *Actual and potential emissions estimates should not be summed together by the inventory agency.*

The generalised decision tree in Figure 3.11, Generalised Decision Tree for All Substitutes for Ozone Depleting Substances, describes *good practice* in choosing between Tier 2 and Tier 1 methods for each end-use in the seven sub-sections that follow. *Good practice* is to use the Tier 2 method for those sub-source categories that were identified as '*key sub-source categories*' as discussed in Chapter 7, Methodological Choice and Recalculation. This determination is done at the level of the IPCC source category level (in this case 'ODS Substitutes') and not at the level of the IPCC sub-source category.

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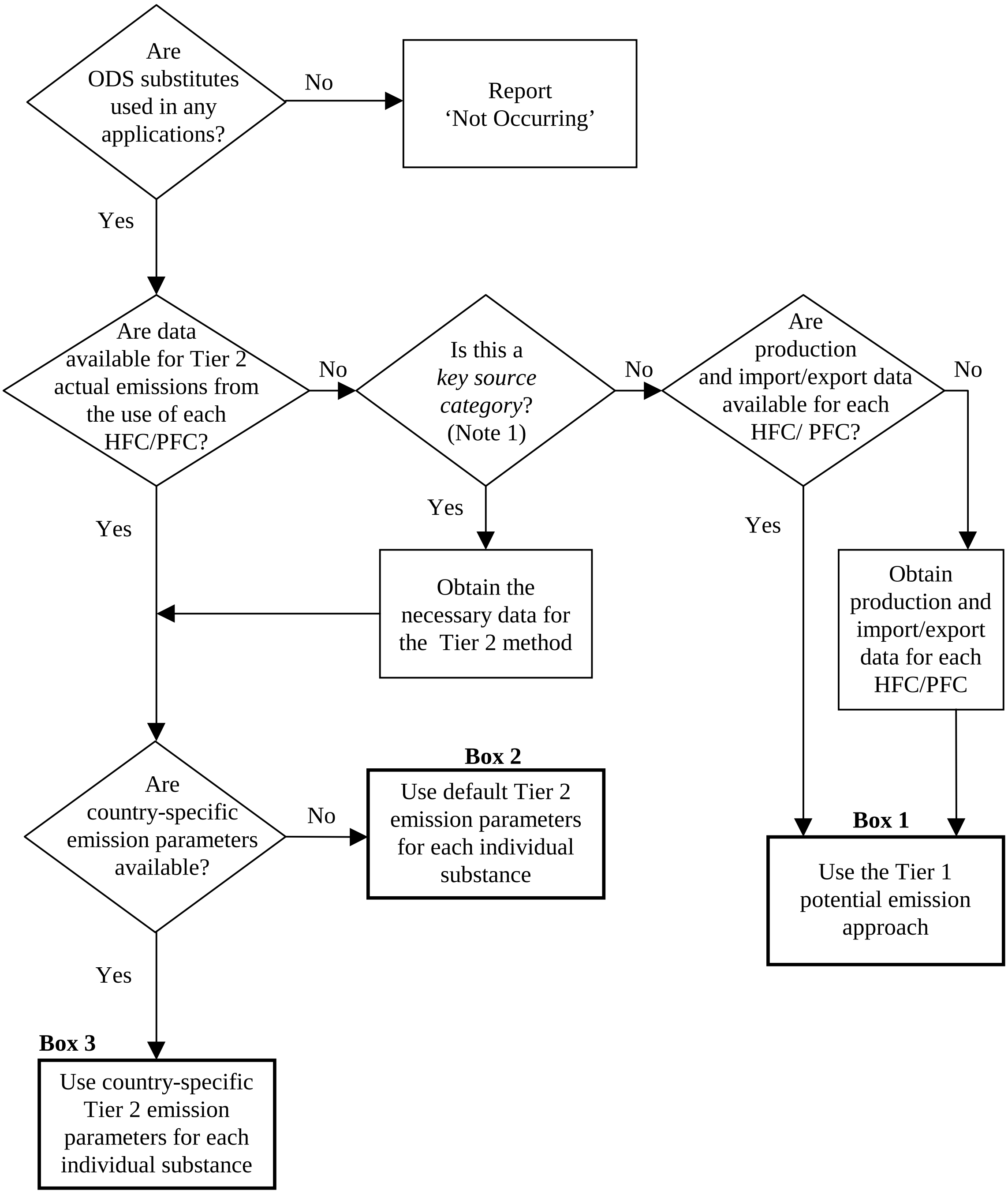
[37] The Conference of the Parties to the UNFCCC, at its third session, affirmed '… that the actual emissions of hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride should be estimated, where data are available, and used for the reporting of emissions. Parties should make every effort to develop the necessary sources of data;'. (Decision 2/CP.3, Methodological issues related to the Kyoto Protocol)

Figure 3.11 Generalised Decision Tree for All Substitutes for Ozone Depleting Substances



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

The *good practice guidance* in this section deals with variations of the Tier 2 method, rather than implementing the potential method. Each sub-section discusses how to apply these methods to specific ODS sub-source categories, reviews existing data sources, and identifies gaps therein. For further guidance on implementing the Tier 1 method, countries can refer to Section 2.17.3 of the *IPCC Guidelines*, Vol. 3.

In general, it is *good practice* to develop appropriate country data for the Tier 2 method when the emissions from the ODS replacement source categories are a significant component of the national inventory. This may require a country-specific model. More detailed decision trees are included for each sub-source category to assist in the further identification of data needs and selection of the Tier 2 approach.

Inventory agencies implementing the Tier 2 method will need to determine whether to use bottom-up or top-down approaches. The bottom-up approach takes into account the time lag between consumption and emissions explicitly through emission factors. The top-down approach takes the time lag into account implicitly, by tracking the amount of virgin chemical consumed in a given year that is used to replace chemical that was emitted to the atmosphere.

Tier 2a – Bottom-up approach

The bottom-up method is based on the number of products and end-uses where ODS substitutes are consumed and emitted. This approach estimates the number of equipment units that use these chemicals, average chemical charges, average service life, emission rates, recycling, disposal, and other pertinent parameters. Annual emissions are then estimated as a function of these parameters through the life of the units. Since equipment units vary significantly in the amount of chemical used, service life, and emission rates, the characterisation of this equipment can be a resource intensive task. The longer-lived the end-use equipment, and the more diverse the types of equipment within a particular application, the more complex the bottom-up approach has to be in order to account for emissions.[38] The bottom-up approach can provide an accurate estimate of emissions if the data called for by the following equation are available for all relevant types and vintages of equipment:

EQUATION 3.33

Total Emissions of Each PFC or HFC = Equipment Assembly Emissions + Equipment Operation Emissions + Equipment Disposal Emissions

Assembly emissions occur as fugitives when equipment is filled or refilled with a chemical. Emissions from equipment also occur as leaks, or intentional releases during *operation*. Finally, when the equipment life ends and it is *disposed*, the remaining charge of HFC/PFC escapes to the atmosphere, is recycled, or possibly destroyed.

The need to update equipment inventories on an annual basis can be a major implementation challenge for inventory agencies with limited resources. The bottom-up method does not require annual chemical consumption data, however, although it could be used as a quality assurance check if available.

Tier 2b – Top-down approach

The top-down approach also estimates emissions from assembly, operation, and disposal, but does not rely on emission factors. Instead, the method uses measured consumption (i.e. sales) of each chemical in the country or facility being considered. The general equation is as follows[39]:

Equation 3.34

Emissions = Annual Sales of New Gas – (Total Charge of New Equipment – Original Total Charge of Retiring Equipment)

Industry purchases new chemical from manufacturers to replace leakage (i.e. emissions) from the current equipment stock, or to make a net change in the size of the total charge of the equipment stock.[40] The total

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[38] As approximately twenty different HFC and PFC chemicals could potentially be used as substitutes for ozone depleting substances, and emissions sources are numerous and extremely diversified, implementing the bottom-up method involves dealing with high volumes of data and levels of complexity.

[39] Boundary conditions: If there is no net change in the total equipment charge, then annual sales are equal to emissions. If the net change in the total equipment charge is equal to annual sales, then emissions are zero.

charge of new equipment minus the original total charge of retiring equipment represents the net change to charge of the equipment stock. Where the net change is positive, some of the new chemical is being used to satisfy the increase in the total charge, and therefore cannot be said to replace emissions from the previous year.

Using this approach, it is *not* necessary to know the total amount of each chemical in equipment stock in order to calculate emissions. One only needs to know the total charges of the new and retiring equipment. This approach is most directly applicable to the refrigeration and mobile air conditioning, and fire protection sub-source categories. Further elaboration and modification of this approach is provided in the description of each sub-source category. In addition, models are being developed that allocate chemical sales for different end uses into different regions of the world. These models are currently being derived for specific ODS Substitute end uses such as foam and fire protection.[41]

CHOICE OF EMISSION FACTORS

The type of emission factor required depends on the Tier 2 approach implemented.

Tier 2a – Bottom-up approach

For the bottom-up approach, specific emission factors are required to estimate emission rates from the major equipment types and sectors. Emission factors should be based on a country-specific study of the equipment units in stock to determine their remaining service lives, average charges, retrofit rates, leak rates, disposal quantities, and recovery practices. The *IPCC Guidelines* include default values for some of these parameters, but these are not country-specific. *Good practice guidance* provides additional default values for some sub-source categories.

A common theme is that management of the disposal of equipment at the end of its service life can have a profound effect on the total emissions. The chemical remaining in systems (called the ‘bank’) can be up to 90% of the original quantity used. Specific issues related to emission factors are discussed in the sub-source category sections.

Tier 2b – Top-down approach

As discussed above, the top-down approach generally relies on chemical sales data and does not use equipment-based emission factors. Where there are exceptions to this rule, *good practice guidance* is provided in each sub-source category section (e.g. fugitive emissions during the filling of equipment with HFCs and PFCs).

CHOICE OF ACTIVITY DATA

Tier 2a – Bottom-up approach

The bottom-up approach requires an inventory of existing HFC/PFC in existing units (i.e. the ‘bank’). Some inventory agencies may have access to national data published in trade magazines or technical reports. However, it is more likely that a study will be necessary to estimate the inventory of existing units or chemicals. Expert panels can also facilitate the generation of this information. Inventory agencies may also decide to conduct annual studies to update their inventories of sector units. An alternative to this may be to calculate or estimate production growth for each one of the sub-source categories under consideration. Data need to reflect new units that are introduced each year, and old or poorly functioning units that are retired.

Tier 2b – Top-down approach

Activity data for the top-down approach focus on chemical deployment rather than sources of emissions. For certain end-uses, such as fire protection and foam, global models are being developed that allocate accurately known production data into end-uses in specific regions. The activity data from these models will be particularly useful for countries with significant imports of chemical and equipment.

For the sales-based approach, data on national chemical use are more easily obtained than data for the national inventory of equipment responsible for emissions. It is *good practice* to obtain data on the total annual sales from the gas manufacturers or importers.[42] The best source of data on the total charge of new equipment is likely to be

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[40] Industry also requires new chemical to replace destroyed gas and for stockpiles. Terms can be added to the general equation to account for these uses; these terms are not included here for simplicity.

[41] For example, see www.greenhousegases.org.

[42] Tier 1b method of the *IPCC Guidelines,* Vol. 3, Section 2.17.3.3, provides the default method for annual sales data.

the equipment manufacturers or the trade associations that represent them. For the total charge of retiring equipment, one must know or estimate (i) equipment lifetime, and (ii) either (a) the historical sales of equipment and the equipment's historical average charge size, or (b) the growth rate of such sales and charge sizes.

Inventory agencies in countries that import all or the majority of new chemicals consumed are likely to encounter different issues of data availability than those in countries with significant domestic chemicals production. If the majority of chemicals are imported, either in bulk or in equipment and products, some form of import data will be necessary for calculating emissions. Ideally, customs officials should track and make available chemical import statistics. For some products, such as foam and aerosols, it may not be possible for customs officials to track the type of chemical in the product (e.g. CFCs vs. HFCs in aerosols), or the presence of the product in the imported equipment (e.g. closed cell foam in automobile seats). In such cases, it may be necessary to collect or estimate data with the assistance of major distributors and end-users.

COMPLETENESS

Completeness, in terms of the total quantity of chemical that could potentially be emitted, is covered by the fact that activity data for the top-down approach are recorded in terms of the quantity of chemical used. Completeness is an important issue for countries that use the Tier 2 bottom-up equipment-based method.

A fraction of new chemical production escapes to the atmosphere during production of each substance. Fugitive emissions from production are not accounted for in either of the Tier 2 methods (or the Tier 1 method). It is *good practice* for inventory agencies in countries with domestic chemical production to include fugitive emissions in their inventories. The suggested approach is to apply an emission factor to chemical production, or to assume that a fixed (additional) percentage of chemical sales was emitted during production. Although the default factor is 0.5%, experience in Japan shows much larger emissions.[43] It is *good practice* to determine the actual emission factor for each plant.

DEVELOPING A CONSISTENT TIME SERIES

Inventory agencies that have prepared potential (Tier 1) estimates in the past are encouraged to develop the capacity to prepare Tier 2 estimates in the future. It is *good practice* that actual and potential estimates are not to be included in the same time series, and that inventory agencies recalculate historical emissions with the actual method, if they change approaches. If data are unavailable, the two methods should be reconciled to ensure consistency, following the guidance on recalculation provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques. It is *good practice* to fully document recalculation, ensuring transparency.

Emission factors generally come from historical data on other chemicals (e.g. CFCs) used in established markets and need to be adapted to new chemicals (e.g. ODS substitutes) in start-of-life markets. National data on base year deployment is now available (or can be calculated with known uncertainty).

UNCERTAINTY ASSESSMENT

Over a long time (greater than 20 years) emissions of ODS substitutes within a country will tend to equal total consumption in the same time frame. For a given year, the quantification of uncertainty for ODS is very difficult to estimate, due to the large number of different sources and the diversity of emission patterns. For the top-down Tier 2 method, the overall uncertainty will be directly related to quality and completeness of chemical sales and import data. For the bottom-up Tier 2 method, the uncertainty will reflect the completeness of the equipment survey, and the appropriateness of the emission functions developed to characterise emissions. Further advice on uncertainties is provided in the separate sections on the seven sub-source categories that follow.

Reporting and documentation for all ODS substitutes sub-source categories

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving.

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[43] Source: The Sixth Meeting of the Committee for Prevention of Global Warming and The Chemical Products Council of Japan, 21 May 1999.

As discussed above, inventory agencies should prepare and report actual emissions estimates for as many end use sub-source categories as possible. For those sub-source categories where it is not possible to prepare actual emissions estimates, inventory agencies should prepare and report potential emissions estimates. Inventory agencies reporting an actual/potential hybrid approach should include a set of potential estimates for each sub-source category so that total ODS substitute emissions can be calculated. As noted above, actual and potential estimates should not be summed together.

The balance between preservation of confidentiality and transparency of the data needs to be carefully addressed. Careful aggregation may solve some problems but will require that results are validated by other means (e.g. third party audit). Where data have been aggregated to preserve the confidentiality of proprietary information, qualitative explanations should be provided to indicate the method and approach for aggregation.

Inventory quality assurance/quality control (QA/QC) for all ODS substitutes sub-source categories

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source categories. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation. In addition to the guidance in Chapter 8, specific procedures of relevance to this source category are outlined below.

Comparison of emissions estimates using different approaches

Inventory agencies should use the Tier 1 potential emissions method for a check on the Tier 2 actual estimates. Inventory agencies may consider developing accounting models that can reconcile potential and actual emissions estimates and may improve determination of emission factors over time.

Inventory agencies should compare bottom-up estimates with the top-down Tier 2 approach, since bottom-up emission factors have the highest associated uncertainty. This technique will also minimise the possibility that certain end-uses are not accounted for in the bottom-up approach.

National activity data check

For the Tier 2a (bottom-up) method, inventory agencies should evaluate the QA/QC procedures associated with estimating equipment and product inventories to ensure that they meet the general procedures outlined in the QA/QC plan and that representative sampling procedures were used. This is particularly important for the ODS substitutes sub-sectors because of the large populations of equipment and products.

For the Tier 2b (top-down) method, inventory agencies should evaluate and reference QA/QC procedures conducted by the organisations responsible for producing chemical deployment information. Sales data may come from gas manufacturers, importers, distributors, or trade associations. If the QC associated with the secondary data is inadequate, then the inventory agency should establish its own QC checks on the secondary data, reassess the uncertainty of the emissions estimates derived from the data, and reconsider how the data are used.

Emission factors check

Emission factors used for the Tier 2a (bottom-up) method should be based on country-specific studies. Inventory agencies should compare these factors with the default values. They should determine if the country-specific values are reasonable, given similarities or differences between the national source category and the source represented by the defaults. Any differences between country specific factors and default factors should be explained and documented.

3.7.1 Aerosols sub-source category

3.7.1.1 Methodological issues

Most aerosol packages contain hydrocarbon (HC) as propellants but, in a small fraction of the total, HFCs and PFCs may be used as propellants or solvents. Emissions from aerosols usually occur shortly after production, on average six months after sale. During the use of aerosols, 100% of the chemical is emitted (Gamlen *et al.*, 1986, USA EPA, 1992a). The 5 main sources are as follows:

(i) Metered Dose Inhalers (MDIs);

(ii) Personal Care Products (e.g. hair care, deodorant, shaving cream);

(iii) Household Products (e.g. air-fresheners, oven and fabric cleaners);

(iv) Industrial Products (e.g. special cleaning sprays, lubricants, pipe-freezers);

(v) Other General Products (e.g. silly string, tire inflators, claxons).

The HFCs currently used as propellants are HFC-134a, HFC-227ea, and HFC-152a. The substance HFC-43-10mee and a PFC, perfluorohexane, are used as solvents in industrial aerosol products.[44]

CHOICE OF METHOD

Aerosol emissions are considered ‘prompt’ because all the initial charge escapes within the first year or two after sale. Therefore, to estimate emissions it is necessary to know the total amount of aerosol initially charged in product containers prior to sale. Emissions of each individual aerosol in year t can be calculated according to the *IPCC Guidelines* as follows:

Equation 3.35

$$\begin{gathered}\text{Emissions of HFCs in year } t = \\ [(\text{Quantity of HFC and PFC Contained in Aerosol Products Sold in year } t) \bullet (EF)] \\ + [(\text{Quantity of HFC and PFC Contained in Aerosol Products Sold in year } (t-1)] \bullet (1 - EF)]\end{gathered}$$

This equation should be applied to each chemical individually. Total carbon equivalent emissions are equal to the sum of the carbon equivalent emissions of each chemical.

Since the lifetime of the product is assumed to be two years, any amount not emitted during the first year must by definition be emitted during the second and final year. In reality, most emissions occur within the first year of product purchase, but this calculation accounts for the lag period from time of purchase to time of use.[45] A decision tree for estimating actual emissions is included in Figure 3.12, Decision Tree for Actual Emissions (Tier 2) from the Aerosol Sub-source Category. The data collection process is described below.

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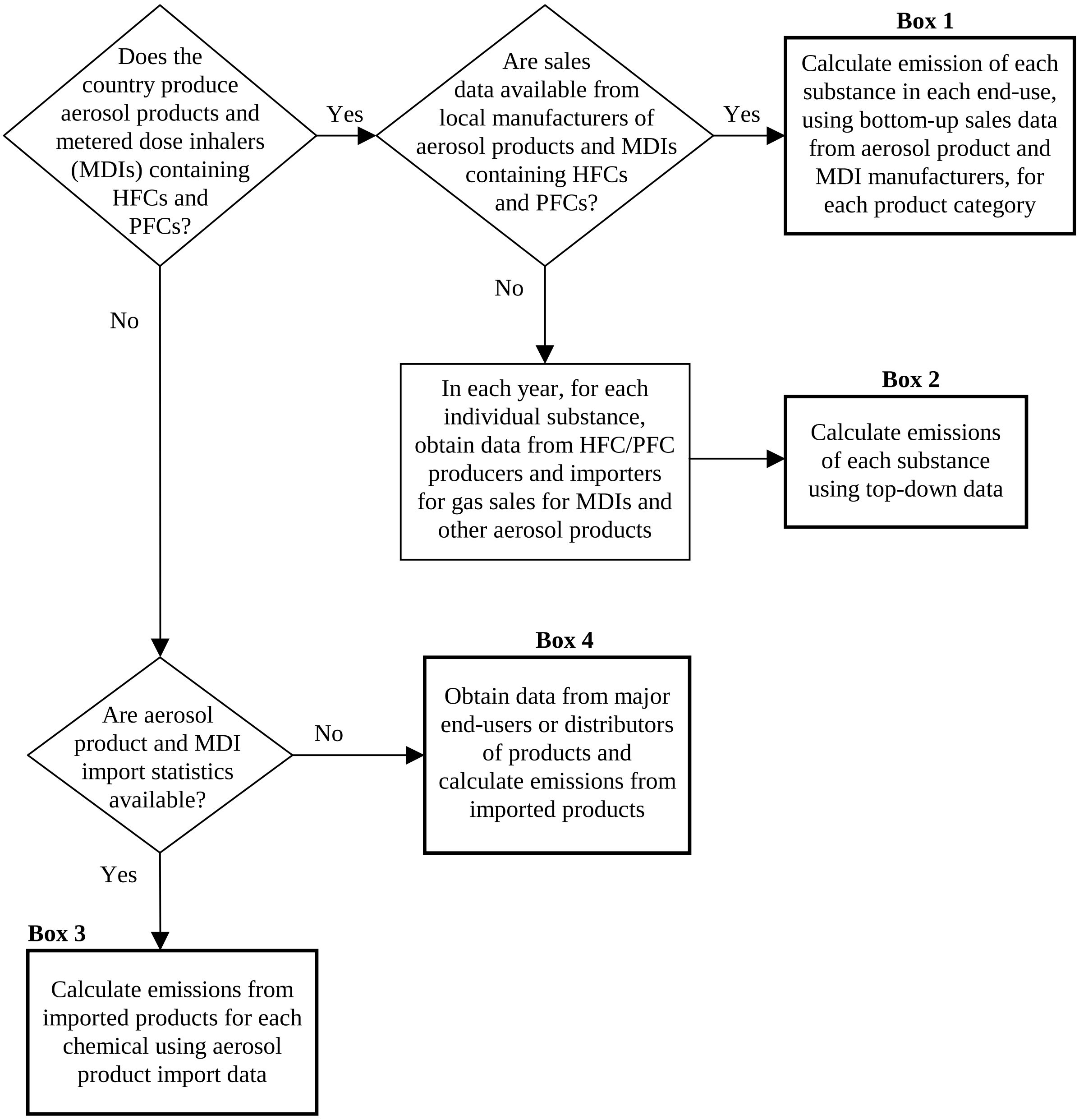
[44] HFC-43-10mee is used solely as a solvent, but is counted as an aerosol when delivered through aerosol canisters.

[45] For short-lived sources such as MDIs and aerosol products, the estimate of potential emissions is equivalent to using an emission factor of 100%. This will produce a result similar to the actual approach if there is no substantial growth in aerosol sales.

Figure 3.12 Decision Tree for Actual Emissions (Tier 2) from the Aerosol Sub-source Category



CHOICE OF EMISSION FACTORS

It is *good practice* to use a default emission factor of 50% of the initial charge per year for the broad spectrum of aerosol products. This means that half the chemical charge escapes within the first year and the remaining charge escapes during the second year (Gamlen *et al.*, 1986). Inventory agencies should use alternative emission factors only when empirical evidence is available for the majority of aerosol products. In any event, the percentage emission factors should in general sum to 100% over the time during which it is assumed that the charge will escape. The development of country-specific emission factors should be documented thoroughly. General aerosol and MDI manufacturers may be able to provide data on process losses.

CHOICE OF ACTIVITY DATA

The activity data required are the total quantity of each relevant chemical contained in all aerosol products consumed within a country (both domestic sales and imports). For countries that import 100% of aerosol products, activity data are equal to imports.

Activity data for this end use sub-source category can be collected using either a bottom-up or a top-down approach, depending on the availability and quality of the data. The bottom-up approach requires data on the number of aerosol products sold and imported (e.g. number of individual metered dose inhalers, hair care products, and tire inflators), and the average charge per container. The top-down approach involves collecting aerosol and MDI chemical sales data directly from chemical manufacturers. In many cases, a mix of bottom-up and top-down data may be necessary.

Domestic aerosol production: For countries with domestic production, general aerosol and MDI manufacturers can provide data on the quantity of aerosol products produced for consumption in the country, the number of aerosols exported, the average charge per aerosol, and the type of propellant or solvent used (i.e. which HFC/PFC). Total use of domestically produced aerosol products in each year can then be calculated as the number of aerosol products sold domestically in a given year times the charge of HFC/PFC in each product. If bottom-up data are not available, domestic chemical producers can provide data on the amount of HFCs sold to domestic manufacturers in metered dose inhalers, and aggregate sales data to producers of other aerosols (categories 2, 3, 4 and 5 above). If domestic aerosol and MDI manufacturers import HFCs, information may also be sought from chemical exporters, although they may not be able to provide data on exports destined for individual countries because of confidential business concerns. Customs officials and chemical distributors are another possible source for chemical import data.

Imported aerosol production: Most countries will import a significant share of their total aerosol products. Data on imports of HFC-containing general aerosols may be difficult to collect because official import statistics for aerosol products do not typically differentiate HFC-containing aerosols from others. When usable import statistics are unavailable from customs agencies, data may be available from product distributors and specific end-users. For example, in the case of MDIs, a limited number of pharmaceutical companies typically import products, and these companies can be surveyed to obtain the required information.

COMPLETENESS

Completeness depends on the availability of activity data. Inventory agencies in countries without domestic aerosol production may need to use expert judgement in estimating activity data, because import statistics are likely to be incomplete (see Chapter 6, Quantifying Uncertainties in Practice, Section 6.2.5, Expert Judgement).

DEVELOPING A CONSISTENT TIME SERIES

Emissions from aerosols should be calculated using the same method and data sources for every year in the time series. Where consistent data are unavailable for any year in the time series, gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

UNCERTAINTY ASSESSMENT

The use of HFCs in the general aerosol sector is larger than in the MDI sector. Data from HFC manufacturers and importers of sales to the general aerosol sector are, at the present time, not well defined other than for HFC-134a on a global scale. These data can be improved through additional data collection activities. The diffuse nature of the general aerosol sector means that the acquisition of reliable bottom-up data requires specific study on a country basis through local industry experts, whose advice should be sought on uncertainties using the approaches to expert judgement outlined in Chapter 6, Quantifying Uncertainties in Practice.

There are several sources of reliable data for the MDI sector, leading to a high level of confidence in the data reported that should be reflected in inventory emissions estimates. However, in reporting for a single country, the absence of reliable data for the general aerosol sector could mean that emission data could be over or under estimated by a factor of between one third and three times.

3.7.1.2 Reporting and documentation

The emission estimate for metered dose inhalers should be reported separately from the emission estimate for other aerosols. Inventory agencies should document the emission factor used. If a country-specific emission factor rather than the default factor is used, its development should be documented. Detailed activity data should be reported to the extent that it does not disclose confidential business information. Where some data are confidential, qualitative information should be provided on the types of aerosol products consumed, imported, and produced within the country. It is likely that the type of HFC used as a propellant or solvent and the sales of MDIs and general aerosols into individual countries could be viewed as confidential.[46] Where there are less than three manufacturers of specific chemicals used as solvents, reporting could be aggregated into this section, because both are considered 100% emissive applications (see Section 3.7.2.2 below).

3.7.1.3 Inventory quality assurance/quality control (QA /QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, Quality Assurance and Quality Control, specific procedures of relevance to this sub-source category are outlined as follows. Both bottom-up and top-down data should be used as a check on the emission estimate. Data used to calculate emissions from year t–1 should be consistent with data used in the previous year’s inventory estimate, so the two-year total sums to 100%. If this is not the case, then the reason for the inconsistency should be reported. Collection of the data described in the section on data collection above should provide adequate quality control. To allow independent assessment of the level of quality of the data reporting, the number of manufacturers of aerosols plus end users should be quantified.

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[46] Quantification of use data for individual general aerosol sectors will enable more reliable future projections to be developed and emission reduction strategies to be considered.

3.7.2 Solvents sub-source category

3.7.2.1 Methodological issues

HFCs and PFCs are used as solvents in four main areas as follows:

(i) Precision Cleaning;

(ii) Electronics Cleaning;

(iii) Metal Cleaning;

(iv) Deposition applications.

The use of HFCs as solvents is still in its infancy. Solvents that have been or may be used include HFC43-10mee, perfluorohexane (a PFC) and others that were not listed in the IPCC Second Assessment Report, including HFC-365mfc.[47]

CHOICE OF METHOD

As is the case in the aerosol sector, emissions from solvent applications generally are considered ‘prompt’ emissions because 100% of the chemical is emitted within two years. To estimate emissions it is necessary to know the total amount of chemical in solvent products sold each year. Emissions of HFCs and PFCs from solvent use in year t can be calculated according to the *IPCC Guidelines* as follows.

EQUATION 3.36

$$\begin{aligned}\text{Emissions in year t} = & \ [(\text{Quantity of Solvents Sold in year t}) \bullet \text{EF}] \\ & + [\text{Quantity of Solvents Sold in year } (t-1) \bullet (1-\text{EF})]\end{aligned}$$

As with aerosols, the equation should be applied to each chemical individually, depending on the disaggregation in available data. Moreover, the equation may also be applied to different equipment classes. Total carbon equivalent emissions are equal to the sum of carbon equivalent emissions of each chemical.

The emission factor EF represents the fraction of chemical emitted from solvents in year t. The product lifetime is assumed to be two years, and thus any amount not emitted during the first year must by definition be emitted during the second and final year. A decision tree for estimating actual emissions is included in Figure 3.13, Decision Tree for Actual Emissions (Tier 2) from the Solvents Sub-source Category. The data collection process is described below.

CHOICE OF EMISSION FACTORS

Good practice is to use a default emission factor of 50% of the initial charge/year for solvent applications.[48] In certain applications with new equipment, it is possible that much lower loss rates will be achieved and that emissions will occur over a period of more than two years. Alternative emission factors can be developed in such situations, using bottom-up data on the use of such equipment and empirical evidence regarding alternative emission factors.[49] Such country-specific emission factors should be documented thoroughly.

Modifications for the recovery and recycling of solvents should not be applied. While HFC and PFC solvents may be recovered and recycled several times during their use due to their high costs, in most emissive end uses the chemical will be released on average six months after sale.

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[47] The *IPCC Guidelines* provide ‘Reporting Instructions’ only for greenhouse gases with global warming potentials listed in the Second Assessment Report.

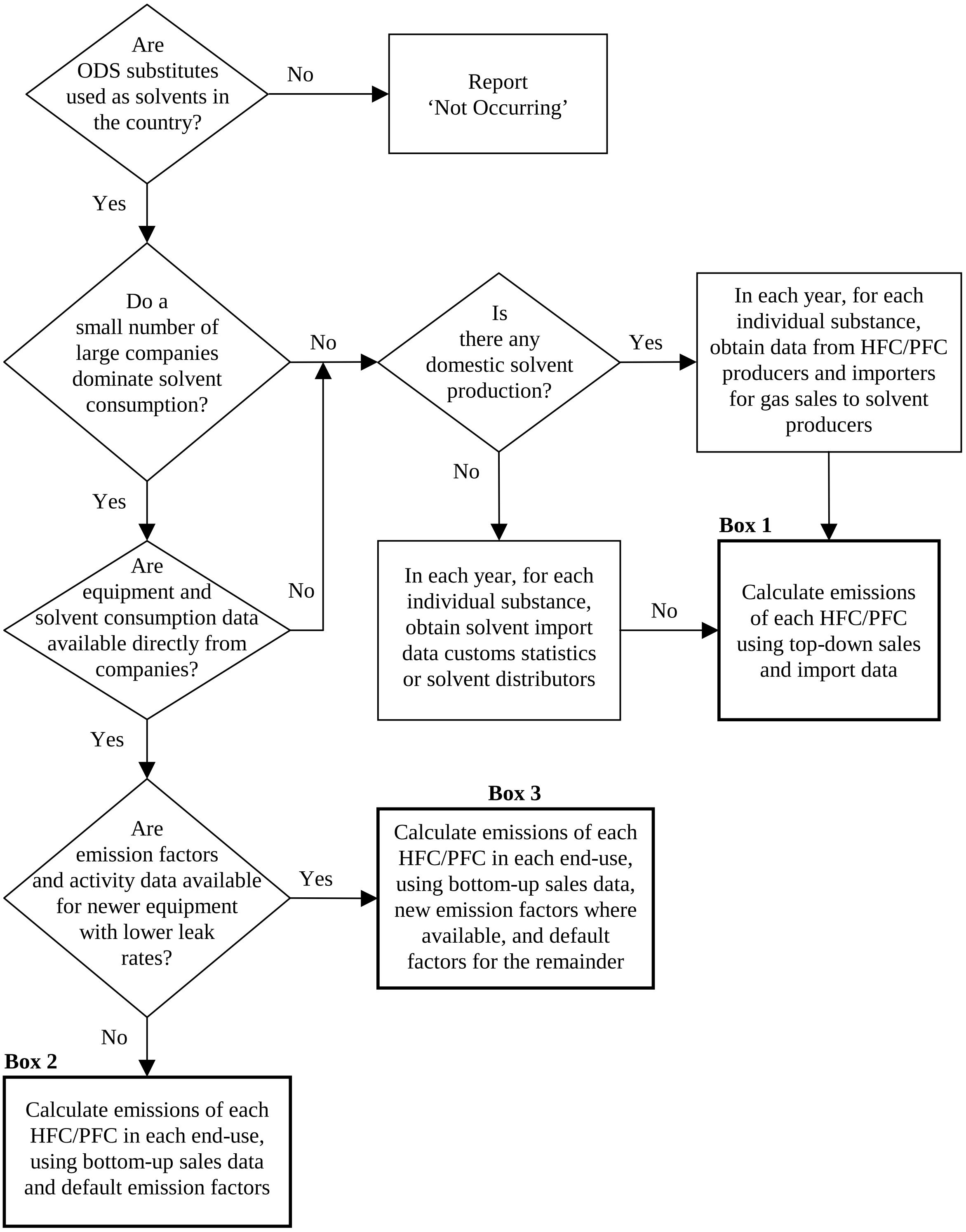
[48] See footnote 47.

[49] As guidance, for sales to new equipment, approximately 10-20% will be emitted with the rest of the gas banked. In subsequent years sales are for servicing volumes and can be considered 100% emitted.

CHOICE OF ACTIVITY DATA

The activity data for this end-use are equal to the quantity of each relevant chemical sold as solvent in a particular year. As with aerosols, data on both domestic and imported solvent quantities should be collected. The required data can be collected using either top-down or bottom-up methods, depending on the character of the national solvent industry. In most countries, the end-users will be extremely diverse and a top-down approach would be practical.

Figure 3.13 Decision Tree for Actual Emissions (Tier 2) from the Solvents Sub-source Category



Top-down data

Top-down data are equal to the amount of chemical solvent sold or imported annually into a country. Domestic solvent sales should be available directly from chemical manufacturers. As solvents are only produced in a few countries, most countries will import some or all of their consumption. Data on imported solvents can be collected from the exporting manufacturers, although information on exports to individual countries may be considered confidential. Alternatively, import statistics from customs agencies or the distributors of imported solvents can be used. Solvent import data are generally more easily obtained than aerosol import data because solvent is usually imported in bulk rather than in small containers.

If specific emission factors are developed for particular types of equipment, it will be necessary to disaggregate the consumption data into these equipment classes. In general, this will require a bottom-up approach.

Bottom-up data

Bottom-up activity data include the number of pieces of equipment or canisters containing solvent and their charge. The bottom-up approach is suitable where large corporations consume most of the solvent sold, because it should be possible to obtain detailed solvent end-use data from a few large entities. The bottom-up approach may also be most appropriate when equipment-specific emission factors are available.

COMPLETENESS

Completeness depends on the availability of activity data. Inventory agencies in countries without domestic solvent production may need to use expert judgement in estimating activity data, because import statistics are likely to be incomplete (see Chapter 6, Quantifying Uncertainties in Practice, Section 6.2.5, Expert Judgement).

DEVELOPING A CONSISTENT TIME SERIES

Emissions from foam should be calculated using the same method and data sources for every year in the time series. Where consistent data are unavailable for any years in the time series, gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

The default assumption that all solvent is emitted within two years is widely accepted and should not lead to a significant error. Similarly, the activity data should be reliable because of the small number of chemical manufacturers, the high cost of the gas leading to little stockpiling, and the 100% emissive nature of the use in most applications.

3.7.2.2 Reporting and documentation

Inventory agencies should report the emission factor used, and the empirical basis for any country-specific factors. For activity data, chemical sales and imports should be reported, unless there are confidentiality concerns due to the limited number and location of manufacturers. (At present, for example, there may be only one producer of each compound.) Where there are less than three manufacturers of specific chemicals used as solvents, reporting could be aggregated into the aerosol section, because both are considered 100% emissive applications (see Section 3.7.1.2 above). In this case, to preserve confidentiality, emissions of individual gases should not be specified and emissions should be reported in CO_2-equivalent tonnes.

3.7.2.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, Quality Assurance and Quality Control, specific procedures of relevance to this source category are outlined below:

- For accurate quality control/assurance both top-down and end-use data should be compiled. To allow independent assessment of the level of quality of the data reporting, the number of manufacturers and distributors plus end users interviewed should be quantified.
- When applying emission factors and activity data specific to various solvent applications, the activity data should be obtained at the same level of detail.

3.7.3 Foam sub-source category

3.7.3.1 Methodological issues

Increasingly, HFCs are being used as replacements for CFCs and HCFCs in foam applications such as insulating, cushioning, and packaging. Compounds that may be used include HFC-245fa, HFC-365mfc, HFC-134a, and HFC-152a. For open-cell foam, emissions of HFCs used as blowing agents are likely to occur during the manufacturing process. In closed-cell foam, emissions occur over a longer time period (e.g. 20 years).

CHOICE OF METHOD

The decision tree in Figure 3.14, Decision Tree for Actual Emissions (Tier 2) from the Foam Sub-source Category, describes *good practice* methods in estimating emissions.

The *IPCC Guidelines* suggest calculating emissions from open-cell foam separately from emissions from closed-cell foam:

Open-Cell Foam: Since HFCs and PFCs used for open-cell foam blowing are released immediately, all of the emissions will occur in the country of manufacture. Emissions are calculated according to the following equation, as presented in the *IPCC Guidelines*:[50]

Equation 3.37

Emissions from Open-cell Foam = Total Annual HFCs and PFCs Used in Manufacturing Open-cell Foam

Closed-Cell Foam: Emissions from closed-cell foam occur at three distinct points:

(i) First Year Losses from Foam Manufacture and Installation: These emissions occur where the product is manufactured.

(ii) Annual Losses (in-situ losses from foam use): Closed-cell foam will lose a fraction of their initial charge each year until decommissioning. These emissions occur where the product is used.

(iii) Decommissioning Losses: Emissions upon decommissioning also occur where the product is used.

Section 2.17.4.3 of the *IPCC Guidelines*, Vol.3, Estimation of Emissions of HFCs and PFCs from Foam Blowing, presents an equation for calculating emissions from the foam blowing that accounts for the first two emission points. In order to prepare a complete estimate of emissions from this source, it is *good practice* to add a third term to the equation to account for decommissioning losses and chemical destruction, where data are available. Thus, the suggested equation is:

Equation 3.38

Emissions from Closed-cell Foam = [(Total HFCs and PFCs Used in Manufacturing New Closed-cell Foam in year t) • (first-year Loss Emission Factor)]

+ [(Original HFC or PFC Charge Blown into Closed-cell Foam Manufacturing between year t and year t – n) • (Annual Loss Emission Factor)]

+ [(Decommissioning Losses in year n) – (HFC or PFC Destroyed)]

Where:

n = Product lifetime of closed-cell foam

Decommissioning losses = the remaining chemical at the end of service life that occur when the losses equipment is scrapped

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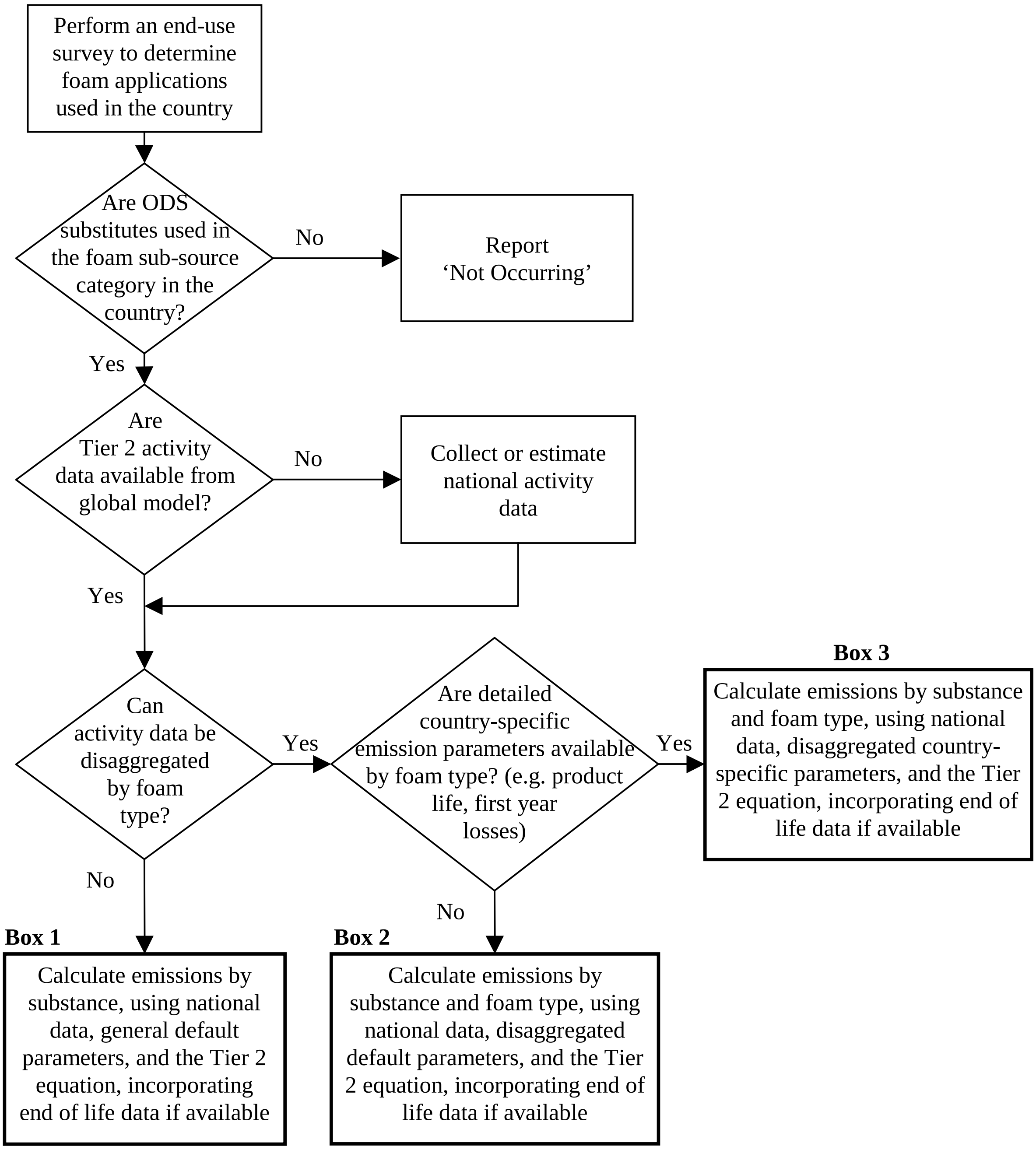
[50] For these applications, actual emissions of each chemical are equal to potential emissions.

This equation should be applied to each chemical and major foam application individually. Total CO_2-equivalent emissions are equal to the sum of CO_2-equivalent emissions of each combination of chemical type and foam application.

To implement this approach it is necessary to collect current and historical data on annual chemical sales to the foam industry for the period up to and including the average lifetime of closed-cell foam (e.g. the most recent twenty years). If it is not possible to collect data for potential losses upon decommissioning, it should be assumed that all chemical not emitted in manufacturing is emitted over the lifetime of the foam.

A modification of this approach is to use activity data provided by a global model that allocates accurately known production data to the different foam applications in various regions around the world. These data can then be used with the disaggregated emission factors provided in Table 3.17, Default Emission Factors for HFC/PFC from Closed-Cell Foam.

Figure 3.14 Decision Tree for Actual Emissions (Tier 2) from the Foam Sub-source Category



CHOICE OF EMISSION FACTORS

As in other sub-source categories, the first choice for emission factors is to develop and use peer-reviewed and well documented country-specific data based on field research. As noted previously, if no information is available for decommissioning losses, then the emission factors used for first-year and annual losses should account for all chemical consumption.[51]

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[51] It has also been noted that decommissioning may not necessarily involve total loss of blowing agent at that point, either because of a level of secondary use or because the item has been discarded intact (e.g. many refrigerators). These could be considered as some of the end-of-life management options available to nations, but are clearly less effective than proper destruction or recovery technologies. Future emission models should focus proper attention to end-of-life issues.

If country-specific data are not available, default assumptions can be used. Table 3.18, Default Emission Factors for HFC-134a Applications (Foam Sub-source Category) – (Derived from existing CFC/HFC information accumulated through national/international research), and Table 3.19, Default Emission Factors for HFC-245a/HFC-365mfc Applications (Foam Sub-source Category) – (Derived from existing CFC/HFC information accumulated through national/international research), present state-of-the-art *good practice* emission factors assumptions for the most important current closed-cell foam applications. Use of these factors will require data on chemical sales and the bank of chemical in equipment for these applications.

If only aggregated chemical sales data for closed-cell foam are available and information on specific foam types cannot be obtained, the general default emission factors listed in the *IPCC Guidelines* should be used.[52] These general default emission factors are shown in Table 3.17, Default Emission Factors for HFC/PFC from Closed-Cell Foam.

TABLE 3.17
DEFAULT EMISSION FACTORS FOR HFC/PFC FROM CLOSED-CELL FOAM

Emission Factor	**Default Values**
Product Lifetime	n = 20 years
First Year Losses	10% of the original HFC or PFC charge/year, although the value could drop to 5% if significant recycling takes place during manufacturing.
Annual Losses	4.5% of the original HFC or PFC charge/year

Source: Gamlen *et al.* (1986).

TABLE 3.18
DEFAULT EMISSION FACTORS FOR HFC-134A APPLICATIONS (FOAM SUB-SOURCE CATEGORY)
(DERIVED FROM EXISTING CFC/HFC INFORMATION ACCUMULATED THROUGH NATIONAL/INTERNATIONAL RESEARCH)

HFC-134a Applications	**Product Life in years**	**First Year Loss %**	**Annual Loss %**
Polyurethane – Integral Skin[a]	12-15	95	2.5
Polyurethane – Continuous Panel	50	10	0.5
Polyurethane – Discontinuous Panel	50	12.5	0.5
Polyurethane – Appliance	15-20	7.5	0.5
Polyurethane – Injected	15	12.5	0.5
One Component Foam (OCF) [a]	50	95	2.5
Extruded Polystyrene/ Polyethylene (XPS/PE) [a]	50	40	3

[a] HFC-152a Applications.

Source: Ashford (1999).

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[52] No emission factors are provided for open-cell foams because all emissions occur during the first year.

TABLE 3.19
DEFAULT EMISSION FACTORS FOR HFC-245A/HFC-365MFC APPLICATIONS (FOAM SUB-SOURCE CATEGORY) – (DERIVED FROM EXISTING CFC/HFC INFORMATION ACCUMULATED THROUGH NATIONAL/INTERNATIONAL RESEARCH)

HFC-245a/HFC-365mfc Applications	Product Life in years	First Year Loss %	Annual Loss %
Polyurethane – Continuous Panel	50	7.5	0.5
Polyurethane – Discontinuous Panel	50	10	0.5
Polyurethane – Appliance	15	4	0.25
Polyurethane – Injected	15	10	0.5
Polyurethane – Continuous Block	15	40	0.75
Polyurethane – Discontinuous Block	15	45	0.75
	50	10	1
Polyurethane – Continuous Laminate	25	10	1
Polyurethane – Spray	50	25	1.5
Phenolic – Discontinuous Block	15	45	0.75
Phenolic – Discontinuous Laminate	50	10	1

Source: Ashford (1999).

Use of these default emission factors will result in 90% of the initial charges being emitted over twenty years of annual use, after the initial 10% during the first year.

CHOICE OF ACTIVITY DATA

Two types of activity data are needed in order to prepare the emissions estimates: the amount of chemical used in foam manufacturing in a country, and the amount of chemical contained in foam used in the country. Data collection issues related to these two areas differ.

- ***Chemical Used in Foam Manufacture*:** The amount of bulk chemicals used in the foam blowing industry should include both domestically produced and imported HFCs and PFCs. Domestic chemical sales data to the foam industry should be available directly from chemical manufacturers. As with other ODS substitute sub-source categories, imported chemical data may be available from customs officials or chemical distributors.

For open-cell foam, all emissions will occur during manufacture. Thus, it is necessary to determine the share of chemical associated with the manufacture of open-celled foam. These data can be determined through an end-use survey, or approximated by reviewing similar end-use data gathered on CFCs and HCFCs.

- ***Chemical Emitted During the Lifetime of Closed-Cell Foam*:** Annual decommissioning losses associated with closed-cell foam should be calculated for all the foam in use in the country. This will require consideration of the import and export of products containing closed-cell foam which can be quite complicated.

Inventory agencies in countries that export closed-cell foam should subtract these volumes from their calculations of annual and decommissioning losses, since the emissions will occur in the importing country. Data on the chemical charge of exported closed-cell foam may be available from large manufacturers.

Inventory agencies in countries that import products containing closed-cell foam, in contrast, should include estimates of emissions from these imported products for completeness. Since import statistics for closed-cell foam products are extremely difficult to collect, inventory agencies in countries whose emissions occur only from imported closed-cell foam may need to use expert judgement in estimating this data (see Chapter 6, Quantifying Uncertainties in Practice, Section 6.2.5, Expert Judgement).

In the future, inventory agencies may be able to use international HFC/PFC production and consumption data sets to develop estimates of chemical contained in imported closed-cell foam. For example, the Alternative Fluorocarbon Environmental Assessment Study (AFEAS) statistics-gathering process compiled global activity data up until 1997 for HFC-134a in the foam sector.[53] Although the global data are relatively well understood, regional breakdowns are not presently available.

COMPLETENESS

Fifteen foam applications and four potential chemicals used as blowing agents (HFC-134a, HFC-152a, HFC-245fa and HFC-365mfc) have been identified in the foam sub-source category. For completeness, inventory agencies should determine whether the blowing agents are used in each application, which suggests 60 theoretically possible combinations (see Table 3.20, Use of ODS Substitutes in the Foam Blowing Industry). In practice, this list reduces to 32 realistic potential chemical/application combinations, although there are some potential regional variations. It should also be noted that, at this stage, the method does not address the potential use of blends and, in reality, it would be difficult to assign different emission factors to such systems. The main problem with the potential use of blends will be one of activity monitoring.

TABLE 3.20
USE OF ODS SUBSTITUTES IN THE FOAM BLOWING INDUSTRY
(FOAM PRODUCT EMISSIONS BY GAS – ODS REPLACEMENTS)

Sub-sectors	**HFC Foam Blowing Agent Alternates**[b]			
	HFC-134a	**HFC-152a**	**HFC-245fa**	**HFC-365mfc**
PU[a] Flexible Foam	X	X	X	X
PU Flexible Molded Foam	X	X	X	X
PU Integral Skin Foam	O	O	X	X
PU Continuous Panel	O	X	O	O
PU Discontinuous Panel	O	X	O	O
PU Appliance Foam	O	X	O	O
PU Injected Foam	O	X	O	O
PU Continuous Block	X	X	O	O
PU Discontinuous Block	X	X	O	O
PU Continuous Laminate	X	X	O	O
PU Spray Foam	X	X	O	O
PU One Component Foam	O	O	X	X
Extruded Polystyrene/Polyethylene	O	O	X	X
Phenolic Block	X	X	O	O
Phenolic Laminate	X	X	O	O

[a] PU = Polyurethane.
[b] X – no anticipated use, O – current or anticipated use.

DEVELOPING A CONSISTENT TIME SERIES

An inventory agency should maintain a consistent method in assessing its emissions over the time period. If, for example, no system is established to monitor actual decommissioning at the outset of the inventory process, it will be very difficult to obtain data retrospectively if a change from 'default' to 'actual' data is considered. This decision should therefore be the subject of careful consideration at the outset of the reporting process. Any recalculation of estimates should be done according to the guidance provided in Chapter 7.

UNCERTAINTY ASSESSMENT

Current sales data indicate that the global estimates are accurate to within 10%, regional estimates are in the 30-40% range, and the uncertainty of country specific top-down information may be more than 50% (McCulloch,

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[53] HFC-134a is the most commonly used HFC. AFEAS data can found at http://www.afeas.org.

1986). The application of emission factors will add to the uncertainties, particularly if only default emissions can be used, although it should be noted that the calculation of the total emissions for a year will be only partially dependent on the accuracy of assumptions for new consumption in that year. The remainder of the emissions will arise from installed foam and from those decommissioned in that year. Since decommissioning will be the trigger for the majority of emissions in many cases, the product life assumptions may introduce the greatest degree of uncertainty in the default emissions calculations. It is therefore very important that inventory agencies keep records of their estimates of HFC containing products and develop some mechanism for monitoring actual decommissioning if possible. These records may help ensure that the summed emissions do not exceed total inputs over time.

3.7.3.2 Reporting and documentation

Emissions factors should be reported, along with documentation for the development of country-specific data. Chemical sales to the foam blowing industry should be reported in a manner that preserves confidential business information. Most confidentiality issues arising from any data collection process relate to the most highly concentrated activities. To deal with this, emissions from foam could be reported as a single number, provided that the development of the number could be reviewed under suitable terms of confidentiality. Of course, a declaration of consolidated emissions from manufacture (first year), use (product life) and decommissioning (end-of-life) will always be preferable to allow continued focus on improvements being made in each of these areas. If, in the future, inventory agencies use the global and regional data sets, they should report the results of how they allocated emissions to the country level.

3.7.3.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

One of the main concerns will be to ensure that the preservation of the integrity of regional and global data will be maintained by the summation of individual country estimates and a major part of the QA/QC review process will need to concern itself with this cross reference.

3.7.4 Stationary refrigeration sub-source category

3.7.4.1 Methodological issues

HFCs and PFCs are used as replacements for CFCs and HCFCs in refrigeration and stationary air conditioning equipment. Examples of refrigeration equipment include household refrigerators, retail food refrigeration, commercial and residential air conditioning, and cold storage warehouses. For the time being this sub-source category also includes transport refrigeration, other than that covered in the Mobile Air-conditioning sub-source category (see Section 3.7.5, Mobile Air-conditioning Sub-source Category).[54]

CHOICE OF METHOD

The Tier 2 approach in the *IPCC Guidelines* is based on calculating emissions from assembly, operation, and disposal of stationary refrigeration equipment. The general equation is shown below:

EQUATION 3.39

$$\text{Total Emissions} = \text{Assembly Emissions} + \text{Operation Emissions} + \text{Disposal Emissions}$$

- ***Assembly emissions*** include the emissions associated with product manufacturing, even if the products are eventually exported.
- ***Operation emissions*** include annual leakage from equipment stock in use as well as servicing emissions. This calculation should include all equipment units in the country, regardless of where they were manufactured.
- ***Disposal emissions*** include the amount of refrigerant released from scrapped systems. As with operation emissions, they should include all equipment units in the country where they were scrapped, regardless of where they were manufactured.

Good practice is to implement a top-down Tier 2 approach, using annual sales of refrigerant. The alternative approach, using bottom-up equipment data and multiple emission factors, is much more data intensive and is unlikely to improve accuracy, but it is still *good practice* under certain national circumstances. The decision tree in Figure 3.15 Decision Tree for Actual Emissions (Tier 2) from the Refrigeration Sub-source Category, describes *good practice* methods in estimating emissions. Table 3.22, Best Estimates (expert judgement) for Charge, Lifetime and Emission Factors for Stationary Refrigeration Equipment, describes the emission factors for the top-down and bottom-up approaches and the improvements to the default data in the Tier 2 method.

Top-down approach

For the top-down approach, the three emission stages are combined into the following simplified equation:

EQUATION 3.40

$$\begin{aligned}\text{Emissions} = {} & (\text{Annual Sales of New Refrigerant}) - (\text{Total Charge of New Equipment}) \\ & + (\text{Original Total Charge of Retiring Equipment}) - (\text{Amount of Intentional Destruction})\end{aligned}$$

Annual Sales of New Refrigerant is the amount of a chemical introduced into the refrigeration sector in a particular country in a given year. It includes all the chemical used to fill or refill equipment, whether the chemical is charged into equipment at the factory, charged into equipment after installation, or used to recharge equipment at servicing. It does not include recycled chemical.

Total Charge of New Equipment is the sum of the full charges of all the new equipment that is sold in the country in a given year. It includes both the chemical required to fill equipment in the factory and the chemical required to fill the equipment after installation. It does not include charging emissions or chemical used to recharge equipment at servicing.

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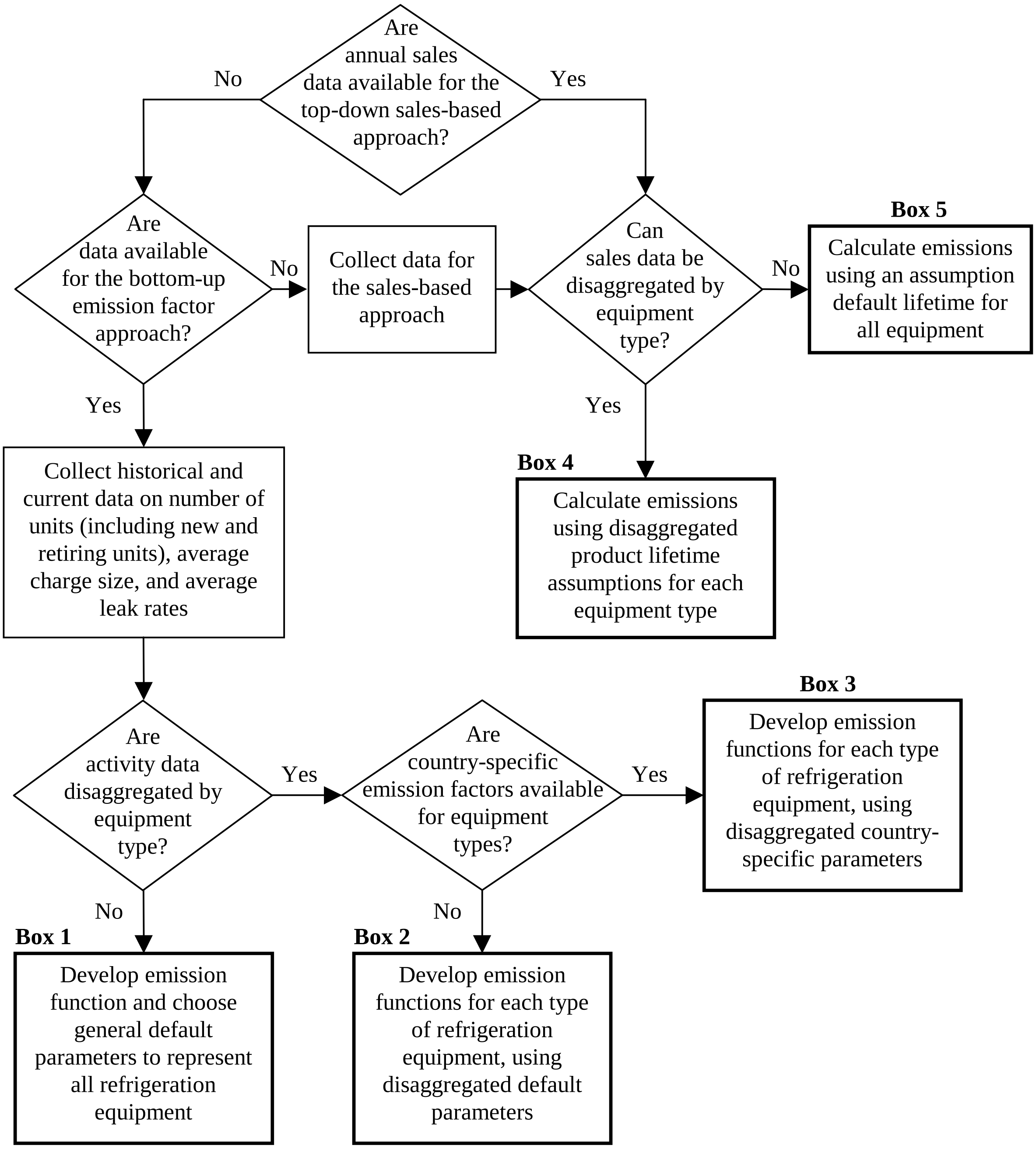
[54] Particularly self-contained systems; engine driven system should be covered as mobile air conditioning (see Section 3.7.5, Mobile Air-conditioning Sub-source Category).

Figure 3.15 Decision Tree for Actual Emissions (Tier 2) from the Refrigeration Sub-source Category



Original Total Charge of Retiring Equipment is the sum of the original full charges of all the equipment that are retired in the country in a given year. It includes both the chemical that was originally required to fill equipment in the factory and the chemical that was originally required to fill the equipment after installation. It does not include charging emissions or chemical used to recharge equipment at servicing.

In each country there is a stock of existing refrigeration equipment that contains an existing stock of refrigerant chemical (bank). Therefore, annual sales of new chemical refrigerant must be used for one of two purposes:[55]

- To increase the size of the existing chemical stock (bank) in use; or
- To replace that fraction of last year's stock of chemical that was emitted to the atmosphere (through, for example, leaks and disposal).

The difference between the total quantity of gas sold and the quantity of that gas used to increase the size of the chemical stock equals the amount of chemical emitted to the atmosphere. The increase in the size of the chemical stock is equal to the difference between the total charges of the new and retiring equipment.

By using data on current and historical sales of gas, rather than emission factors referenced from literature, the equation reflects assembly, operation, and disposal emissions at the time and place where they occur. Default emission factors are likely to be inaccurate because emissions rates may vary considerably from country to country and even within a single country.

This equation can be applied either to individual types of equipment, or more generally to all air conditioning and refrigeration equipment in a country, depending on the level of disaggregation of available data. If disaggregated data are available, emissions estimates developed for each type of equipment and chemical are summed to determine total emissions for sector.

Bottom-up approach

Implementing the bottom-up Tier 2 approach requires an estimation of the amount of refrigerant in the stock of equipment, and emission factors to represent equipment various types of leakage (i.e. assembly, operation, and disposal emissions):

For assembly emissions, the following equation should be used:

EQUATION 3.41

$$\text{Assembly Emissions} = (\text{Total HFC and PFC Charged in year t}) \bullet (k / 100)$$

Where:

k = Emission factor that represents the percentage of initial charge that is released during assembly

Operation emissions are calculated from the total bank of HFCs/PFCs contained in equipment presently in use. The following equation should be used:

EQUATION 3.42

$$\text{Operation Emissions} = (\text{Amount of HFC and PFC Stock in year t}) \bullet (x / 100)$$

Where:

x = Annual leak rate as a percentage of total charge. Since different types of refrigeration equipment will leak at different rates, *good practice* is to disaggregate data into homogeneous classes (i.e. by age or size) and develop values of x specific to different types of equipment

To calculate disposal emissions, it is necessary to know the average lifetime (n) of equipment and the initial charge n years ago. Disposal emissions can then be calculated according to the following equation:

EQUATION 3.43

$$\text{Disposal Emissions} = (\text{HFC and PFC Charged in year t} - n) \bullet (y / 100) \bullet (1 - z / 100) - (\text{Amount of Intentional Destruction})$$

Where:

y = Percentage of the initial charge remaining in the equipment at the time of disposal

z = Recovery efficiency at the time of disposal. If any chemical is recycled during disposal, the percentage should be subtracted from the total. If there is no recycling, this term will be zero

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[55] Industry also requires new chemicals for stockpiles. A term can be added to the general equation to account for this use; this term is not included here for simplicity.

CHOICE OF EMISSION FACTORS

Top-down approach (sales-based)

As this approach is based on chemical sales and not equipment leak rates, it does not require the use of emission factors.

Bottom-up approach

Good practice for choosing bottom-up emission factors is to use country-specific data, based on information provided by equipment manufacturers, service providers, and disposal companies. When national data are unavailable, inventory agencies should use the default emission factors shown in Table 3.22, Best Estimates (expert judgement) for Charge, Lifetime and Emission Factors for Stationary Refrigeration Equipment , which summarises best estimates of equipment charge, lifetime, and emission factors. These default values reflect the current state of knowledge about the industry, and are provided as ranges rather than point estimates. Inventory agencies should choose from the range according to country-specific conditions, and document the reasons for their choices. If bottom-up data cannot be broken down into the equipment classes as in Table 3.21, Good Practice Documentation for Stationary Refrigeration , it is *good practice* to use expert judgement to estimate the relative share of each type of equipment, and choose default emission factors appropriate to the most common types of equipment (see Chapter 6, Quantifying Uncertainties in Practice, Section 6.2.5, Expert Judgement).

CHOICE OF ACTIVITY DATA

Top-down approach (sales-based)

Inventory agencies in countries that manufacture refrigerant chemicals should estimate *Annual Sales of New Refrigerant* using information provided by chemical manufacturers. Data on imported chemical should be collected from customs statistics, importers, or distributors. (See Box 3.4 for a discussion of how to treat imports and exports in estimating *Annual Sales* and the other quantities in the equation.)

Total Charge of New Equipment can be estimated using either:

- Information from equipment manufacturers/importers on the total charge of the equipment they manufacture or import; or
- Information from chemical manufacturers/importers on their sales to equipment manufacturers.

The first data source may be preferable to the second because some new equipment may not be charged by the equipment manufacturers, while some of the refrigerant sold to equipment manufacturers may not be used to fill new equipment (e.g. because it is used to service existing equipment).

Original Total Charge of Retiring Equipment can be estimated using the same sources as are used for *Total Charge of New Equipment*. In this case, however, the data are historical, coming from the year in which this year's retiring equipment was built. That year is determined by subtracting the lifetime of the equipment from the current year. Information on equipment lifetimes can be gathered from equipment manufacturers and users. Default values for the lifetimes of seven different types of equipment are provided in Table 3.22, Best Estimates (expert judgement) for Charge, Lifetime and Emission Factors for Stationary Refrigeration Equipment. The default product lifetime value for air-conditioning and refrigeration equipment as a whole, for use when data for specific types of equipment are not available, is 10-15 years.

COMPLETENESS

Completeness for the top-down method is achievable if data for new refrigerant, and refrigerant in equipment being retired in the current year are available. For the bottom-up method, completeness depends on a thorough accounting of the existing equipment stock that may involve tracking large amounts of data.

DEVELOPING A CONSISTENT TIME SERIES

Emissions from stationary refrigeration should be calculated using the same method and data sources for every year in the time series. Where consistent data are unavailable for the more rigorous method for any years in the time series, these gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

BOX 3.4
ACCOUNTING FOR IMPORTS AND EXPORTS OF REFRIGERANT AND EQUIPMENT

In estimating *Annual Sales of New Refrigerant*, *Total Charge of New Equipment*, and *Original Total Charge of Retiring Equipment*, inventory agencies should account for imports and exports of both chemicals and equipment. This will ensure that they capture the actual domestic consumption of chemicals and equipment. For example, if a country imports a significant share of the HFC-134a that it uses, the imported quantity should be counted as part of **Annual Sales**. Alternatively, if a country charges and then exports a significant number of household refrigerators, the total charge of the exported refrigerators should be subtracted from the total charge of the household refrigerators manufactured in the country to obtain Total Charge of New Equipment.

GENERAL APPROACH: In general, the quantity Annual Sales should be estimated using the following formula:

Annual Sales =	**Domestically Manufactured Chemical**	**+ Imported Bulk Chemical**	**– Exported Bulk Chemical**	**+ Chemical Contained in Factory-Charged Imported Equipment**	**– Chemical Contained in Factory-Charged Exported Equipment**

All quantities should come from the year for which emissions are being estimated. Similarly, the quantity of Total Charge of New Equipment should be estimated using the following:

Total Charge of New Equipment=	**Chemical to Charge Domestically Manufactured Equipment**	**+ Chemical to Charge Imported Equipment that is not Factory-Charged**	**+ Chemical Contained in Factory-Charged Imported Equipment**	**– Chemical Contained in Factory-Charged Exported Equipment**

Original Total Charge of Retiring Equipment should be estimated the same way as *Total Charge of New Equipment,* except all quantities should come from the year of manufacture or import of the retiring equipment.

SIMPLIFIED APPROACH: In estimating Annual Sales and Total Charge of New Equipment, it is possible to ignore the quantities of chemical imported or exported inside of factory-charged equipment because these quantities cancel out in the calculation of emissions. However, inventory agencies that use the simplified calculation should ensure that: (1) they treat imports and exports of factory-charged equipment consistently in estimating both Annual Sales and Total Charge New of Equipment; and (2) they continue to account for imports and exports of factory-charged equipment in estimating Original Total Charge of Retiring Equipment. As new equipment will eventually become retiring equipment, countries may wish to track imports and exports of factory-charged equipment even if this information is not strictly necessary to develop the current year's estimate.

The simplified formula for **Annual Sales** is:

Annual Sales =	**Domestically Manufactured Chemicals**	**+ Imported Bulk Chemicals**	**– Exported Bulk Chemicals**

The simplified formula for **Total Charge of New Equipment** is:

Total Charge of New Equipment =	**Chemicals to Charge Domestically Manufactured Equipment**	**+ Chemicals to Charge Imported Equipment that is not factory-charged**

The full formula, accounting for imports and exports of pre-charged equipment, must be used to calculate *Original Total Charge of Retiring Equipment***.**

UNCERTAINTY ASSESSMENT

Table 3.22, Best Estimates (expert judgement) for Charge, Lifetime and Emission Factors for Stationary Refrigeration Equipment, presents emission factor ranges that highlight the uncertainty associated with this sector. Generally, bottom-up actual methods that rely on emission factors have more uncertainty than top-down methods that use chemical sales data. Inventory agencies should seek industrial advice on uncertainties, using the approaches to obtaining expert judgements outlined in Chapter 6, Quantifying Uncertainties in Practice.

3.7.4.2 Reporting and documentation

The supporting information necessary to ensure transparency in reported emissions estimates is shown in Table 3.21, Good Practice Documentation for Stationary Refrigeration.

TABLE 3.21
GOOD PRACTICE DOCUMENTATION FOR STATIONARY REFRIGERATION

Good practice **Reporting Information by Method**	**Tier 2 (Top-Down)**	**Tier 2 (Bottom-Up)**
Total annual sales of new refrigerant	X	
Total charge of new equipment	X	X
Original total charge of retiring equipment	X	X
Total charge of entire equipment stock		X
Lifetime of equipment	X	X
Documentation for lifetime, if country-specific	X	X
Emission/recovery factors		X
Documentation for factors, if country-specific		X

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts, Emissions of Substitutes for Ozone Depleting Substances).

3.7.4.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1, General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, Quality Assurance and Quality Control, specific procedures of relevance to this sub-source category are outlined as follows:

- Implementing both the bottom-up approach and the simplified top-down approach will enable a cross-check of the final emission estimate.
- It is particularly important to check the accuracy of emission factors used in the bottom-up method with top-down data, since emission factors are likely to have the highest associated uncertainty.

This technique will also minimise the possibility that certain end-uses will not be accounted for.

This is similar to the ‘Reference Approach’ calculation in the Energy Sector. The combination uses the simple top-down approach as a cross-check of a more detailed technology and application-based method.

TABLE 3.22
BEST ESTIMATES (EXPERT JUDGEMENT) FOR CHARGE, LIFETIME AND EMISSION FACTORS FOR STATIONARY REFRIGERATION EQUIPMENT

Application	**Charge (kg)**	**Lifetimes (years)**	**Emission Factors (% of initial charge/year)**		
Factor in Equation	**(Ei_{charge})**	**(n)**	**(k)**	**(x)**	**(z)**
			Initial Emission	**Lifetime Emission**	**End-of-Life Emission (recovery efficiency)**
Domestic Refrigeration	$0.05 \leq c \leq 0.5$	$12 \leq t \leq 15$	$0.2 \leq e \leq 1$	$0.1 \leq e \leq 0.5$	70% of remainder
Stand-alone Commercial Applications	$0.2 \leq c \leq 6$	$8 \leq t \leq 12$	$0.5 \leq e \leq 3$	$1 \leq e \leq 10$	$70 \leq r \leq 80\%$ of remainder
Medium & Large Commercial Refrigeration	$50 \leq c \leq 2000$	$7 \leq t \leq 10$	$0.5 \leq e \leq 3$	$10 \leq e \leq 30$	$80 \leq r \leq 90\%$ of remainder
Transport Refrigeration	$3 \leq c \leq 8$	$6 \leq t \leq 9$	$0.2 \leq e \leq 1$	$15 \leq e \leq 50$	$70 \leq r \leq 80\%$ of remainder
Industrial Refrigeration including Food Processing and Cold Storage	$10 \leq c \leq 10K$	$10 \leq t \leq 20$	$0.5 \leq e \leq 3$	$7 \leq e \leq 25$	$80 \leq r \leq 90\%$ of remainder
Chillers	$10 \leq c \leq 2000$	$10 \leq t \leq 30$	$0.2 \leq e \leq 1$	$2 \leq e \leq 15$	$80 \leq r \leq 95\%$ of remainder
Residential and Commercial A/C, including Heat Pumps	$0.5 \leq c \leq 100$	$10 \leq t \leq 15$	$0.2 \leq e \leq 1$	$1 \leq e \leq 5$	$70 \leq r \leq 80\%$ of remainder

Note: Distribution Losses = 2 to 10% of annual sales of refrigerant (heel left in the tanks from and losses during transfer (ICF 1998). Analysis of Refrigerant Emissions Resulting from Improper Disposal of 30-lb Cylinders. Prepared by ICF Incorporated, Washington, DC. June 2, 1998).
It should be noted that each country will use its own national data when preparing its national greenhouse gas inventory.

Source: Clodic (1999).

3.7.5 Mobile air-conditioning sub-source category

3.7.5.1 Methodological issues

The automotive industry has used HFC-134a for mobile air-conditioning (MAC) in new vehicles since 1995. Mobile air-conditioning provides cooling for passengers in cars, trucks, trains, trams and buses. In addition, some trucks cool their cargo area with an automotive system (compressor mounted to the engine) using HFC-134a.

In the past, the procedure for mobile air-conditioning systems has been to release the refrigerant to the atmosphere during service. The requirement for new refrigerant can be greatly reduced by implementing a refrigerant recovery/recycling program when servicing MACs.

CHOICE OF METHOD

The choice of *good practice* methods depends on national circumstances (see decision tree in Figure 3.16, Decision Tree for Actual Emissions (Tier 2) from the Mobile Air-conditioning Sub-source Category). The general Tier 2 approach for estimating emissions from all types of refrigeration and air conditioning units is outlined in the *IPCC Guidelines*, Vol. 3, Section 2.17.4.2, Estimation of Emissions of HFCs and PFCs from Use in Refrigeration and Air Conditioning Equipment, and also in the *good practice* description for stationary refrigeration. The general equation for Tier 2 is as follows:[56]

Equation 3.44

$$\text{Annual Emissions of HFC-134a} = \text{'First-Fill' Emissions} + \text{Operation Emissions} + \text{Disposal Emissions} - \text{Intentional Destruction}$$

First-Fill emissions include emissions of refrigerant released during the filling of all MAC units (potential future emissions) at the time of assembly by a vehicle manufacturer or the aftermarket MAC system installer in a country, even if the vehicles are eventually exported. Operation emissions include the annual leakage from all MACs in use in a country, including servicing emissions, regardless of where they were manufactured. Disposal emissions include the amount of refrigerant released from scrapped MAC systems.

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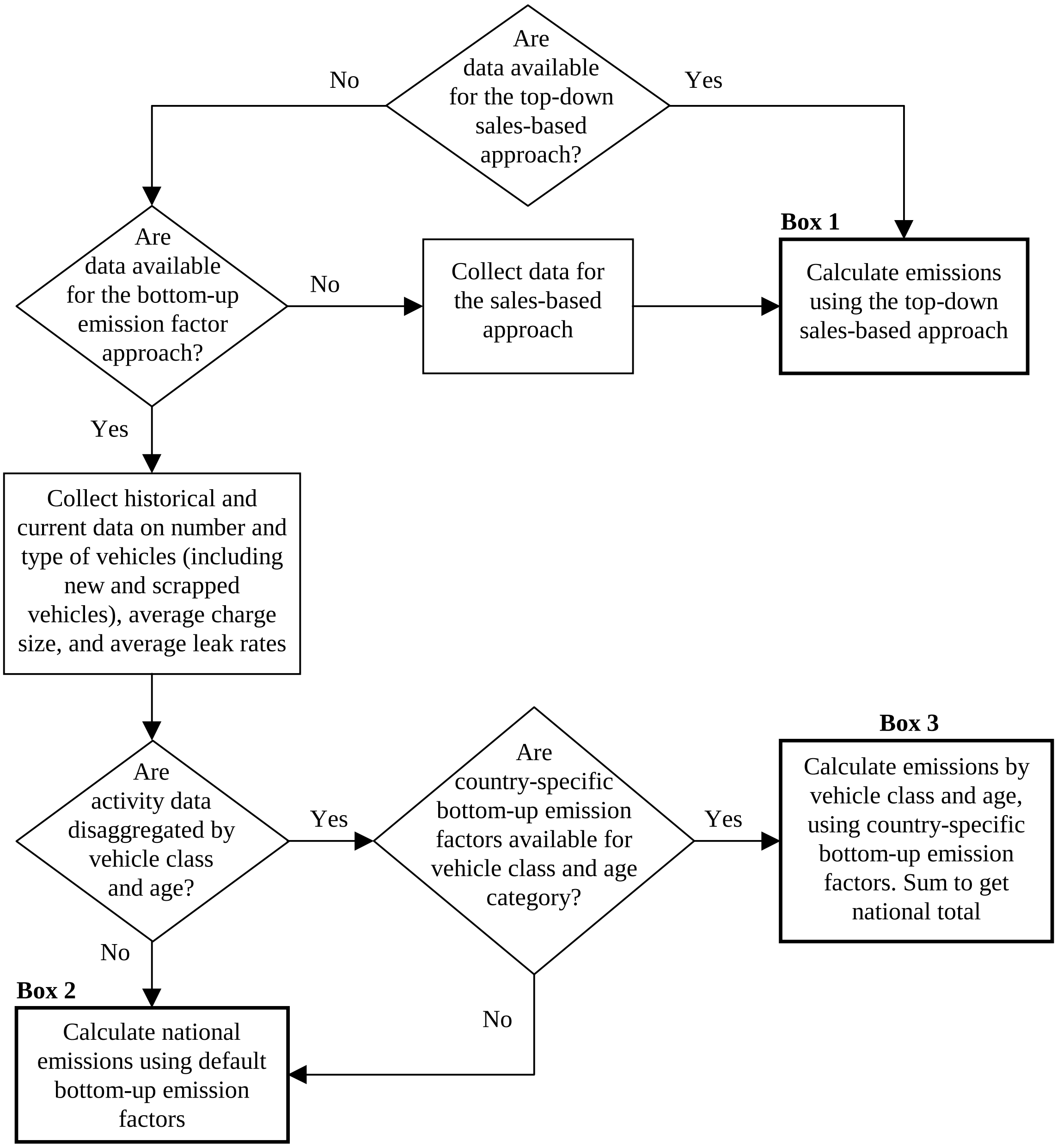
[56] For the purpose of this sub-source category, 'first-fill' emissions are equivalent to the term 'assembly' emissions as used in the stationary refrigeration sub-source category.

Figure 3.16 Decision Tree for Actual Emissions (Tier 2) from the Mobile Air-conditioning Sub-source Category



Top-down approach

The top-down Tier 2 approach is the most accurate method because it is less data intensive, uses more robust and reliable data, and requires fewer assumptions. The top-down approach estimates emissions by using chemical sales data to calculate the share of total HFC-134a sales used by the mobile air conditioning industry to replace refrigerant leaked to the atmosphere (e.g. car manufacturers, aftermarket installers and service companies). This value, when added to 'first-fill' and disposal emissions, is equal to total annual emissions. The top-down equation is presented at the end of this section in its complete form. Below, the equation is broken out into its constituent parts.

First-fill emissions are calculated by using an emission factor (EF) to represent the fraction of HFC-134a (e.g. 0.005) that escapes as fugitive emissions (assembly process loss) during equipment first fill:

EQUATION 3.45

$$\text{First-Fill Emissions} = (\text{EF}) \bullet (\text{Annual Virgin HFC-134a for First-Fill of New MAC Units})$$

Any new HFC-134a that did not escape as fugitives during first-fill, and did not go into new MAC units, must therefore be used for servicing existing units that leaked during operation in the previous year. Thus, operation emissions can be calculated according to following equation:

EQUATION 3.46

$$\begin{aligned}\text{Operation Emissions} = {} & (\text{Total Annual Virgin HFC-134a Sold to the MACs Industry}) \\ & - (\text{Total Annual Virgin HFC-134a for First-Fill of New MAC Units})\end{aligned}$$

Recycled and recovered refrigerant is implicitly accounted for in this equation because it reduces the amount of total virgin material needed in the country or region.[57]

Emissions occurring after the final service of MAC units are equal to the total amount of HFC-134a present in vehicles scrapped during the year, after subtracting any destruction. As a boundary condition, this equation would continue to estimate (vintage) emissions into the future even if no new HFC-134a were introduced into the MACs sector:

EQUATION 3.47

$$\begin{aligned}\text{Disposal Emissions} = {} & (\text{Annual Scrap Rate of Vehicles with MACs Using HFC-134a}) \\ & \bullet (\text{Number of Vehicles with MACs Using HFC-134a}) \\ & \bullet (\text{Average HFC-134a Charge/Vehicle}) - \text{Destruction}\end{aligned}$$

As noted previously, recovered and recycled HFC-134a captured during service or salvage should not be included in this equation, because it reduced the amount of virgin (new) HFC-134a needed in the country, and thus reduced emissions implicitly. Subtracting recovered and recycled HFC-134a at this point would lead to an underestimation of emissions.

Bottom-up approach

The Tier 2 method can also be implemented from the bottom-up, by estimating number of MAC units in the country, the average charge per vehicle, and applying emission factors that represent leak rates. The first-fill equation is similar to the top-down approach:

EQUATION 3.48

$$\text{First-Fill Emissions} = (\text{Total HFC-134a Charged in year t}) \bullet (k / 100)$$

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[57] Countries or regions that perform recycling during service and recovery at vehicle scrap would benefit significantly from reduced total emissions. Recycling at service and recovery at scrap can reduce total emissions by an estimated 60%.

The variable k is comparable to the variable EF used in the top-down approach because it represents the percentage of initial charge that is released during assembly.

EQUATION 3.49

$$\text{Operation Emissions} = (\text{Amount of HFC-134a Stock in year t}) \bullet (x / 100)$$

The emission factor x represents the annual emissions rate as a percentage of total charge. This equation should be applied for different types of MACs, because leak rates depend on the age and type of vehicles. Older MAC units are likely to have higher leak rates than new units. The total HFC-134a in the vehicle bank should include all systems in operation in the country. A recovery/recycling program for vehicle service and scrap will substantially reduce the requirement for new refrigerant.

To calculate disposal emissions, it is necessary to know the average lifetime (n) of vehicles, and the initial charge n years ago. Disposal emissions can then be calculated according to the following equation:

EQUATION 3.50

$$\text{Disposal emissions} = (\text{HFC-134a Charged in year } t - n) \bullet (y / 100) \bullet (1 - z / 100)$$

The variable y is the percentage of the initial charge remaining in MAC units at the time of disposal, and z equals the recovery efficiency at the time of disposal. If any refrigerant is recycled during disposal, the percentage should be subtracted from the total. If there is no recycling, z will be zero.

CHOICE OF EMISSION FACTORS

Top-down approach

The top-down approach only requires an emission factor for first-fill emissions. *Good practice* is to apply a factor of 0.5% (0.005)) if measured data are unavailable. Use of alternate assumptions should be fully documented.

Bottom-up approach

Inventory agencies using the bottom-up approach should make every effort to develop current country-specific values for the parameters x, n, k, y and z. If country-specific values are used, they must be fully documented. If country-specific values are unavailable, Table 3.23, Default Emission Parameters for ODS Substitutes from the MAC Sub-source Category (Bottom-up Approach), lists default emission parameters from the *IPCC Guidelines*, and updates for some parameters based on recent industry experience.

TABLE 3.23
DEFAULT EMISSION PARAMETERS FOR ODS SUBSTITUTES FROM THE MAC SUB-SOURCE CATEGORY (BOTTOM-UP APPROACH)

Bottom-up Emission Parameters	IPCC Default Values	Updated Default Values
Average vehicle lifetime (n)	12 years	12 years
MAC system emission rate (x)	10-30%	10-20%
First-Fill emission rate (k)	4-5%	0.5%
Typical remaining charge (y)	75%	40%
Fraction Recovered [a] (z)	0%	0%

[a] The fraction recovered by a recovery/recycling program is a function of the efficiency of the recovery equipment, the skill of the technician (amount of potential HFC-134a recovered/recycled) and the program effectiveness (fraction of service operations adopting the program).

Source: Baker (1999).

The MAC system emissions rate (x) is highly dependent on the presence of recovery and recycling programs. If a country has such a program, the low end of the range (i.e. 10%) is appropriate. Without a program, the value may be closer to 20%. The choice of system emission rate is tied to the choice of the fraction recovered (z). If a country has a recovery and recycling program, it is likely to reduce emissions both during service and at the end of the vehicle air-conditioning system lifetime. Consequently, the inventory agency in this country should use a recycling rate value greater than zero for z. Similarly, an inventory agency in a country without a recovery/recycling program should choose a higher value for x and a value of 0% for z.

Verification of emissions

The 'Top-Down' and 'Bottom-Up' results should agree within 10%.

CHOICE OF ACTIVITY DATA

Top-down approach

Under the top-down approach, activity data include the amount of HFC-134a sold to the MAC industry, the amount used for first-fill, the variables needed to determine the amount of HFC-134a in scrapped vehicles, and the amount of HFC-134a destroyed (if any). Data collection issues related to each term are discussed below.

- ***Total virgin HFC-134a*** includes only newly-produced refrigerant sold to MAC end-users. End-users include automobile manufacturers, aftermarket system installers, and repair shops that charge systems with refrigerant prior to sale. HFC-134a present in a refrigerant distributor's inventory, and refrigerant not sold for use in the mobile air-conditioning systems should not be included in the current year's estimate. If there is a large number of end-users, inventory agencies should obtain sales data directly from chemical manufacturers and refrigerant distributors. Data on imported virgin chemical should be available from customs officials, or importers and distributors.

- ***Total first fill HFC-134a*** is the total amount of HFC-134a purchased and used to charge new mobile air-conditioning systems by vehicle manufacturers (OEMs) or aftermarket MAC system installers. This includes losses during the charging process (First-Fill Emissions). In countries with domestic automobile industries, automobile manufacturers should be able to supply this data. Additional data should be available from installers of aftermarket air conditioning units.[58]

- ***Disposal emissions*:** If the actual number of scrapped vehicles containing HFC-134a is unknown, it should be estimated on the basis of the *Vehicle Scrap Rate* that is the rate at which vehicles are taken out of service in the country or region. If possible, scrap rates should be disaggregated by model year, and the average scrap rate for the model years in which MACs were charged with HFC-134a should be applied. If the vehicle scrap rate cannot be obtained from vehicle registration statistics, the 8% can be used as a default value of the total fleet. The total number of registered vehicles in the country should be obtained from official government statistics. The share of the total fleet equipped with MACs can be obtained from vehicle manufacturers and importers. The penetration of HFC-134a into the MACs market should be estimated on the basis of industry expert judgement.

- ***The average HFC-134a charge*** is the weighted average of refrigerant charge in vehicles in the country. The default value in the *IPCC Guidelines* is 0.8 kg per vehicle.

- ***HFC-134a destruction*** is not widely practised at the present time. However, if an inventory agency has data on this practice, it should be included in the equation and documented to ensure that emissions are not overestimated.

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[58] When new automobiles are shipped, the refrigerant is considered to be in a container, (i.e. the mobile A/C system), and does not produce emissions.

Default parameters are shown below, in Table 3.24, Default IPCC Emission Parameters for ODS Substitutes from the MAC Sub-source Category (Top-down Approach):

TABLE 3.24
DEFAULT IPCC EMISSION PARAMETERS FOR ODS SUBSTITUTES FROM THE MAC SUB-SOURCE CATEGORY (TOP-DOWN APPROACH)

Top-down Emissions Parameters	Default Values
Average HFC-134a Charge	0.80 kg per vehicle [a]
Vehicle Scrap Rate	8%
Refrigerant released during new vehicle 'First Fill'	EF = 0.5% of average system charge

[a] This applies to passenger cars. A value of 1.2 kg/vehicle should be used for light trucks (Atkinson, 1999).

Source: Atkinson and Baker (1999).

Bottom-up approach

The bottom-up approach requires data on the amount of HFC-134a charged per year, the stock of HFC-134a in all MACs each year, and the amount remaining at the end of the MACs lifetime, as follows:

- The ***total HFC-134a*** used for first-filling of new MAC units is the same value needed for the top-down approach, and can be obtained from vehicle manufacturers, and aftermarket MAC installers.
- The ***stock of HFC-134a*** in operating vehicles during the year is equal to the number of vehicles in the total fleet using HFC-134a multiplied by the average charge per vehicle. This information should be available from annual data supplied by automobile manufacturers for the last n years. The default value of 0.8 kg/vehicle for the top-down approach can be used for the bottom-up approach as well, if fleet-specific data are not available.
- The ***amount of HFC-134a*** that was *originally* charged into MAC units n years ago should include units produced and charged domestically, as well as imported units. As with the total charge, determining original charges requires historical data on first-fill. Given that HFCs have only been used extensively in MACs in recent years, it is not necessary to go back more than a few years at this time to obtain the required data.

COMPLETENESS

For the top-down approach, it is not necessary to account for imported automobiles or imported air conditioning units because they are essentially 'containers'. Emissions from first-fill are accounted for in the country of manufacture. Once imported, however, emissions from imported vehicles are accounted for by the importing country based on the refrigerant used to service them, and by their 'post-service emissions' estimated from total vehicle registrations (that include imports). Similarly, it is not necessary to report exports as a separate class of systems because they are accounted for in the equation. Only processing emissions from first filling (0.5% of system charge) are charged to the country or region of manufacture in the equation, and all future emissions are accounted for by the importing country or region.

For the bottom-up approach, completeness will depend on the coverage of automobile activity data, particularly import data and data on after-market MAC units in operation.

DEVELOPING A CONSISTENT TIME SERIES

Emissions from mobile air-conditioning should be calculated using the same method and data sources for every year in the time series. Where consistent data are unavailable for the same method for any years in the time series, these gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

UNCERTAINTY ASSESSMENT

Uncertainty in the bottom-up approach will be considerably higher than that of the top-down approach because there are no internal checks to ensure that the accounting is complete. The top-down method provides an upper-bound, and thus the likelihood is low that the true value will exceed the top-down estimate. Inventory agencies should seek industrial advice on uncertainties, using the approaches to obtaining expert judgements outlined in Chapter 6, Quantifying Uncertainties in Practice.

3.7.5.2 Reporting and documentation

The background data in Table 3.25, Good Practice Documentation for Mobile Air-conditioning, should be collected and reported:

For the bottom-up method, it is important the inventory agencies report on the method of accounting for recovery of HFC-134a during service (i.e. choice of value x). The linkage with the value for fraction recovered (z) should be clearly documented.

3.7.5.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

TABLE 3.25
GOOD PRACTICE DOCUMENTATION FOR MOBILE AIR-CONDITIONING

Data Source	**Data to be Reported**	**Top-down**	**Bottom-up**	**Data Source**[a]
Government Statistics	Number of scrapped vehicles	X	X	G
	Car registrations in the country	X	X	G
Refrigerant Distributors	All virgin HFC-134a sold to end users in the MACs market	X		I/G
Vehicle Manufacturers	All virgin HFC-134a purchased directly from refrigerant producers (Including imported HFC-134a)	X		I
	All refrigerant used for ‘First Fill’ of new HFC-134a A/C systems (t for the bottom-up method)	X	X	I
	Weighted average HFC-134a A/C system charge	X	X	I
	Vehicles sold and the percentage equipped with HFC-134a A/C systems	X	X	I
Vehicle Importers	The total number of vehicles imported and the percentage equipped with HFC-134a air-conditioning system	X	X	I/G
After-market System Manufacturers/Installers	All virgin HFC-134a used for ‘First Fill’ of new systems. (t for the bottom up method.)	X	X	I
	Number of HFC-134a A/C systems sold in the country or region	X	X	I/G
Manufacturers and installers of new systems	Actual process emissions if they differ significantly from the default emissions	X	X	I
Other Information for the Bottom-up Method	Fraction of HFC-134a recovered during disposal (z)		X	I/G
	Annual leakage rate for existing systems (x)		X	I
	Average vehicle lifetime (n)		X	I
	Initial Charge of systems in year t – n		X	I
	Amount of HFC-134a in systems at time of disposal (y)		X	I
	Initial charge of A/C systems in year t – n		X	I

[a] ‘I’ = Industry, ‘G’ = Government.

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts, Emissions of Substitutes for Ozone Depleting Substances).

3.7.6 Fire protection sub-source category

3.7.6.1 Methodological issues

There are two general types of fire protection (fire suppresion) equipment that use halons, and their partial substitutes HFCs and PFCs: portable (streaming) equipment, and fixed (flooding) equipment. HFCs and PFCs are mainly used as substitutes for halons in flooding equipment.

CHOICE OF METHOD

Fire protection equipment is designed to release its initial charge during an actual fire incident. Studies have shown that annual use on fires accounts for less than 2% of the installed base. Other emissions resulting from leakage and accidental release account for less than 5% of the installed base on an annual basis. Due to the cost of the substance used as extinguishing agents and as the result of lessons learned from the phase-out of halons, a very high percentage (approximately 85%) of the HFCs and PFCs are typically recovered at the end of useful life of the equipment. The useful life of the fire protection equipment is usually based on the useful life of the application that is being protected. As fire protection systems that employ HFCs or PFCs are most commonly used to protect electronic equipment, useful life is normally less than 10 years, due to rapid changes in electronic equipment technology. The choice of *good practice* methods depends on national circumstances (see decision tree in Figure 3.17, Decision Tree for Emissions of ODS Substitutes from the Fire Protection Sub-source Category). The method in the *IPCC Guidelines* calculates emissions as a function of the HFCs and PFCs charged into new equipment during the year:

EQUATION 3.51

$$\text{Emissions of HFCs or PFCs in year t} = (\text{HFCs/PFCs Used to Charge New Fire Protection Equipment}) \bullet (\text{Emission Factor in Percent})$$

The emission factor represents the fraction of newly charged HFCs and PFCs released during the year. In reality, HFCs and PFCs are emitted over a period longer than one year, so this emission factor also represents emissions from equipment charged during previous years. Choosing an annual production-based emission factor to reflect a multi-year emission process can lead to considerable error.[59]

Good practice is to model emissions based on a top-down approach similar to that used by the Montreal Protocol Halons Technical Options Committee for estimating emissions of halons. However, until this model becomes available for use with ODS substitutes, the IPCC equation should be modified to account for equipment filled with HFCs and PFCs during previous years. With this modification, the equation is comparable to the top-down Tier 2 approach outlined for stationary refrigeration and mobile air conditioning: [60]

EQUATION 3.52

$$\begin{aligned}\text{Emissions} = {} & \text{Annual Sales of HFCs/PFCs for Fire Protection} \\ & - (\text{HFCs/PFCs used to Charge New Fire Protection Equipment} \\ & \quad - \text{HFCs or PFCs Originally Used to Charge Retiring Fire Protection Equipment})\end{aligned}$$

The difference between the annual quantity of each HFC/PFC sold to the fire protection industry, and the change in size of the total stock of each HFC/PFC, equals the amount of chemical emitted to the atmosphere. The change in stock of each HFC/PFC is equal to the difference between the total charges of the new and retiring equipment.

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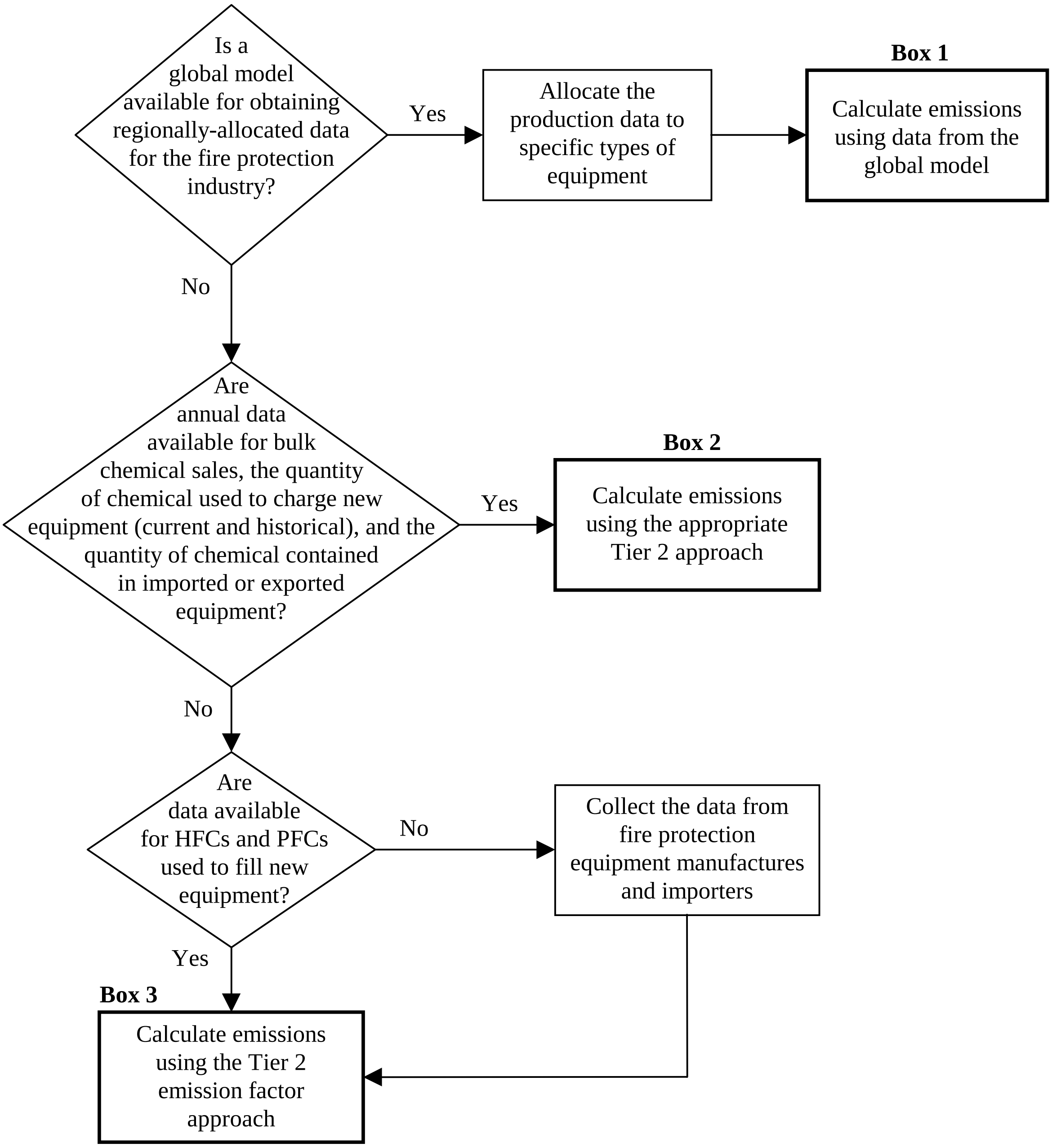
[59] The emissions rate as a function of the equipment base is more important than the emission rate as a function of production. As experienced with halons, when production ceased, the emissions did not cease but continued to follow a consistent pattern based on the equipment base.

[60] The sales-based approach as applied to the Fire Protection sub-source category is essentially the same approach as for the Stationary Refrigeration sub-source category.

This equation should be applied to each individual HFC/PFC used in fire protection equipment. Total carbon equivalent emissions are equal to the sum of carbon equivalent emissions of all HFCs and PFCs. Tracking of exports/imports of fire protection equipment that uses HFCs or PFCs is essential to ensure that the modified equation yields accurate emissions estimates.

A bottom-up Tier 2 approach is not suitable for the fire protection sub-source category because the required activity data do not exist for most countries. Existing customs codes and government statistics do not differentiate between equipment containing ODS substitutes and other compounds. For example, although a fire protection unit would be accounted for, at present there is no specific procedure to differentiate and account for those that use an ODS substitute versus another type of chemical.

Figure 3.17 Decision Tree for Emissions of ODS Substitutes from the Fire Protection Sub-source Category



CHOICE OF EMISSION FACTORS

The top-down Tier 2 method does not require emission factors. However, if activity data for previous years are unavailable and an emission factor is required, the default emission factors presented in the *IPCC Guidelines* and shown in Table 3.26, Default IPCC Emission Parameters for the Fire Protection Sub-source Category (Bottom-up Approach), should be used.

TABLE 3.26
DEFAULT IPCC EMISSION PARAMETERS FOR THE FIRE PROTECTION SUB-SOURCE CATEGORY (BOTTOM-UP APPROACH)

Equipment Type	Percent of HFCs/PFCs Installed
Streaming (Portable)	5%
Flooding (Fixed)	5%

Source: HTOC (1998).

CHOICE OF ACTIVITY DATA

Activity data for the top-down method focus on chemical deployment rather than sources of emissions. For the higher tier approach, all of the following types of data are required. If the default emission factor approach is used, only the second type of data is required:

- ***Annual sales and imports of each HFC and PFC to the fire protection industry*:** Domestic sales data can be obtained from HFC/PFC producers. Customs officials and chemical distributors should be able to provide imported chemical data.
- ***Amount of each HFC and PFC used to charge new fire protection equipment*:** These data can be estimated using information from fire protection equipment manufacturers/importers on the total charge of the equipment they manufacture/import.
- ***Amount of each HFC and PFC originally used to charge retiring fire protection equipment*:** Fire protection equipment manufacturers/importers can supply data on average product lifetimes, and the initial charge of retiring equipment. Equipment lifetimes can be long, however, possibly up to 35 years, and ODS substitutes have only recently been introduced to the industry. Consequently, at present, there may be only a minimal amount of HFCs and PFCs contained in retiring equipment.

A top-down model for estimating global halon emissions was developed in 1991, based on the magnitude of the halons contained in equipment and the supply that would be available from recovery and recycle.[61] In the future, a similar model could be developed to determine the share of global HFC/PFC production sold to the fire protection industry, and subsequently this production could be allocated to global regions.[62] Such a model could assist countries experiencing difficulty obtaining national HFC/PFC data for the fire protection industry data.

COMPLETENESS

Inventory agencies should ensure that all HFCs and PFCs used in the fire protection industry are included in the estimate. If chemical sales and imports data are complete, the final estimate should be complete as well.

Aggregate global production will always equal aggregate global emissions plus the aggregate total of ODS substitutes contained in equipment. For inventory agencies that use a global model in the future, estimates will be complete if the global and regional data are allocated accurately.

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[61] The model was published in the 1992 Report of the Halons Technical Options Committee (HTOC) of the Montreal Protocol and widely accepted at that time.

[62] The expert group recommended that the model include ten regions as follows: North America, Europe, Japan, Australia/New Zealand, Indian sub-continent, Northeast Asia, ASEAN, Africa including Turkey, Central and South America, and countries with economies in transition (CEITs).

DEVELOPING A CONSISTENT TIME SERIES

In some countries, historical activity data for HFCs and PFCs charged into new equipment may be difficult to determine because of the recent introduction of these substances. If inventory agencies use preliminary emission factors for these years based on historical data for halons, and then switch to the chemical sales approach, they should follow *good practice* in ensuring time series consistency, as described in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

The Tier 2 top-down approach will be more accurate than the simplified emission factor approach because emissions do not correlate well to a fixed percentage of annual production, and an emission factor cannot properly account for emissions from older equipment. The accuracy of the top-down approach will depend on the quality of chemical sales data. It should be possible to estimate annual emissions to ±10% using this method.

A high degree of certainty could be expected for the global model because it will be based on known production and provides for a complete material balance. At any time, Aggregate Global Production will always equal Aggregate Global Emissions plus the Aggregate Total of ODS substitutes Contained in Equipment. There is more uncertainty in the regional and country-specific disaggregation of the data.

3.7.6.2 Reporting and documentation

The balance between preservation of confidentiality and transparency of the data is an important issue, especially in a low use sub-source category such as fire protection. One major ODS substitute is manufactured by only one producer, in quantities very much lower than ODS substitutes used in other sub-source categories. Careful aggregation of GWP-weighted data may be a means to resolve this issue.

3.7.6.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1, General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, Quality Assurance and Quality Control, specific procedures of relevance to this sub-source category are outlined as follows. The potential for global validation of the quantity of chemicals used and their sources cannot be used to substantiate individual country data. However, quality control can be addressed by emissions cross checks using regional and global data as country data is a subset of these. Agreement on factors, reached by a consensus on a regional and global basis, will maintain the integrity of the overall model.

3.7.7 Other applications sub-source category

3.7.7.1 Methodological issues

HFCs and PFCs represent a large range of gases whose properties make them attractive for a variety of niche applications not covered in other sub-source categories. These include electronics testing, heat transfer, dielectric fluid, medical applications and potentially many new applications not yet developed. There are also some historical uses of PFCs, as well as emerging use of HFCs, in these applications. These applications have leakage rates ranging from 100% emissive in year of application to around 1% per annum.

CHOICE OF METHOD

The choice of *good practice* methods depends on national circumstances (see decision tree in Figure 3.18, Decision Tree for Actual Emissions (Tier 2) from the Other Applications Sub-source Category). The end-users for these niche applications will be extremely diverse. As a result, investigating each of these applications separately may not be feasible. Instead, it is suggested that these other miscellaneous applications be divided into highly emissive applications similar to solvents and aerosols, and less emissive contained applications similar to closed-cell foam and refrigerators. The breakdown of annual gas consumption going to either category should be determined by a survey of end-use applications.

The following default split of usage is suggested:

- Emissive = X% of total consumption
- Contained = (100 – X)% of total consumption

Modelling of these two circumstances are considered in turn.

Emissive applications

It is *good practice* to use a top-down method, similar to the methods described for aerosols and solvents. During use of fluids in these applications, 100% of the chemical is emitted on average six months after sale. In other words, as with aerosol uses, emissions in year t can be calculated according to the equation for solvents and aerosols as follows:

EQUATION 3.53

$$\text{Emissions of HFCs and PFCs in year t} = [\text{Quantity of HFCs and PFCs Sold in year t} \bullet (\text{EF})] + [\text{Quantity of HFCs and PFCs Sold in year } (t-1) \bullet (1-\text{EF})]$$

The emission factor (EF) represents that fraction of chemical emitted during the first year of sale. By definition, emissions over two years must equal 100%. This equation should be applied to each chemical individually. Total CO_2-equivalent emissions are equal to the sum of CO_2-equivalent emissions of each chemical.

Contained applications

Certain applications have much lower loss rates. Where bottom-up data are available, a separate emissions model will be required to adjust for this lower leakage rate. Where no data exist, a bottom-up model with default emission factors should be used. Thus, the equation for annual emissions is as follows:

EQUATION 3.54

$$\text{Emissions} = \text{Product Manufacturing Emissions} + \text{Product Life Emissions} + \text{Product Disposal Emissions}$$

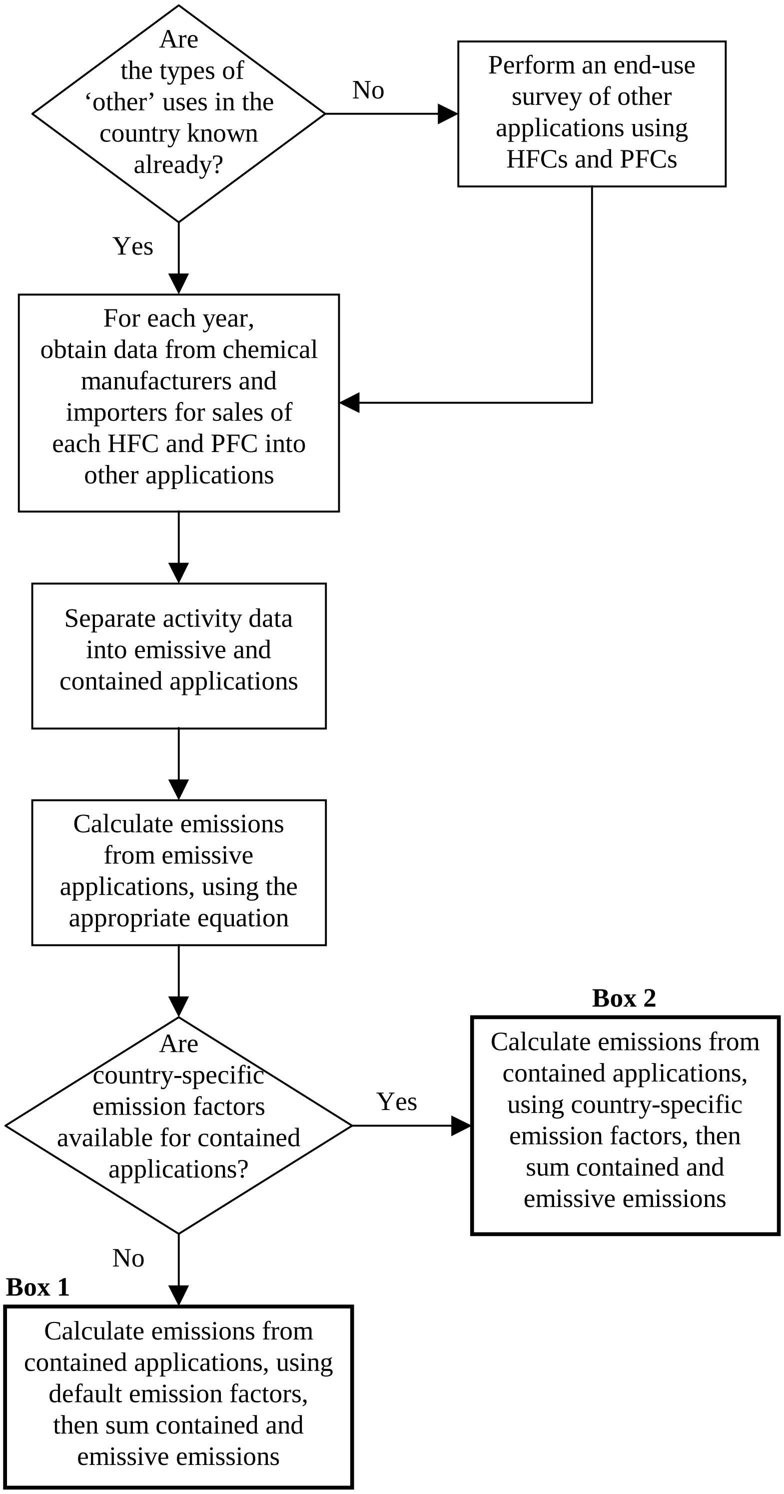
Where:

Product Manufacturing emissions = Annual Sales • Manufacturing Emission Factor

Product Life emissions = Bank • Leakage Rate

Product Disposal emissions = Annual Sales • Disposal Emission Factor

Figure 3.18 Decision Tree for Actual Emissions (Tier 2) from the Other Applications Sub-source Category



CHOICE OF EMISSION FACTORS

Emissive applications

In the absence of empirical end-use data, *good practice* is to use the IPCC default emission factor of 50%. This means that half of the initial charge is emitted during the first year, and the remainder is emitted during the second year. If alternative emission factors are used, they should be fully documented.

Contained applications

The suggested approach is to obtain data directly from the end-use sectors. If it is impossible to obtain such data, default values are presented below in Table 3.27, Default IPCC Emission Parameters for Contained Applications (Other Applications Sub-source Category). These defaults assume a low annual leakage rate and a long equipment life, as should be expected from contained applications.

TABLE 3.27
DEFAULT IPCC EMISSION PARAMETERS FOR CONTAINED APPLICATIONS (OTHER APPLICATIONS SUB-SOURCE CATEGORY)

Emissions Parameter	**Default Value**
Manufacturing emission factor	1% of Annual Sales
Leakage rate	2% of Annual Sales
Disposal emission factor	5% of Annual Sales
Equipment lifetime	15 years

Source: Gamlen *et al.* (1986).

CHOICE OF ACTIVITY DATA

The value for total sales going to other uses should be obtained directly from chemical HFC/PFC producers and importers. Data on the import of HFCs and PFCs can be collected from distributors. Most countries will import a significant amount of these substances because there are few produced. Data can also be collected from end-users but this will be difficult. The fraction of sales going to emissive uses, as opposed to contained uses, should be determined by a survey of end uses.

For contained applications, it is also necessary to determine the size of the bank of fluid accumulated. The suggested approach is to use data directly from end-use sub-source categories to determine the size of the bank. If it is impossible to obtain such data, it is *good practice* to use a default value of 10 times annual sales. Thus, annual emissions including manufacturing losses and disposal will average 26% of annual chemical sales to contained applications, compared to the emissive applications where 100% of annual sales is lost.

COMPLETENESS

Completeness will be difficult to achieve because there is no fixed list of other sources. Inventory agencies should investigate possible end-uses by obtaining qualitative information from chemical manufacturers and importers about other industries that purchase HFCs and PFCs.

DEVELOPING A CONSISTENT TIME SERIES

Emissions of ODS substitutes from other applications should be calculated using the same method and data sources for every year in the time series. Where consistent data are unavailable for any years in the time series, these gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation.

UNCERTAINTY ASSESSMENT

As there are a small number of chemical manufacturers, and the high cost of the gas provides an incentive for keeping records, the activity data should be reasonably accurate. There is more uncertainty in determining the breakdown between emissive and contained applications, particularly when no end-use survey is performed. For emissive applications, the default emission factor of 50%/yr applied over two years will be most accurate if gas sales are relatively constant. Emissions factors for contained applications have a higher uncertainty, although data from end-use sectors is likely to be more accurate than defaults. It is *good practice* to discuss uncertainty estimates with the chemical supplier and end user sectors concerned, using the approaches to obtaining expert judgement outlined in Chapter 6, Quantifying Uncertainties in Practice.

3.7.7.2 Reporting and documentation

Inventory agencies should report total emissions from these other sub-source categories, and qualitatively list the types of uses included in this sub-source category if available. The fraction of chemical used in emissive versus contained applications should also be reported, along with any country-specific emission factors. There may be confidentiality issues due to the limited number and location of chemical manufacturers that will affect the level of transparency. In this case, to preserve confidentiality, it may be necessary to avoid specifying emissions of individual gases, and reports should be as aggregated tonnes of carbon equivalent emissions, weighted by global warming potential.

3.7.7.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, Quality Assurance and Quality Control, specific procedures of relevance to this sub-source category are outlined as follows:

- For accurate quality control/assurance it is suggested that both top-down and end-use data be compiled.
- To allow independent assessment of the level of quality of the data and underlying assumptions, the number of manufacturers and distributors plus end users interviewed should be quantified.

3.8 ESTIMATION OF HFC-23 EMISSIONS FROM HCFC-22 MANUFACTURE

3.8.1 Methodological issues

Trifluoromethane (HFC-23 or CHF_3) is generated as a by-product during the manufacture of chlorodifluoromethane (HCFC-22 or $CHClF_2$)[63] and emitted through the plant condenser vent. There are a small number of HCFC-22 production plants globally and thus a discreet number of point sources of HFC-23 emissions.

CHOICE OF METHOD

The choice of *good practice* method will depend on national circumstances. The decision tree in Figure 3.19, Decision Tree for HFC-23 Emissions from HCFC-22 Production, describes *good practice* in adapting the methods in the *IPCC Guidelines* to these country-specific circumstances.

The *IPCC Guidelines* (Vol. 3, Section 2.16.1, By-product Emissions) present two broad approaches to estimating HFC-23 emissions from HCFC-22 plants. The Tier 2 method is based on measurement of the concentration and flow-rate from the condenser vent at individual plants. The product of HFC-23 concentration multiplied by the volumetric flow-rate gives the mass rate of HFC-23 emissions. The Tier 1 method is relatively simple, involving the application of a default emissions factor to the quantity of HCFC-22 produced. This method can be applied at the plant level or the national level. In cases where there are Tier 2 data available for some plants, the Tier 1 method can be applied to the remainder to ensure complete coverage. Regardless of the method, emissions abated should be subtracted from the gross estimate to determine net emissions.

It is *good practice* to use the Tier 2 method if possible. Direct measurement is significantly more accurate than Tier 1 because it reflects the conditions specific to each manufacturing facility. In most cases, the data necessary to prepare Tier 2 estimates should be available because facilities operating to good business practice perform regular or periodic sampling of the final process vent or within the process itself as part of routine operations. For facilities using abatement techniques such as HFC-23 destruction, verification of the abatement efficiency is also done routinely. The Tier 1 method should be used only in rare cases where plant-specific data are unavailable.

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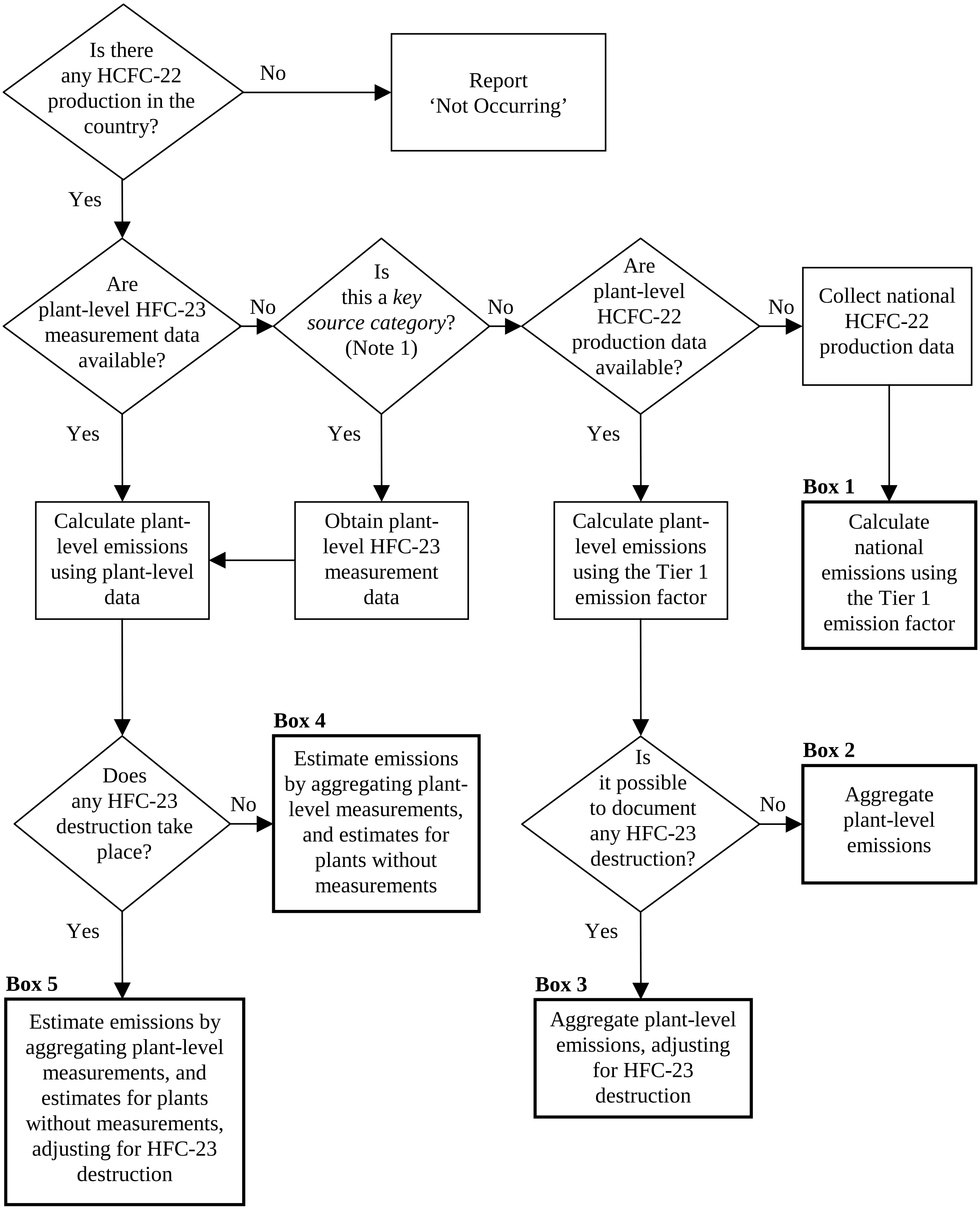
[63] HCFC-22 is used as a refrigerant in several different applications, as a blend component in foam blowing, and as a chemical feedstock for manufacturing synthetic polymers.

Figure 3.19 Decision Tree for HFC-23 Emissions from HCFC-22 Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country’s total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

CHOICE OF EMISSION FACTORS

There are several measurement options within the Tier 2 method relating to the location and frequency of the sampling. In general, direct measurement of the emissions of HFC-23 provides the highest accuracy. Continuous or frequent measurement of parameters within the production process area itself is almost as accurate. In both cases, the frequency of measurement must be high enough to represent the variability in the process (e.g. across the life of the catalyst). Issues related to measurement frequency are summarised in Box 3.5, Plant Measurement Frequency. General advice on sampling and representativeness is provided in Chapter 8, Quality Assurance and Quality Control. In cases where plant-specific measurements or sampling are not available and Tier 1 methods are used, the default emission factor of 4% (tonnes of HFC-23 produced per tonne of HCFC-22 manufactured) presented in the *IPCC Guidelines* should be used, assuming no abatement methods.

BOX 3.5
PLANT MEASUREMENT FREQUENCY

The accuracy and precision of the estimates of annual HFC-23 emissions are directly correlated with the number of samples and the frequency of sample collection. Since production processes are not completely static, the greater the process variability, the more frequently plants need to measure. As a general rule, sampling and analysis should be repeated whenever a plant makes any significant process changes. Before choosing a sampling frequency, the plant should set a goal for accuracy and use statistical tools to determine the sample size necessary to achieve the goal. For example, a study of HCFC-22 producers indicates that sampling once per day is sufficient to achieve an extremely accurate annual estimate. This accuracy goal should then be revised, if necessary, to take into account the available resources.

RTI, Cadmus, ‘*Performance Standards for Determining Emissions of HFC-23 from the Production of HCFC-22*’, *draft final report* prepared for USEPA, February 1998.

CHOICE OF ACTIVITY DATA

When using the Tier 1 method, production data should be obtained directly from producers. There are several ways producers may determine their production levels, including shipment weights and measuring volume-times-density, using flow meters. These data should account for all HCFC-22 production for the year, whether for sale or for use internally as feedstock, and the plant should describe how the HCFC-22 production rate is determined. In some circumstances, producers may consider plant production data to be confidential. For national-level activity data, submission of HCFC-22 production data is already required under the Montreal Protocol.

COMPLETENESS

It should be possible to obtain complete sampling data because there are only a small number of HCFC-22 plants in each country, and it is standard practice for each plant operator to monitor emissions. Review of plant data indicates that at properly run manufacturing facilities, fugitive emissions of HFC-23 (e.g. from valves, water scrubbers, and caustic washes) are insignificant (RTI, 1996). If information is available that indicates fugitive emissions are significant, they should be reported and well documented.

DEVELOPING A CONSISTENT TIME SERIES

Emission of HFC-23 from HCFC-22 production should be estimated using the same method for the entire time series. If data for any years in the time series are unavailable for the Tier 2 method, these gaps should be filled according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

UNCERTAINTY ASSESSMENT

The Tier 2 method is significantly more accurate than the Tier 1 default method. An error of approximately 50% could be considered for Tier 1 method based upon knowledge of the variability in emissions from different manufacturing facilities. Regular Tier 2 sampling of the vent stream can achieve an accuracy of 1-2% at a 95% confidence level in HFC-23 emissions. Tier 1 uncertainties can be identified through expert judgement whereas Tier 2 uncertainties should be based on empirical measurement.

3.8.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving.

Some examples of specific documentation and reporting relevant to this source category are provided below:

- To provide for completely transparent reporting, emissions of HFC-23 from HCFC-22 production should be reported as a separate item, rather than included with other HFC emissions.
- Documentation should also include:
  - (i) Methodological description;
  - (ii) Number of HCFC-22 plants;
  - (iii) HCFC-22 production (if multiple producers);
  - (iv) Presence of abatement technology;
  - (v) Emission factors.

Confidentiality

- The use of the Tier 2 method would mean that the plant emissions of HFC-23 are reported separately from the production of HCFC-22. By de-coupling the HFC-23 emissions and HCFC-22 production, the emission data on HFC-23 cannot be considered to be of commercial confidence as it does not reveal the levels of production of HCFC-22 without detailed and confidential knowledge of the individual manufacturing facility.
- The use of the Tier 1 method would enable the production of HCFC-22 to be calculated from published emissions of HFC-23 if there were less than three producers. Such production data could be considered confidential business information for the manufacturing facility concerned. In such cases, steps should be taken to protect confidentiality through, for example, the aggregation of all HFC emissions. For transparency reasons, whenever there is aggregation, a qualitative discussion of HCFC-22 production should be included.

3.8.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in Chapter 8, Section 8.7, Source Category-specific QC Procedures (Tier 2), and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

In addition to the guidance in Chapter 8, Quality Assurance and Quality Control, specific procedures of relevance to this sub-source category are outlined below:

Comparison of emissions estimates using different approaches

Inventory agencies should compare reported plant emissions estimates against those determined using the Tier 1 default factor and production data. If only national production data are available, they should compare aggregated plant emissions to a national default estimate. If significant differences are found in the comparison, they should answer the following questions:

(i) Are there inaccuracies associated with any of the individual plant estimates (e.g. an extreme outlier may be accounting for an unreasonable quantity of emissions)?

(ii) Are the plant-specific emission factors significantly different from one another?

(iii) Are the plant-specific production rates consistent with published national level production rates?

(iv) Is there any other explanation for a significant difference, such as the effect of controls, the manner in which production is reported or possibly undocumented assumptions?

Direct emission measurement check

- Inventory agencies should confirm that internationally recognised, standard methods were used for plant measurements. If the measurement practices fail this criterion, then the use of these emissions data should be carefully evaluated. It is also possible that, where a high standard of measurement and QA/QC is in place at sites, the uncertainty of the emissions estimates may be revised downwards.

- Each plant's QA/QC process should be evaluated to assess if the number of samples and the frequency of sample collection is appropriate given the variability in the process itself.

- Where possible, inventory agencies should verify all measured and calculated data through comparison with other systems of measurement or calculation. For example, emissions measurement within the process itself can be verified periodically with measurement of the vent stream. Inventory agencies should verify abatement system utilisation and efficiency.

- With a periodic external audit of the plant measurement techniques and results, it is also possible to compare implied emission factors across plants and account for major differences.

Verification of national emissions

- While it is not feasible to verify a single country's estimate, an overall global cross-check of estimated emissions could be carried out through the measurement of HFC-23 atmospheric levels. As there are a small number of facilities, this will serve as an order-of-magnitude check for emissions from the industry world-wide that in turn may be compared to national estimates.

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4

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4.1 LIVESTOCK POPULATION CHARACTERISATION

4.1.1 Methodological issues

The methods for estimating methane (CH_4) and nitrous oxide (N_2O) emissions from livestock-related source categories all require information such as the definitions of livestock sub-categories, annual populations and feed intake estimates. To ensure that these definitions and data are used consistently across the source categories a single 'characterisation' should be developed for each species. A coordinated livestock characterisation ensures consistency across the following source categories:

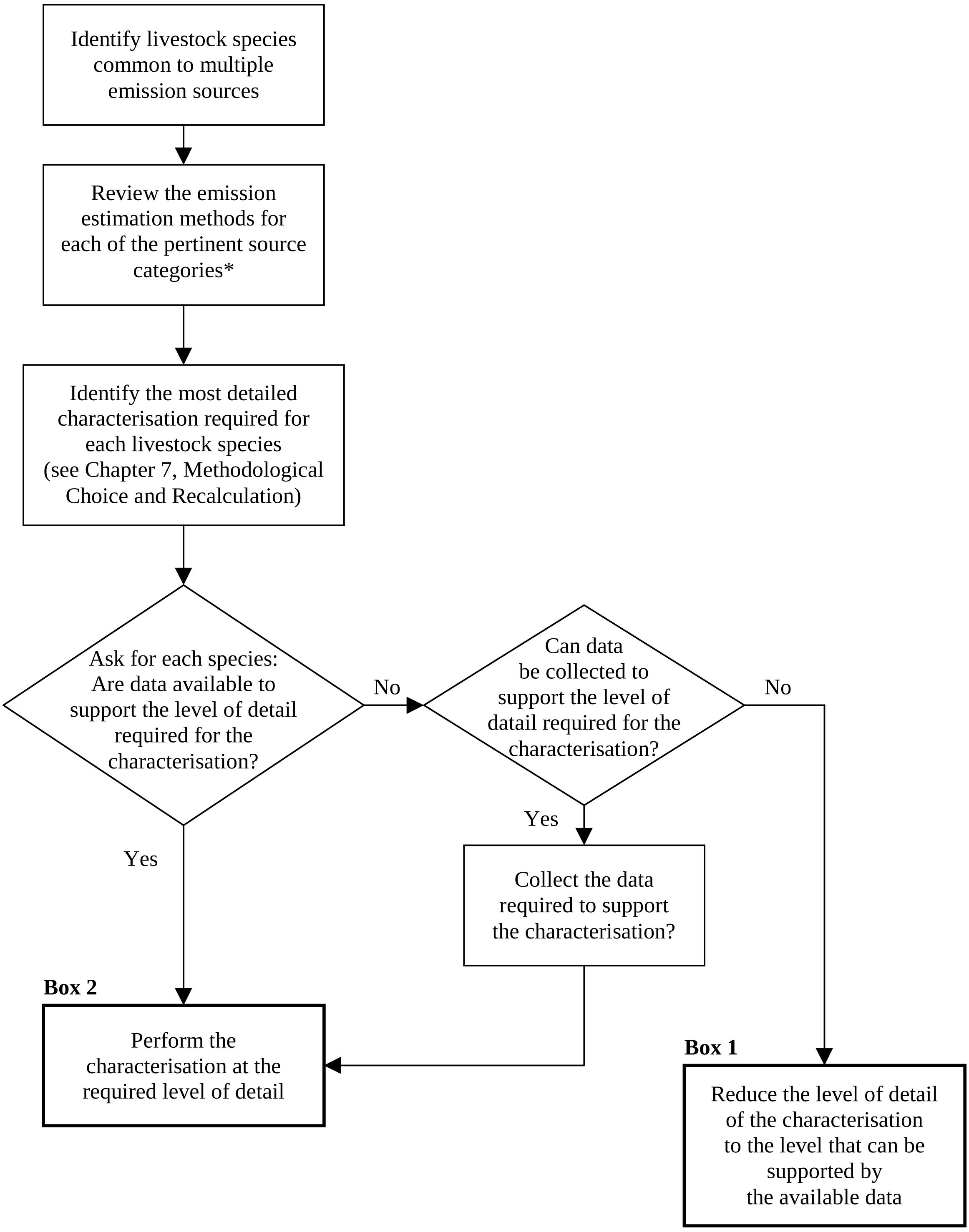
- Section 4.2 - CH_4 emissions from enteric fermentation in domestic livestock;
- Section 4.3 - CH_4 emissions from manure management;
- Section 4.4 - N_2O emissions from manure management;
- Section 4.7 - Direct N_2O emissions from agricultural soils;
- Section 4.8 - Indirect N_2O emissions from nitrogen used in agriculture.

4.1.1.1 CHOICE OF CHARACTERISATION DETAIL

Good practice is to identify the appropriate method for estimating emissions for each source category, and then base the characterisation on the most detailed requirements identified for each livestock species. The livestock characterisation ultimately developed will likely undergo multiple iterations as the needs of each source category are assessed during the emissions estimation process (see Figure 4.1, Decision Tree for Livestock Population Characterisation). The steps required are as follows:

- **Identify the Species Contributing to Multiple Emission Source Categories.** The livestock species that contribute to multiple emission source categories should first be listed. These species are typically: cattle, buffalo, sheep, goats, swine, horses, camels, mules/asses, and poultry.
- **Review the Emission Estimation Method for each of the Pertinent Source Category.** For the source categories of enteric fermentation, CH_4 and N_2O from manure management, as well as direct and indirect N_2O emissions, identify the emission estimating method for that species for that source category. For example, enteric fermentation emissions from cattle, buffalo, and sheep should each be examined to assess whether emissions are large enough to warrant the Tier 2 emissions estimate for each of these species. Similarly, manure management methane emissions from cattle, buffalo, swine, and poultry should be examined to determine whether the Tier 2 emissions estimate is appropriate. Existing inventory estimates can be used to conduct this assessment. If no inventory has been developed to date, Tier 1 emissions estimates should be calculated to provide initial estimates for conducting this assessment. See Chapter 7, Methodological Choice and Recalculation, for guidance on the general issues of methodological choice.
- **Identify the Most Detailed Characterisation Required for each Livestock Species.** Based on the assessments for each species under each source category, identify the most detailed characterisation required to support each emissions estimate for each species. Typically, the 'Basic' characterisation can be used across all relevant source categories if the enteric fermentation and manure sources are both estimated with their Tier 1 methods. An 'Enhanced' characterisation should be used to estimate emissions across all the relevant sources if the Tier 2 method is used for either enteric fermentation or manure.

Figure 4.1 Decision Tree for Livestock Population Characterisation



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*These sources include: CH_4 from Enteric Fermentation, CH_4 from Manure Management, N_2O from Manure Management, Direct N_2O from Agricultural Soils, and Indirect N_2O from Nitrogen used in Agriculture

BASIC CHARACTERISATION

For the 'Basic' Characterisation it is *good practice* to collect the following livestock characterisation data to support the emissions estimates:

Livestock Species and Categories: A complete list of all significant livestock populations that have default emission factor values provided in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (*IPCC Guidelines*) must be developed (i.e. dairy cows, other cattle, buffalo, sheep, goats, camels, horses, mules and asses, swine, and poultry).[1] More detailed categories can (and should) be used if the data are available.

Annual Population: If possible, inventory agencies should use population data from official national statistics or industry sources. Food and Agriculture Organisation (FAO) data can be used if national data are unavailable. Seasonal births or slaughters may cause the population size to expand or contract at different times of the year, which will require the population numbers to be adjusted accordingly. It is important to fully document the method used to estimate the annual population, particularly if adjustments to the original data are required.

Milk Production: Average annual milk production for dairy cows is required. Milk production data are used in estimating an emission factor for enteric fermentation using the Tier 1 method. Country-specific data sources are preferred, but FAO data may also be used.

Climate: For some large countries, livestock may be managed in regions with different climates. For each livestock category, the percentage of animals in each climate region should be estimated. In the *IPCC Guidelines,* Reference Manual, Table 4-1, three climate regions are defined in terms of annual average temperature: cool (<15°C), temperate (15°C - 25°C), and warm (>25°C). Livestock population data by region can be developed from country-specific climate maps.

ENHANCED CHARACTERISATION

The 'Enhanced' livestock characterisation provides detailed information on:

- Definitions for livestock sub-categories;
- Livestock population by sub-category;
- Feed intake estimates for the typical animal in each sub-category.

The livestock population sub-categories should be defined to create relatively homogenous sub-groupings of animals. By dividing the population into these sub-categories, country-specific variations in age structure and animal performance within the overall livestock population can be reflected.

The feed intake estimates developed through the 'Enhanced' characterisation are used in the Tier 2 enteric fermentation emissions estimate for cattle, buffalo, and sheep. Additionally, these same feed intake estimates should be used to harmonise the estimated manure and nitrogen excretion rates used to estimate CH_4 and N_2O emissions from manure management and direct and indirect N_2O emissions.

Define Livestock Sub-categories: It is *good practice* to classify cattle and buffalo populations into a minimum of three main sub-categories for each species:

- Cattle: Mature Dairy Cows, Mature Non-Dairy Cattle, and Young Cattle.
- Buffalo: Mature Dairy Buffalo (females only), Mature Non-Dairy Buffalo, and Young Buffalo.

Depending on the level of detail in the implementation of the emissions estimation method, these main categories can be further classified into sub-categories based on animal or feed characteristics. The most common sub-categories for cattle and buffalo are shown in Table 4.1, Representative Cattle and Buffalo Categories, although other sub-categories could be developed in particular countries.

For sheep, the national flock can be disaggregated into categories according to animal and management class as presented in Table 4.2, Representative Sheep Categories. Subdivisions similar to those used for cattle and buffalo can be used to further disaggregate the sheep population with the goal of creating sub-categories with relatively homogenous characteristics.

When completing the Tier 2 manure management methane estimate for swine, it is preferable to classify the swine population into the following sub-categories: sows, boars, and growing animals. Sows could be further

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[1] The *IPCC Guidelines* uses the term 'dairy cattle' to refer to cows that have calved at least once and are being kept to produce milk. For good practice, the term 'dairy cattle' has been changed to 'dairy cows' to avoid possible confusion with other cattle (e.g. replacement dairy heifers) connected with the dairy industry. The term 'other cattle' is used to refer to cattle that are not in other defined categories.

classified into farrowing and gestation sows, and growing animals further divided into nursery, growing and finisher pigs. It should be noted, however, that this disaggregation is only necessary if detailed data are available on manure management system usage by these animal species/categories.

For large countries or for countries with distinct regional differences, it may be useful to designate regions and then define categories within those regions. Regional subdivisions are generally defined to represent differences in feeding systems and diet.

TABLE 4.1

REPRESENTATIVE CATTLE AND BUFFALO CATEGORIES

Main Categories	**Sub-categories**
Mature Dairy Cows or Mature Dairy Buffalo	• High-producing dairy cows or dairy buffalo that have calved at least once and are used principally for milk production; • Low-producing dairy cows or dairy buffalo that have calved at least once and are used principally for milk production.
Other Mature Cattle or Mature Non-dairy Buffalo	Females: • Cows used principally for producing meat; • Cows used for more than one production purpose: milk, meat, draft. Males: • Bulls used principally for breeding purposes; • Bullocks used principally for draft power; • Steers used principally for producing meat.
Young Cattle or Young Buffaloes	• Pre-Weaned Calves; • Growing cattle or buffaloes; • Feedlot-fed cattle or buffalo on high-grain diets.

Source: *IPCC Guidelines*, Reference Manual, Table 4-7.

TABLE 4.2

REPRESENTATIVE SHEEP CATEGORIES

Main Categories	**Sub-categories**
Mature Ewes	• Breeding ewes where either meat or wool production or both is the primary purpose; • Milking ewes where commercial milk production is the primary purpose.
Other Mature Sheep (>1 year)	• No further sub-categorisation recommended
Young Sheep	• Intact males; • Castrates; • Females.

Source: Lassey and Ulyatt (1999).

Livestock Population by Sub-category: For each livestock sub-category, the average annual population should be estimated in terms of the number of head per year, although in some cases a period of less than a year may be used. Regardless of the length of time chosen, it is important to ensure temporal consistency between the activity data and the emission factor. As far as possible inventory agencies are encouraged to use their own population data from official national statistics or industry sources, but FAO data can be used if necessary. Seasonal births and slaughters may cause the population to expand or contract at different times of the year, which will require the population numbers to be adjusted accordingly. It is important to fully document the method used to estimate the average annual population, particularly if adjustments to the original data are required.

Feed Intake Estimates: The feed intake of a representative animal in each sub-category is estimated to support the Tier 2 emissions estimates. Feed intake is typically measured in terms of energy (e.g. Mega Joules (MJ) per day) or dry matter (e.g. kilograms (kg) per day). To support the enteric fermentation Tier 2 method (see Section 4.2), detailed data requirements and equations are included in the *IPCC Guidelines* to estimate feed intake. The *good practice guidance* presented below updates the *IPCC Guidelines* for cattle and buffalo to make the equations more applicable to a wider range of animal species/categories and management conditions. In addition, an enhanced characterisation to support the Tier 2 method for sheep is presented, recognising that for some countries sheep are a significant source of emissions. Feed intake for other species can be estimated using similar country-specific methods appropriate for each. The remainder of this sub-section presents the data requirements and equations used to estimate feed intake for cattle, buffalo, and sheep. For all estimates of feed intake, *good practice* is to:

- Collect data to describe the performance of the typical animal in each sub-category;
- Estimate feed intake from the animal performance data for each sub-category.

In some cases, the equations should be applied on a seasonal basis, for example under conditions in which livestock gain weight in one season and lose weight in another.

The following animal performance data are required for each animal sub-category to estimate feed intake for the sub-category:

- *Weight (W), kg*: Live-weight data should be collected for each animal sub-category, and the data should be based on weight measurements of live animals. As it is unrealistic to perform a complete census of live-weights, live-weight data could be obtained from research studies, expert assessments or statistical databases. Live-weight data should be checked to ensure that it is representative of country conditions. Comparing the live-weight data with slaughter-weight data is a useful cross-check to assess whether the live-weight data are representative of country conditions. However, slaughter-weight data should not be used in place of live-weight data. Additionally it should be noted that the relationship between live-weight and slaughter-weight varies between countries. For cattle, buffalo and mature sheep, the yearly average weight for each animal category (e.g. mature beef cows) is needed. For young sheep, weights are needed at: birth, weaning, one year of age, and at slaughter if slaughter occurs prior to one year.
- *Average weight gain (or loss) per day (WG), kg/d (for cattle and buffalo)*: Data on average weight gain are generally collected for feedlot animals and young growing animals. Mature animals are generally assumed to have no net weight gain or loss over an entire year. However, collecting data on weight gain and loss for mature animals may be appropriate for countries with wet and dry seasons or extreme temperatures. Mature animals lose weight during the dry season and under extreme temperatures gain weight during the wet season. In this circumstance, the feed intake would be estimated separately for the wet and dry seasons and hot and cold seasons.
- *Mature weight (MW), kg (for cattle and buffalo)*: The mature weight is the potential body weight of an adult animal were it to reach 28% body fat (NRC 1996). The mature weight will vary among breeds. Mature body weight may be similar to ‘reference weight’ or ‘final shrunk body weight’ values as used in different countries. Estimates of mature weight are typically available from livestock specialists and producers.
- *Average number of hours worked per day*: For draft animals, the average number of hours worked per day must be determined.
- *Feeding situation*: The feeding situation that most accurately represents the animal sub-category must be determined using the definitions shown below. If the feeding situation falls between the definitions, the feeding situation should be described in detail. This detailed information may be needed when calculating the enteric fermentation emissions, because interpolation between the feeding situations may be necessary to assign the most appropriate coefficient. For cattle and buffalo the feeding situations are:

    (i) *Stall or housed* – animals are confined to a small area (i.e. tethered, pen, barn) with the result that they expend very little energy to acquire feed;

    (ii) *Pasture* – animals are confined in areas with sufficient forage requiring modest energy expense to acquire feed;

    (iii) *Grazing large areas* – animals graze open range land or hilly terrain and expend significant energy to acquire feed.

  For sheep, the feeding situations are:

    (i) *Housed ewes* – animals are confined due to pregnancy in final trimester (50 days);

    (ii) *Grazing flat pasture* – animals walk up to 1000 meters per day and expend very little energy to acquire feed;

    (iii) *Grazing hilly pasture* – animals walk up to 5,000 meters per day and expend significant energy to acquire feed;

(iv) *Housed fattening lambs* – animals are housed for fattening.

- *Average milk production per day, kg/d*: These data are for milking ewes, dairy cows and buffalo and other cows or non-dairy buffalo nursing calves. The average daily production should be calculated by dividing the total annual production by 365, or reported as average daily production along with days of lactation per year, or estimated using seasonal production divided by number of days per season. (Note: If using seasonal production data, the emission factor must be developed for that seasonal period).
- *Fat content, %*: Average fat content of milk is required for all lactating cows and buffalo.
- *Percent of females that give birth in a year*: This is collected only for mature cattle, buffalo, and sheep.
- *Feed digestibility, (DE)*: The proportion of energy in the feed not excreted in the feces is known as feed digestibility. The feed digestibility is commonly expressed as a percentage (%). Common ranges of feed digestibility are 50-60% for crop by-products and range lands; 60-75% for good pastures, good preserved forages, and grain supplemented forage-based diets; and 75-85% for grain-based diets fed in feedlots. Digestibility data should be based on measured values for the dominant feeds or forages being consumed, considering seasonal variations. Although a complete census of digestibility is considered unrealistic, at a minimum digestibility data from research studies should be consulted. While developing the digestibility data, associated feed characteristic data should also be recorded when available, such as measured values for Neutral Detergent Fiber (NDF), Acid Detergent Fiber (ADF) and crude protein. NDF and ADF are feed characteristics measured in the laboratory that are used to indicate the nutritive value of the feed for ruminant animals. The concentration of crude protein in the feed can be used to estimate nitrogen excretion.
- *Average annual wool production per sheep (kg/yr)*: The amount of wool produced in kilograms (after drying out but before scouring) is needed to estimate the amount of energy allocated for wool production.

The first step in collecting these data should be to research national statistics, industry sources, research studies and FAO statistics. If published data are not available from these sources, interviews of key industry and academic experts can be undertaken. Section 6.2.5 of Chapter 6, Quantifying Uncertainties in Practice, describes how to elicit expert judgement for uncertainty ranges. Similar expert elicitation protocols can be used to obtain the information required for the livestock characterisation if published data and statistics are not available.

The animal performance data are used to estimate gross energy (GE) intake, which is the amount of energy (MJ/day) an animal needs to perform activities such as growth, lactation, and pregnancy. For inventory agencies that have well-documented and recognised country-specific methods for estimating GE intake based on animal performance data, it is *good practice* to use the country-specific methods. All the metabolic functions listed in Table 4.3, Summary of the Equations Used to Estimate Gross Energy Intake for Cattle and Buffalo and for Sheep, should be included in the GE intake estimate. If no country-specific methods are available, GE intake should be calculated using the equations listed in Table 4.3. As shown in the table, separate equations are used to estimate net energy requirements for sheep as compared with cattle and buffalo. The equations used to calculate GE are as follows:

***Maintenance*:** NE_m is the net energy required for maintenance, which is the amount of energy needed to keep the animal in equilibrium where body tissue is neither gained nor lost (Jurgen, 1988).

EQUATION 4.1

NET ENERGY FOR MAINTENANCE

$$NE_m = Cf_i \bullet (Weight)^{0.75}$$

Where:

NE_m = net energy required by the animal for maintenance, MJ/day

Cf_i = a coefficient which varies for each animal category as shown in Table 4.4 (Coefficients for Calculating NE_m)

Weight = live-weight of animal, kg

***Activity*:** NE_a is the net energy for activity, that is the energy needed for animals to obtain their food. The net energy for activity was previously termed NE_{feed} in the *IPCC Guidelines*. NE_{feed} is now called NE_a because the net energy refers to the amount of energy the animal expends to acquire its feed and is based on its feeding situation rather than characteristics of the feed itself. As presented in Table 4.3, the equation for estimating NE_a for cattle and buffalo is different from the equation used for sheep.

EQUATION 4.2a
NET ENERGY FOR ACTIVITY (FOR CATTLE AND BUFFALO)

$$NE_a = C_a \bullet NE_m$$

Where:

NE_a = net energy for animal activity, MJ/day

C_a = coefficient corresponding to animal’s feeding situation (Table 4.5, Activity Coefficients)

NE_m = net energy required by the animal for maintenance (Equation 4.1), MJ/day

EQUATION 4.2b
NET ENERGY FOR ACTIVITY (FOR SHEEP)

$$NE_a = C_a \bullet (\text{weight})$$

Where:

NE_a = net energy for animal activity, MJ/day

C_a = coefficient corresponding to animal’s feeding situation (Table 4.5)

weight = live-weight of animal, kg

For Equations 4.2a and 4.2b, the coefficient C_a corresponds to a representative animal’s feeding situation as described earlier. Values for C_a are shown in Table 4.5. If a feeding situation falls between the definitions provided or occurs for only part of the year, NE_a must be weighted accordingly.

TABLE 4.3

SUMMARY OF THE EQUATIONS USED TO ESTIMATE GROSS ENERGY INTAKE FOR CATTLE AND BUFFALO AND FOR SHEEP

Metabolic Functions and Other Estimates	Equations for Cattle and Buffalo	Equations for Sheep
Maintenance (NE_m)	Equation 4.1	Equation 4.1
Activity (NE_a)	Equation 4.2a	Equation 4.2b
Growth (NE_g)	Equation 4.3a	Equation 4.3b
Weight Loss ($NE_{mobilized}$).	Equations 4.4a and 4.4b	NA
Lactation (NE_l)*	Equation 4.5a	Equations 4.5b and 4.5c
Draft Power (NE_w)	Equation 4.6	NA
Wool Production (NE_{wool})	NA	Equation 4.7
Pregnancy (NE_p)*	Equation 4.8	Equation 4.8
$\{NE_{ma}/DE\}$	Equation 4.9	Equation 4.9
$\{NE_{ga}/DE\}$	Equation 4.10	Equation 4.10
Gross Energy	Equation 4.11	Equation 4.11

Source: Beef equations based on NRC (1996) and sheep based on AFRC (1993).

NA means ‘not applicable’.

* Applies only to the proportion of females that give birth.

TABLE 4.4
COEFFICIENTS FOR CALCULATING NE_m

Animal Category	Cf_i	Comments
Cattle/Buffalo (non-lactating)	0.322	
Cattle/Buffalo (lactating)	0.335	NRC (1989) provides a higher maintenance allowance for lactation
Sheep (lamb to 1 year)	0.236	15% higher for intact males
Sheep (older than 1 year)	0.217	15% higher for intact males

Source: NRC (1984) and AFRC (1993).

TABLE 4.5
ACTIVITY COEFFICIENTS CORRESPONDING TO ANIMAL'S FEEDING SITUATION

Situation	Definition	C_a
CATTLE AND BUFFALO		
Stall	Animals are confined to a small area (i.e. tethered, pen, barn) with the result that they expend very little or no energy to acquire feed.	0
Pasture	Animals are confined in areas with sufficient forage requiring modest energy expense to acquire feed.	0.17
Grazing large areas	Animals graze in open range land or hilly terrain and expend significant energy to acquire feed.	0.36
SHEEP		
Housed ewes	Animals are confined due to pregnancy in final trimester (50 days).	0.0090
Grazing flat pasture	Animals walk up to 1000 meters per day and expend very little energy to acquire feed.	0.0107
Grazing hilly pasture	Animals walk up to 5,000 meters per day and expend significant energy to acquire feed.	0.024
Housed fattening lambs	Animals are housed for fattening.	0.0067

Source: *IPCC Guidelines.*

Growth: NE_g is the net energy needed for growth (i.e. weight gain). The current NE_g equation based on NRC (NRC, 1996) is different from the NE_g equation in the *IPCC Guidelines*. The main difference is that the current NE_g equation for cattle and buffalo (shown in Equation 4.3a) includes a mature weight-scaling factor. When characterising an animal category that has a net weight loss for a period of time (e.g. cattle during the dry season), do not use Equation 4.3a, go directly to Equation 4.4a or 4.4b. For sheep, NE_g is estimated using Equation 4.3b.

EQUATION 4.3a
NET ENERGY FOR GROWTH (FOR CATTLE AND BUFFALO)

$$NE_g = 4.18 \bullet \{0.0635 \bullet [0.891 \bullet (BW \bullet 0.96) \bullet (478/(C \bullet MW))]^{0.75} \bullet (WG \bullet 0.92)^{1.097}\}$$

Where:

NE_g = net energy needed for growth, MJ/day

BW = the live body weight (BW) of the animal, kg

C = a coefficient with a value of 0.8 for females, 1.0 for castrates and 1.2 for bulls (NRC, 1996)

MW = the mature body weight of an adult animal, kg

WG = the daily weight gain, kg/day

EQUATION 4.3b

NET ENERGY FOR GROWTH (FOR SHEEP)

$$NE_g = \{WG_{lamb} \bullet [a + 0.5b\ (BW_i + BW_f)]\} / (365\ days/year)$$

Where:

NE_g = net energy needed for growth, MJ/day

WG_{lamb} = the corresponding weight gain ($BW_f – BW_i$), kg

BW_i = the bodyweight at weaning, kg

BW_f = the bodyweight at 1-year old or at slaughter (live-weight) if slaughtered prior to 1 year of age, kg

Note that lambs will be weaned over a period of weeks as they supplement a milk diet with pasture feed or supplied feed. The time of weaning should be taken as the time at which they are dependent on milk for half their energy supply.

The NE_g equation used for sheep includes two constants that vary by animal species/category, and are presented in Table 4.6, Constant for Use in Calculating NE_g for Sheep:

TABLE 4.6

CONSTANTS FOR USE IN CALCULATING NE_g FOR SHEEP

Animal species/category	a	b
Intact Males	2.5	0.35
Castrates	4.4	0.32
Females	2.1	0.45

Source: AFRC (1993).

***Weight Loss for Cattle and Buffalo*:** When an animal loses weight, $NE_{mobilised}$ represents the energy in the weight loss that can be used by the animal for maintenance. Weight loss is typically not observed when performing an inventory because data are generally collected to describe the change in weight for a year, and mature cattle and buffalo typically have no net change in weight from one year to the next. However, animals sometimes lose weight during part of the year and gain weight during part of the year. For example, in some countries animals lose weight during the dry season and gain weight during the wet season. Additionally, a high producing dairy cow typically loses weight early in lactation, as body tissues are used to supply energy for milk production. This weight is typically gained back later in the year.

Equations 4.4a and 4.4b are provided for estimating $NE_{mobilised}$ for high-producing lactating dairy cows and for other cattle and buffalo. These equations would typically only be used if feed intake is being estimated for portions of a year during which weight loss is observed.

For lactating dairy cows, approximately 19.7 MJ of NE is mobilised per kilogram of weight loss. Therefore, the $NE_{mobilised}$ is calculated as follows (NRC, 1989):

EQUATION 4.4a

NET ENERGY DUE TO WEIGHT LOSS (FOR LACTATING DAIRY COWS)

$$NE_{mobilised} = 19.7 \bullet Weight\ Loss$$

Where:

$NE_{mobilised}$ = net energy due to weight loss (mobilised), MJ/day

Weight Loss = animal weight lost per day, kg/day

Note that weight loss is taken as a negative quantity in Equation 4.4a, such that the estimated $NE_{mobilised}$ is a negative number.

For other cattle and buffalo, the amount of energy mobilised through weight loss is calculated by: (1) inserting the amount of weight lost (kg/day) as a positive number into Equation 4.3a as WG to calculate NE_g; and (2) calculating $NE_{mobilised}$ as negative 0.8 times this NE_g value (NRC, 1996).

EQUATION 4.4b

NET ENERGY DUE TO WEIGHT LOSS (FOR BUFFALO AND OTHER CATTLE)

$$NE_{mobilised} = NE_g \bullet (-0.8)$$

Where:

$NE_{mobilised}$ = net energy due to weight loss (mobilised), MJ/day

NE_g = net energy needed for growth, MJ/day

The result from Equation 4.4b is also a negative number.

***Lactation*:** NE_l is the net energy for lactation. For cattle and buffalo the net energy for lactation is expressed as a function of the amount of milk produced and its fat content expressed as a percentage (e.g. 4%) (NRC, 1989):

EQUATION 4.5a

NET ENERGY FOR LACTATION (FOR CATTLE AND BUFFALO)

$$NE_l = \text{kg of milk per day} \bullet (1.47 + 0.40 \bullet \text{Fat})$$

Where:

NE_l = net energy for lactation, MJ/day

Fat = fat content of milk, %

Two methods for estimating the net energy required for lactation (NE_l) are presented for sheep. The first method (Equation 4.5b) is used when the amount of milk produced is known, and the second method (Equation 4.5c) is used when the amount of milk produced is not known. Generally, milk production is known for ewes kept for commercial milk production, but it is not known for ewes that suckle their young to weaning. With a known amount of milk production, the total annual milk production is divided by 365 days to estimate the average daily milk production in kg/day (Equation 4.5b). When milk production is not known, AFRC (1990) indicates that for a single birth, the milk yield is about 5 times the weight gain of the lamb. Consequently, total annual milk production can be estimated as five times the increase in lamb weight prior to weaning. The daily average milk production is estimated by dividing the resulting estimate by 365 days as shown in Equation 4.5c.

EQUATION 4.5b

NET ENERGY FOR LACTATION FOR SHEEP (MILK PRODUCTION KNOWN)

$$NE_l = \text{kg of milk/day} \bullet EV_{milk}$$

Where:

NE_l = net energy for lactation, MJ/day

EV_{milk} = the energy value for milk. A default value of 4.6 MJ/kg (AFRC, 1993) can be used

EQUATION 4.5C

NET ENERGY FOR LACTATION FOR SHEEP (MILK PRODUCTION UNKNOWN)

$$NE_l = ((5 \bullet WG_{lamb})/365 \text{ days/year}) \bullet EV_{milk}$$

Where:

NE_l = net energy for lactation, MJ/day

WG_{lamb} = the weight gain of the lamb between birth and weaning in kg/day

EV_{milk} = the energy value for milk. A default value of 4.6 MJ/kg (AFRC, 1993) can be used

Equations 4.5b and 4.5c assume that the characterisation is being developed for a full year (365 days). If a shorter period is being characterised (e.g. a wet season), then the number of days must be adjusted accordingly.

***Work*:** NE_w is the net energy for work. It is used to estimate the energy required for draft power for cattle and buffalo. Various authors have summarised the energy intake requirements for providing draft power (e.g. Lawrence, 1985; Bamualim and Kartiarso, 1985; and Ibrahim, 1985). The strenuousness of the work performed by the animal influences the energy requirements, and consequently a wide range of energy requirements have been estimated. The values by Bamualim and Kartiarso show that about 10 percent of a day's NE_m requirements are required per hour for typical work for draft animals. This value is used as follows:

EQUATION 4.6

NET ENERGY FOR WORK (FOR CATTLE AND BUFFALO)

$$NE_w = 0.10 \bullet NE_m \bullet \text{hours of work per day}$$

Where:

NE_w = net energy for work, MJ/day

NE_m = net energy required by the animal for maintenance (Equation 4.1), MJ/day

***Wool Production*:** NE_{wool} is the net energy required for sheep to produce a year of wool. The NE_{wool} is calculated as follows:

EQUATION 4.7

NET ENERGY TO PRODUCE WOOL (FOR SHEEP)

$$NE_{wool} = (EV_{wool} \bullet \text{annual wool production per sheep, kg/year})/(365 \text{ days/year})$$

Where:

NE_{wool} = net energy required to produce a year of wool, MJ/day

EV_{wool} = the energy value of each kg of wool produced (weighed after drying but before scouring)

AFRC provides for EV_{wool} the value 24 MJ/kg. At a typical wool production of about 4 kg/sheep/year, the energy demand will normally be quite small.

***Pregnancy*:** NE_p is the energy required for pregnancy. For cattle and buffalo, the total energy requirement for pregnancy for a 281-day gestation period averaged over an entire year is calculated as 10% of NE_m. For sheep, the NE_p requirement is similarly estimated for the 147-day gestation period, although the percentage varies with the number of lambs born (Table 4.7, Constant for Use in Calculating NE_p in Equation 4.8). Equation 4.8 shows how these estimates are applied.

EQUATION 4.8

NET ENERGY FOR PREGNANCY (FOR CATTLE/BUFFALO AND SHEEP)

$$NE_p = C_{pregnancy} \bullet NE_m$$

Where:

NE_p = net energy required for pregnancy, MJ/day

$C_{pregnancy}$ = pregnancy coefficient (see Table 4.7)

NE_m = net energy required by the animal for maintenance (Equation 4.1), MJ/day

When using NE_p to calculate GE for cattle and sheep, the NE_p estimate must be weighted by the portion of the mature females that actually go through gestation in a year. For example, if 80% of the mature females in the animal category give birth in a year, then 80% of the NE_p value would be used in the GE equation below.

TABLE 4.7

CONSTANTS FOR USE IN CALCULATING NE_p IN EQUATION 4.8

Animal Category	$C_{pregnancy}$
Cattle and Buffalo	0.10
Sheep	
Single birth	0.077
Double birth (twins)	0.126
Triple birth or more (triplets)	0.150

Source: Estimate for cattle and buffalo developed from data in NRC (1996). Estimates for sheep developed from data in AFRC (1993).

To determine the proper coefficient for sheep, the portion of ewes that have single births, double births, and triple births is needed to estimate an average value for $C_{pregnancy}$. If these data are not available, the coefficient can be calculated as follows:

- If the number of lambs born in a year divided by the number of ewes that are pregnant in a year is less than or equal to 1.0, then the coefficient for single births can be used.
- If the number of lambs born in a year divided by the number of ewes that are pregnant in a year exceeds 1.0 and is less than 2.0, calculate the coefficient as follows:

  $C_{pregnancy} = [(0.126 \bullet \text{Double Birth Fraction}) + (0.077 \bullet \text{Single Birth Fraction})]$

  Where:

  Double Birth Fraction = [(lambs born) / (pregnant ewes)] – 1

  Single Birth Fraction = 1 – Double Birth Fraction

- If the number of lambs born in a year divided by the number of ewes that are pregnant in a year exceeds 2, then expert judgement should be sought on how to estimate NE_p.

***NE_{ma}/DE*:** For cattle, buffalo and sheep, the ratio of net energy available in a diet for maintenance to digestible energy consumed NE_{ma}/DE is estimated using the following equation:

EQUATION 4.9

RATIO OF NET ENERGY AVAILABLE IN A DIET FOR MAINTENANCE TO DIGESTIBLE ENERGY CONSUMED

$$NE_{ma}/DE = 1.123 - (4.092 \bullet 10^{-3} \bullet DE) + [1.126 \bullet 10^{-5} \bullet (DE)^2] - (25.4/DE)$$

Where:

NE_{ma}/DE = ratio of net energy available in a diet for maintenance to digestible energy consumed

DE = digestible energy expressed as a percentage of gross energy

***NE_{ga}/DE*:** For cattle, buffalo and sheep the ratio of net energy available for growth (including wool growth) in a diet to digestible energy consumed NE_{ga}/DE is estimated using the following equation:

EQUATION 4.10

RATIO OF NET ENERGY AVAILABLE FOR GROWTH IN A DIET TO DIGESTIBLE ENERGY CONSUMED

$$NE_{ga}/DE = 1.164 - (5.160 \bullet 10^{-3} \bullet DE) + (1.308 \bullet 10^{-5} \bullet (DE)^2) - (37.4/DE)$$

Where:

NE_{ga}/DE = ratio of net energy available for growth in a diet to digestible energy consumed

DE = digestible energy expressed as a percentage of gross energy

Gross Energy, GE**:** As shown in Equation 4.11, GE is derived based on the net energy estimates and the feed characteristics. Equation 4.11 is similar to Equation 4.13 from the *IPCC Guidelines*, but it corrects a typesetting error and changes the subscripts on some of the terms to distinguish between the net energy available in the feed to meet a net energy requirement (i.e. NE_{ga}) and the net energy requirement of the animal (i.e. NE_g). It is *good practice* to use the corrected equation presented as Equation 4.11 below. Although the *IPCC Guidelines* do not present an equation specifically for sheep, Equation 4.11 represents *good practice* for calculating GE requirements for sheep using the results of the equations presented above.

In using Equation 4.11, only those terms relevant to each animal category are used (see Table 4.3).

EQUATION 4.11

GROSS ENERGY FOR CATTLE/BUFFALO AND SHEEP

$$GE = \{[(NE_m + NE_{mobilized} + NE_a + NE_l + NE_w + NE_p)/(NE_{ma}/DE)] + [(NE_g + NE_{wool}) / (NE_{ga}/DE)]\} / (DE/100)$$

Where:

GE = gross energy, MJ/day

NE_m = net energy required by the animal for maintenance (Equation 4.1), MJ/day

$NE_{mobilised}$ = net energy due to weight loss (mobilised) (Equations 4.4a and 4.4b), MJ/day

NE_a = net energy for animal activity (Equations 4.2a and 4.2b), MJ/day

NE_l = net energy for lactation (Equations 4.5a, 4.5b, and 4.5c), MJ/day

NE_w = net energy for work (Equation 4.6), MJ/day

NE_p = net energy required for pregnancy (Equation 4.8), MJ/day

NE_{ma}/DE = ratio of net energy available in a diet for maintenance to digestible energy consumed (Equation 4.9)

NE_g = net energy needed for growth (Equations 4.3a and 4.3b), MJ/day

NE_{wool} = net energy required to produce a year of wool (Equation 4.7), MJ/day

NE_{ga}/DE = ratio of net energy available for growth in a diet to digestible energy consumed (Equation 4.10)

DE = digestible energy expressed as a percentage of gross energy

Once the values for GE are calculated for each animal sub-category, the feed intake in units of kilograms of dry matter per day (kg/day) should also be calculated and compared to the weight of the typical animal in the sub-category. To convert from GE in energy units to dry matter intake, divide by the energy density of the feed. A default value of 18.45 MJ/kg can be used if feed-specific information is not available. The resulting daily dry matter intake should be on the order of 1% to 3% of the body weight of the animal.

CHARACTERISATION FOR ANIMALS WITHOUT EMISSION ESTIMATION METHODS

Some countries may have domesticated animals for which there are currently no Tier 1 or Tier 2 emissions estimating methods (e.g. llamas, alpacas, wapiti, emus, and ostriches). *Good practice* in estimating emissions from these animals is to first assess whether their emissions are likely to be significant enough to warrant characterising them and developing country-specific emission factors. Chapter 7, Methodological Choice and Recalculation, presents guidance for assessing the significance of individual source categories within the national inventory. Similar approaches can be used to assess the importance of sub-source categories (i.e. species) within a source category such as enteric fermentation. If the emissions from a particular sub-species are determined to be significant, then country-specific emission factors should be developed, and a characterisation should be performed to support the development of the emission factors. The characterisation used to support the Tier 2 emissions estimate for enteric fermentation from cattle is one example of how to develop an emission factor. The data and methods used to characterise the animals should be well documented.

As emissions estimation methods are not available for these animals, approximate emission factors based on ‘order of magnitude calculations’ are appropriate for conducting the assessment of the significance of their emissions. One approach for developing the approximate emission factors is to use the Tier 1 emissions factor for an animal with a similar digestive system and to scale the emissions factor using the ratio of the weights of the animals raised to the 0.75 power. The Tier 1 emission factors can be classified by digestive system as follows:

- Ruminant animals: cattle, buffalo, sheep, goats, camels
- Non-ruminant herbivores: horses, mules/asses
- Poultry: chickens, ducks, turkeys
- Non-poultry monogastric animals: swine

For example, an approximate enteric fermentation methane emissions factor for alpacas could be estimated from the emissions factor for sheep (also a ruminant animal) as follows:

Approximate emissions factor = [(alpaca weight)$^{0.75}$ / (sheep weight)$^{0.75}$] • sheep emissions factor.

Similarly, an approximate manure methane emissions factor for ostriches could be estimated using the Tier 1 emission factor for chickens. Approximate emission factors developed using this method can only be used to assess the significance of the emissions from the animals, and are not considered sufficiently accurate for estimating emissions as part of a national inventory.

4.1.1.2 DEVELOPING A CONSISTENT TIME SERIES

Developing a consistent time series may require estimating past livestock population characteristics. Typically, livestock population, milk production, and meat production data are available from national statistics for the complete time series. The other key attributes, which may not be as easily obtained through a review of past production data records, do not change rapidly, so back-estimating on the basis of ongoing trends (e.g. trends in live-weights) should be reliable. It should be noted, however, that some countries are experiencing rapid changes in livestock populations as a result of economic restructuring and changing market conditions. Additional investigation will be warranted in these circumstances to ensure that an adequate time series is developed. For general *good practice guidance* related to ensuring a consistent time series, see Chapter 7, Methodological Choice and Recalculation.

4.1.1.3 UNCERTAINTY ASSESSMENT

Each data element in the livestock characterisation has associated uncertainty that depends on how data were obtained. The factors that contribute most to the sensitivity of the feed intake estimates should be identified so that efforts are focused on estimating the uncertainties in these factors. The uncertainty of these factors should then be propagated through to the final estimates of feed intake to estimate the total uncertainty of the feed intake estimate.

The uncertainty in livestock population data is larger than typically recognised. There may well be systematic biases in the reporting of the livestock population to national census takers (positive and negative). The migration of livestock within or between countries may lead to double counting or under counting of some animals. Seasonal changes in populations may not be adequately reflected in annual census data. The population data should be examined in cooperation with the national statistical agencies with these factors in mind.

4.1.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. The current IPCC reporting tables do not provide a mechanism for reporting detailed livestock characteristics. It is *good practice* to provide additional tables for reporting detailed livestock characterisation. The detailed livestock characteristics could be reported in a summary table, such as shown in Table A-1 (p. 4.31) and Table A-2 (pp. 4.32-4.33) in Section 4 of the *IPCC Guidelines,* Reference Manual. The sources for the data in the summary table should be identified and cited clearly.

4.1.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to implement quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in the Tier 2 procedures in Chapter 8, QA/QC, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source. The general check of data processing, handling, and reporting could be supplemented with source specific procedures discussed below:

Activity data check

- The inventory agency should check for consistency in the livestock characterisation data that are used in the emission estimates for each of the pertinent source categories. Standard QC checks should verify that there is consistency in the data used across source categories.
- If data are available, the inventory agency should compute the change in total population over time using the population, birth and death rates, slaughter rates, and imports/exports for each of the animal categories or sub-categories and compare this to statistics on total population to ensure consistency. The inventory agency should make this calculation across years (e.g. 1990 to 1991 to 1992, and so on) as well as across seasons within individual years. The analysis across seasons is particularly important in countries with seasonal production conditions that create large variations in livestock populations during the year.
- The inventory agency should compare total production (e.g. meat, milk and wool) for the animal categories and sub-categories with the statistics on total production to ensure consistency.
- Feed intake estimates developed to support the Tier 2 enteric fermentation emissions estimates should be checked for reasonableness. For ruminant animals, the feed intake in dry matter (kg/day) should be on the order of 1% to 3% of the weight of the animals.
- The inventory agency should review QA/QC associated with secondary data sources (e.g. national food and agriculture agencies, agricultural trade associations, agricultural research organisations). Many of the organisations preparing the livestock-related data will have their own procedures for assessing the quality of the data, independent of what the end use of the data may be. If the QA/QC satisfies the minimum activities listed in the QA/QC plan, reference the QC activity conducted by the statistical organisation. If it is inadequate, establish independent QC checks on the secondary data, re-assess the uncertainty of the emissions estimates derived from the data, or reconsider how the data is used.
- The inventory agency should cross-check activity data against other available reference sources. For example, country-specific data should be compared to FAO statistics for livestock population data and milk production data. Investigate large discrepancies.

External review

- The inventory agency should conduct expert peer review on the livestock characterisation data, involving agricultural experts and specialists.

4.2 CH_4 EMISSIONS FROM ENTERIC FERMENTATION IN DOMESTIC LIVESTOCK

4.2.1 Methodological issues

Livestock are produced throughout the world and are a significant source of global methane (CH_4) emissions. The amount of enteric methane emitted is driven primarily by the number of animals, the type of digestive system, and the type and amount of feed consumed. Cattle, buffalo and sheep are the largest sources of enteric methane emissions.

4.2.1.1 CHOICE OF METHOD

To estimate CH_4 emissions from enteric fermentation, the *IPCC Guidelines* recommend multiplying the number of animals for each animal category by an appropriate emissions factor. Emissions from all animal categories are then summed to get total emissions. In order to maintain consistency in underlying data, it is *good practice* to use a single livestock population characterisation as a framework for estimating CH_4 emissions from enteric fermentation as well as CH_4 and N_2O emissions from manure management. The *Livestock Population Characterisation* section (see Section 4.1) provides guidance on preparing the characterisation.

The *IPCC Guidelines* describe two general methods for estimating emissions from enteric fermentation (see Figure 4.2, Decision Tree for CH_4 Emissions from Enteric Fermentation):

- The Tier 1 method is a simplified approach that relies on default emission factors drawn from previous studies. The Tier 1 approach is likely to be sufficient for many countries and can be used to estimate emissions for the following animals: dairy cows, other cattle, buffalo, sheep, goats, camels, horses, mules, asses and swine.
- The Tier 2 method is a more complex approach that requires detailed country-specific data on nutrient requirements, feed intake and CH_4 conversion rates for specific feed types, which are used to develop emission factors for country-defined livestock categories. The Tier 2 approach should be used if enteric fermentation is a key source category (as defined in Chapter 7, Methodological Choice and Recalculation) for the animal categories that represent a large portion of the country's total emissions.[2]

Tier 1 Method

Under the Tier 1 method, data on livestock categories and milk production should be used to select default emission factors. Tables 4.3 and 4.4 in the Reference Manual of the *IPCC Guidelines* provide default emission factors for each livestock category. As shown in Equation 4.12, the emission factor is multiplied by the number of animals to determine total emissions for each livestock category. Total emissions for this source category are the sum of all livestock categories as shown in Equation 4.13. It is *good practice* to review the Tier 1 emission factors to ensure that the underlying animal characteristics such as weight, growth rate and milk production used to develop them are similar to the conditions in the country. The *IPCC Guidelines* currently provide detailed information for cattle and buffalo. These data should be reviewed by livestock experts in the country and if the underlying characteristics are significantly different, the emission factors should be adjusted accordingly.

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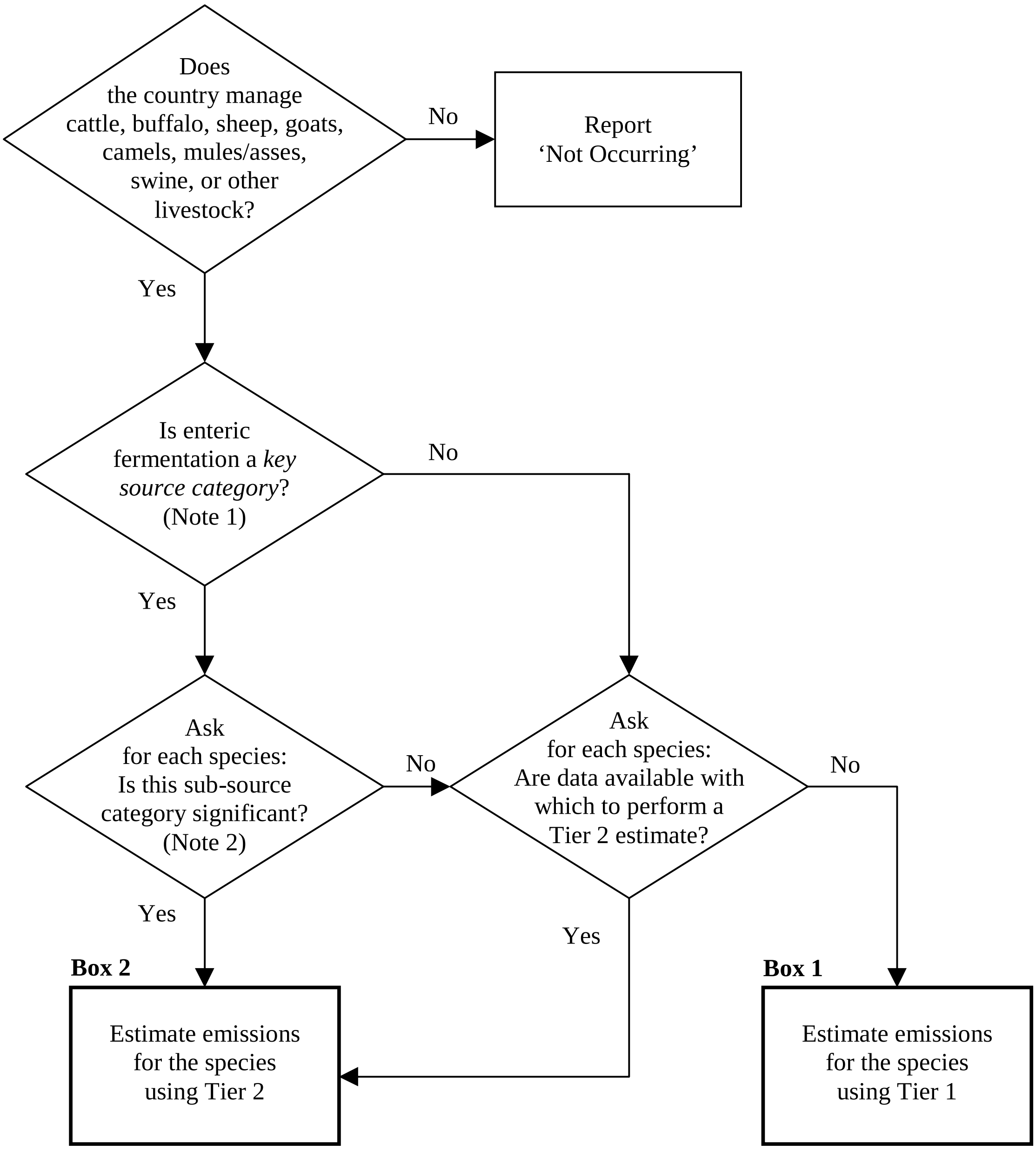
[2] Countries, with large populations of domesticated animal species for which there are no IPCC default emission factors (e.g. llamas and alpacas), are encouraged to develop national methods that are similar to the Tier 2 approach and are based on well-documented research (if it is determined that emissions from these animals are significant). See Section 4.1 under the heading 'Characterisation for Animals Without Emission Estimation Methods' for more information.

Figure 4.2 Decision Tree for CH_4 Emissions from Enteric Fermentation



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: As a rule of thumb, a sub-source category would be significant if it accounts for 25-30% of emissions from the source category.

EQUATION 4.12

EMISSIONS FROM A LIVESTOCK CATEGORY

$$\text{Emissions} = \text{EF} \bullet \text{population}/(10^6\ \text{kg/Gg})$$

Where:

Emissions = methane emissions from enteric fermentation, Gg CH_4/year

EF = emission factor for the specific population, kg/head/year

Population = the number of animals, head

EQUATION 4.13

TOTAL EMISSIONS FROM LIVESTOCK

$$\text{Total } CH_4 \text{ Emissions} = \sum_i E_i$$

Where:

Total Emissions = total methane emissions from enteric fermentation, Gg CH_4/year

index i = sums all livestock categories and sub-categories

E_i = is the emissions for the i^{th} livestock categories and sub-categories

Tier 2 Method

The Tier 2 method also uses Equation 4.12 to calculate emissions, but applies it to more disaggregated livestock population categories and uses calculated emission factors, as opposed to default values. Equation 4.13 should be used to sum the emissions from the disaggregated categories of livestock species for all livestock species to obtain the total emissions for a country. The key issues for the Tier 2 method are the development of emission factors and the collection of detailed activity data. The development of emission factors is described in the next section. Issues related to the collection of activity data are covered in Section 4.1, Livestock Population Characterisation.

4.2.1.2 CHOICE OF EMISSION FACTORS

When the Tier 1 method is used, default emission factors should be taken from the *IPCC Guidelines* Tables 4-3 and 4-4, unless documented country-specific factors are available. When Tier 2 methods are used, in contrast, emission factors specific to the country and its animal species/categories need to be developed. As described in Chapter 7, Methodological Choice and Recalculation, inventory agencies are encouraged to determine what source sub-categories are significant, as some species are likely to represent the major share of enteric fermentation emissions. It is considered *good practice* to develop disaggregated emission factors for those sub-categories that are most significant in terms of emissions.

When the Tier 2 method is used, emission factors are estimated for each animal category using the detailed data developed through the livestock characterisation as set out in the Livestock Population Characterisation section (see Section 4.1). The *IPCC Guidelines* discuss how to develop emission factors for cattle. G*ood practice* in developing these factors is discussed below. In the absence of data for buffalo, the approach described for cattle can be applied to buffalo, given the similarities between these bovine species. In addition, *good practice* for developing sheep emission factors is described below, since this is an important animal species in many countries.

An emission factor for each animal category should be developed using Equation 4.14:

EQUATION 4.14

EMISSION FACTOR DEVELOPMENT

$$EF = (GE \bullet Y_m \bullet 365\ \text{days/yr}) \ / \ (55.65\ \text{MJ/kg}\ CH_4)$$

Where:

EF = emission factor, kg CH_4/head/yr

GE = gross energy intake, MJ/head/day

Y_m = methane conversion rate which is the fraction of gross energy in feed converted to methane

This emission factor equation assumes that the emission factors are being developed for an animal category for an entire year (365 days). While a full year emission factor is typically used, in some circumstances the animal category may be defined for a shorter period (e.g. for the wet season of the year or for a 150-day feedlot feeding period). In this case, the emission factor would be estimated for the specific period (e.g. the wet season) and the 365 days would be replaced by the number of days in the period. The definition of the period to which the emission factor applies is described as part of the livestock characterisation.

The gross energy intake value (GE) for each animal category is taken from the livestock characterisation presented in Section 4.1.

Obtaining the Methane Conversion Rate (Y_m)

The extent to which feed energy is converted to CH_4 depends on several interacting feed and animal factors. If CH_4 conversion rates are unavailable from country-specific research, the values provided in Table 4.8, Cattle/Buffalo CH_4 Conversion Rates, can be used for cattle and buffalo. These general estimates are a rough guide based on the general feed characteristics and production practices found in many developed and developing countries. When good feed is available (i.e. high digestibility and high energy value) the lower bounds should be used. When poorer feed is available, the higher bounds are more appropriate. A CH_4 conversion rate of zero is assumed for all juveniles consuming only milk (i.e. milk-fed lambs as well as calves).

Due to the importance of Y_m in driving emissions, substantial ongoing research is aimed at improving estimates of Y_m for different animals and feed combinations. Such improvement is most needed for animals fed on tropical pastures as the available data is sparse. For example, a recent study (Kurihara *et al.*, 1999) observed Y_m values outside the ranges described in Table 4.8.

TABLE 4.8

CATTLE/BUFFALO CH_4 CONVERSION RATES (Y_m)

Countries	**Livestock type**	**Y_m [b]**
Developed Countries	Feedlot fed cattle [a]	0.04 ± 0.005
	All other cattle	0.06 ± 0.005
Developing Countries	Dairy cows (cattle and buffalo) and their young	0.06 ± 0.005
	Other cattle and buffaloes that are primarily fed low quality crop residues and by-products	0.07 ± 0.005
	Other cattle or buffalo in Africa - grazing	0.07 ± 0.005
	Other cattle or buffalo in developing countries other than Africa-grazing	0.06 ± 0.005

[a] When fed diets contain 90 percent or more concentrates.

[b] The ± values represent the range.

Source: *IPCC Guidelines.*

The Y_m value for sheep may not be the same as for cattle. Lassey *et al.* (1997) suggest that the Y_m for 8-month-old lambs is less (0.045) than for lactating dairy cows (0.062) fed near-identical high quality pasture. Sheep should not be viewed as merely small cattle as far as nutritional performance is concerned, as they differ behaviourally (feed selection) and may also differ in their rumen microbiology. Using Table 4.9, Sheep CH_4 Conversion Rates, Y_m values are selected according to feed quality (as measured by digestibility) and sheep maturity. They are based on data by Lassey *et al.* (1997), Judd *et al.* (1999) and on unpublished data from the same research group [K.R. Lassey and M.J. Ulyatt, personal communication]. The median of each range may be adopted, including 0.07 for mature sheep on all pastures. These values are consistent with measurements by other researchers (Murray *et al.*, 1998; Leuning *et al.*, 1999) but may not span the full range of pastures that may be found.

TABLE 4.9
SHEEP CH_4 CONVERSION RATES (Y_m)

Category	**Diets less than 65% digestible**	**Diets greater than 65% digestible**
Lambs (<1 year old)	0.06 ± 0.005	0.05 ± 0.005
Mature sheep	0.07	0.07

Note: The ± values represent the range.

Source: Lassey *et al.* (1997); Lassey and Ulyatt (1999).

4.2.1.3 CHOICE OF ACTIVITY DATA

The activity data should be collected following the guidance from the Livestock Population Characterisation section (see Section 4.1). This approach will ensure consistency with the other related source categories.

4.2.1.4 COMPLETENESS

It is likely that all the major animals managed in the country are known. Consequently, completeness should be achievable. In the event that animals are included in the inventory for which default data are not available and for which no guidelines are provided, the emissions estimate should be developed using the same general principles presented in the discussion of how to develop Tier 2 emission factors.

4.2.1.5 DEVELOPING A CONSISTENT TIME SERIES

The key issues associated with developing a consistent time series are discussed in the Livestock Population Characterisation section (Section 4.1). Care must be taken to use a consistent set of estimates for the CH_4 conversion rate over time. In some cases, there may be reasons to modify these values of methane conversion rates over time. These changes may be due to the implementation of explicit greenhouse gas (GHG) mitigation measures, or may be due to changing agricultural practices such as feed conditions or other management factors without regard to GHGs. Regardless of the driver of change, the data and methane conversion rates used to estimate emissions must reflect the change in data and methods, and the results must be thoroughly documented. If methane conversion rates over a time series are affected by a change in farm practices and/or the implementation of GHG mitigation measures, the inventory agency is encouraged to ensure that the inventory data reflect these practices and that the inventory text thoroughly explains how the change in farm practices and/or implementation of mitigation measures has affected the time series of methane conversion rates. For general *good practice* guidance on developing a consistent time series, see Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2.

4.2.1.6 UNCERTAINTY ASSESSMENT

Below is a description of the major uncertainty issues for the Tier 1 and Tier 2 methods.

Tier 1 Method

As the emission factors for the Tier 1 method are not based on country-specific data, they may not accurately represent a country’s livestock characteristics, and may be highly uncertain as a result. Emission factors estimated using the Tier 1 method are unlikely to be known more accurately than ± 30% and may be uncertain to ± 50%.

There will be an added uncertainty associated with the livestock population characterisation (see Section 4.1) which can be minimised provided the *good practice* approach to agricultural census data outlined in the section on livestock population characterisation is followed.

Tier 2 Method

The uncertainty under the Tier 2 approach will depend on the accuracy of the livestock characterisation (e.g. homogeneity of livestock categories), and also on the extent to which the methods for defining the coefficients in the various relationships that make up the net energy approach correspond to national circumstances. Improving the livestock characterisation will often be the priority in reducing overall uncertainty. Emission factor estimates using the Tier 2 method are likely to be in the order of ± 20%. Inventory agencies using the Tier 2 method are encouraged to undertake an analysis of uncertainties reflecting their particular situation, and in the absence of this analysis the uncertainty under the Tier 2 method should be assumed similar to the uncertainty under the Tier 1 method.

4.2.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. To improve transparency, emission estimates from this source category should be reported along with the activity data and emission factors used to determine the estimates.

The following information should be documented:

- All activity data, including :
    (i) Animal population data by category and region.
- Activity data documentation including:
    (i) The sources of all activity data used in the calculations (i.e. complete citation for the statistical database from which data were collected);
    (ii) The information and assumptions that were used to develop the activity data, in cases where activity data were not directly available from databases;
    (iii) The frequency of data collection, and estimates of accuracy and precision.
- If the Tier 1 method is used, all default emission factors used in the emissions estimations for the specific animal categories
- If the Tier 2 method is used
    (i) Values for Y_m;
    (ii) GE values estimated or taken from other studies;
    (iii) Documentation of the data used, including their references.

In inventories in which country- or region-specific emission factors were used or in which new methods (other than those described in the *IPCC Guidelines*) were used, the scientific basis of these emission factors and methods should be documented. Documentation should include definitions of input parameters providing a description of the process by which these emission factors and methods are derived, as well as describing sources and magnitudes of uncertainties.

4.2.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to implement quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8, QA/QC, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. In addition to the guidance in Chapter 8, QA/QC, specific procedures of relevance to this source category are outlined below:

Review of emission factors

- If using the Tier 2 method, the inventory agency should cross-check country-specific factors against the IPCC defaults. Significant differences between country-specific factors and default factors should be explained and documented.

External review

- If the Tier 2 method is being used, the inventory agency should conduct expert peer review, including from industry, academic institutions, and extension expertise.
- It is important to maintain internal documentation on review results.

4.3 CH_4 EMISSIONS FROM MANURE MANAGEMENT

4.3.1 Methodological issues

Livestock manure is principally composed of organic material. When this organic material decomposes in an anaerobic environment, methanogenic bacteria produce methane (CH_4). These conditions often occur when large numbers of animals are managed in confined areas (e.g. dairy, swine and poultry farms, and beef feedlots, where manure is typically stored in large piles or disposed of in storage tanks or lagoons).

4.3.1.1 CHOICE OF METHOD

To estimate emissions of CH_4 from manure management systems, the animal population must first be divided into the appropriate species and categories to reflect the varying amounts of manure produced per animal and the manner in which the manure is handled. Detailed information on how to characterise the livestock population for this source is provided in the section on Livestock Population Characterisation (see Section 4.1).

As described in the *IPCC Guidelines*, the four main steps used to estimate CH_4 emissions from livestock manure are as follows:

(i) Collect population data from Livestock Population Characterisation;

(ii) Use default IPCC emission factors or develop emission factors on the basis of manure characteristics (B_o, VS, MCF) for each relevant livestock population (species, category or subcategory) and manure management system;

(iii) Multiply each emission factor by the defined livestock population to obtain the CH_4 emission estimate for that livestock population;

(iv) Sum emissions from all defined livestock population to determine national emissions.

Emission estimates should be reported in gigagrams (Gg). As the emission factors are to be reported in kilograms per head per year, the emissions are divided by 10^6. Equation 4.15 shows how to calculate emissions for a defined population:

EQUATION 4.15

CH_4 EMISSION FROM MANURE MANAGEMENT

$$CH_4 \text{ Emissions}_{(mm)} = \text{Emission Factor} \bullet \text{Population} \; / \; (10^6 \text{ kg/Gg})$$

Where:

CH_4 Emissions$_{(mm)}$ = CH_4 emissions from manure management, for a defined population Gg/year

Emission Factor = emission factor for the defined livestock population, kg/head/year

Population = the number of head in the defined livestock population

The *IPCC Guidelines* include two tiers to estimate CH_4 emissions from livestock manure. The Tier 1 approach is a simplified method that only requires livestock population data by animal species/category and climate region (cool, temperate, warm), in order to estimate emissions.

The Tier 2 approach provides a detailed method for estimating CH_4 emissions from manure management systems, and is encouraged to be used for countries where a particular livestock species/category represents a significant share of emissions. This method requires detailed information on animal characteristics and the manner in which manure is managed. Using this information, emission factors are developed that are specific to the conditions of the country.

The method chosen will depend on data availability and natural circumstances. *Good practice* in estimating CH_4 emissions from manure management systems entails making every effort to use the Tier 2 method, including calculating emission factors using country-specific factors. The Tier 1 approach should only be used if all possible avenues to use the Tier 2 approach have been exhausted. The process for determining which tier to use is shown in the decision tree (see Figure 4.3).

4.3.1.2 CHOICE OF EMISSION FACTORS

The ideal means of determining emission factors is to conduct non-invasive or non-disturbing measurements of emissions in actual production systems (feedlot, pasture). These field results can be used to develop models to estimate emission factors. Such measurements are difficult to conduct, however, and require significant resources, unique expertise, and equipment that may not be available. Thus, while such an approach is recommended to improve accuracy, it is not necessarily required for *good practice* depending on national circumstances.

When using the Tier 1 method, default emission factors are used. Default emission factors are presented in Table 4-6 of the *IPCC Guidelines*, Reference Manual for each of the recommended population subgroups.[3]

If region-specific or country-specific measurement data are not available, Tier 2 emission factors should be developed using the method described in the *IPCC Guidelines*. The process of developing Tier 2 emission factors involves determining the mass of volatile solids excreted by the animals (VS, in kg) along with the maximum CH_4 producing capacity for the manure (B_o, in m^3/kg of VS). In addition, a CH_4 conversion factor (MCF) that accounts for the influence of climate on CH_4 production must be obtained for each manure management system.

As emissions can vary significantly by region and animal species/category, emission estimates should reflect to the maximum extent possible the diversity and range of animal populations and manure management practices between different regions within a country. This may require separate estimates to be developed for each region. Emission factors should be periodically updated to account for changes in manure management practices, animal characteristics, and technologies. These revisions should be based on the most reliable scientifically reviewed data available. Frequent monitoring is desirable to verify key model parameters, but this may not be feasible.

VS Excretion Rates: The best way to obtain average daily VS excretion rates is to use data from country-specific published sources. If average daily VS excretion rates are not available, country-specific VS excretion rates can be estimated from feed intake levels. Feed intake for cattle and buffalo can be estimated using the ‘Enhanced’ characterisation method described in the Livestock Population Characterisation section (see Section 4.1). This will also assure consistency in the data underlying the emissions estimates. For swine, country-specific swine production data may be required to estimate feed intake. Once feed intake is estimated, the VS excretion rate is estimated as:

EQUATION 4.16

VOLATILE SOLID EXCRETION RATES

$$VS = GE \bullet (1 \text{ kg-dm}/18.45 \text{ MJ}) \bullet (1 - DE/100) \bullet (1 - ASH/100)$$

Where:

VS = volatile solid excretion per day on a dry-matter weight basis, kg-dm/day

GE = Estimated daily average feed intake in MJ/day

DE = Digestible energy of the feed in percent (e.g. 60%)

ASH = Ash content of the manure in percent (e.g. 8%)

Note: The value 18.45 is the energy density of feed expressed in MJ per kg dry matter. This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.

For cattle, the DE value used should be the value used in the ‘Enhanced’ characterisation method described in the Livestock Population Characterisation (see Section 4.1). The ash content of cattle and buffalo manure is generally around 8% (IPCC,1996). For swine, default values for digestibility are 75% and 50% for developed

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[3] It should be noted, however, that there is an error in Table 4-6 of the *IPCC Guidelines*. The error is the default CH_4 emission factor for non-dairy cattle in temperate regions in Latin America. The value should be 1 instead of 2, as shown correctly in Appendix B of the *IPCC Guidelines*, Vol. 3.

and developing countries, respectively. As to ash content, values of 2% and 4% can be used for developed and developing countries, respectively (IPCC, 1996).

If country-specific VS values cannot be developed, the default VS production rates presented in the *IPCC Guidelines* Reference Manual (Tables B1-B7) can be used. These default factors were developed based on average feed intake and feed digestibility data, and are considered reasonably reliable.

B_o values: The preferred method to obtain B_o measurement values is to use data from country-specific published sources, measured with a standardised method. It is important to standardise the B_o measurement, including the way of sampling. If country-specific B_o measurement values are not available, default values are provided in Appendix B of the *IPCC Guidelines*, Reference Manual.[4]

MCF Values: Default MCF values are provided in the *IPCC Guidelines* for different manure management systems and climate zones. These default values may not, however, encompass the potentially wide variation within the defined categories of management systems. Therefore, country-specific MCFs that reflect the specific management systems used in particular countries or regions should be developed as far as possible. This is particularly important for countries with large animal populations or with multiple climate regions. In such cases, and if possible, field measurements should be conducted for each climate region to replace the laboratory-based default MCF values. Measurements should include the following factors:

- Timing of storage/application;
- Length of storage;
- Manure characteristics;
- Determination of the amount of manure left in the storage facility (methanogenic inoculum);
- Time and temperature distribution between indoor and outdoor storage;
- Daily temperature fluctuation;
- Seasonal temperature variation.

If country-specific MCF measurements are not available, default MCF values are presented in the *IPCC Guidelines* Reference Manual (Table 4-8). Some of these default values are revised as shown in Table 4.10, MCF Values for Manure Management Systems Defined in the *IPCC Guidelines*, (revisions are in italics). The revisions in Table 4.10 present an approach for subdividing digester and anaerobic lagoon systems to account for the recovery, flaring and use of biogas. Such subdivision is important in order to account for policy measures that encourage CH_4 recovery from these systems. Table 4.11, MCF Values for Manure Management Systems not Specified in the Guidelines, presents MCF values for some additional manure management systems currently in use in various countries that were not specifically addressed in the *IPCC Guidelines*. In countries where these systems are in use, disaggregation into these categories is encouraged. The default MCF values presented in Table 4.11 can be used if country-specific values are unavailable.

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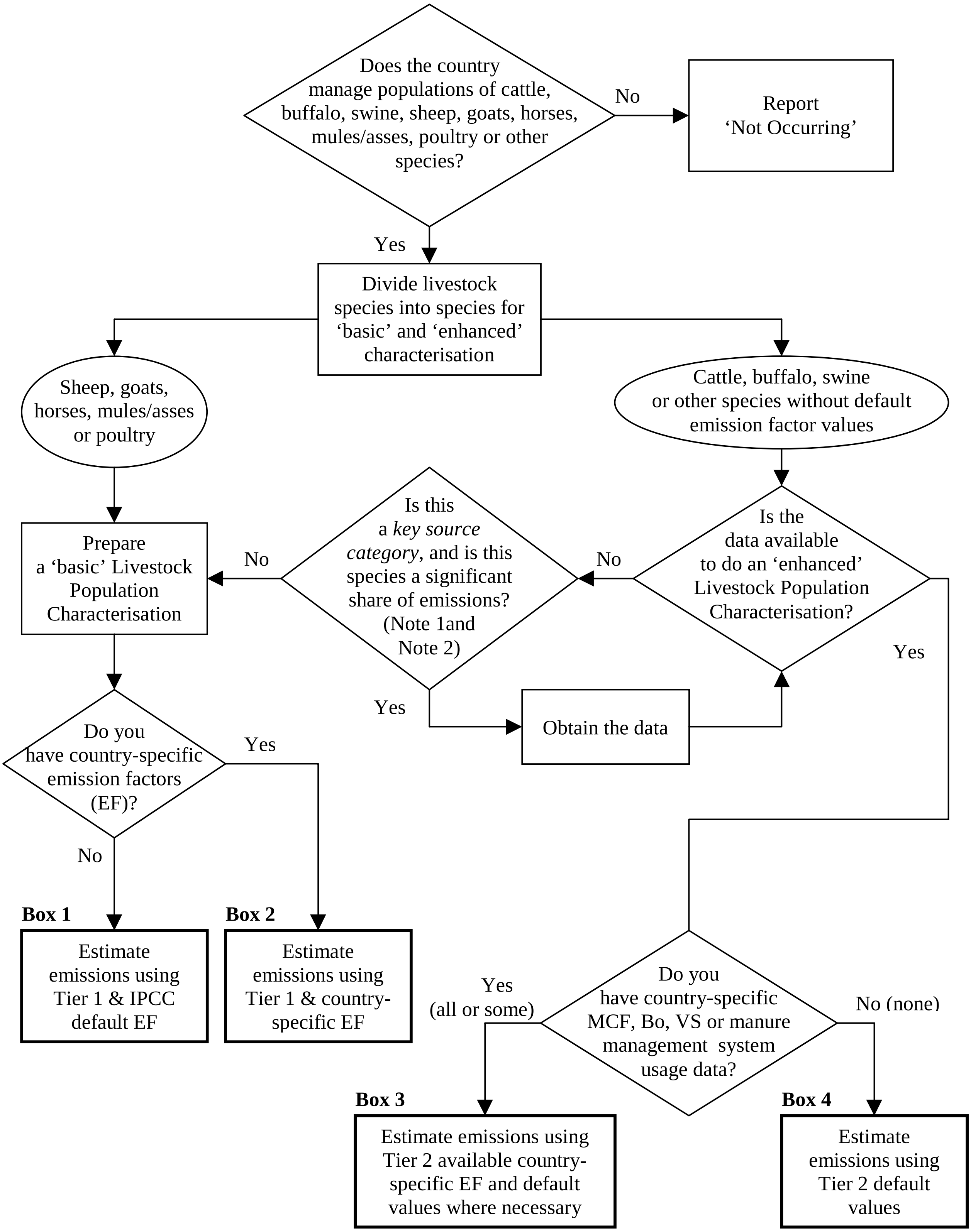
[4] When choosing default B_o values, if the production practices in the developing country are similar to those in developed countries, then the value for developed countries should be chosen.

Figure 4.3 Decision Tree for CH_4 Emissions from Manure Management



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country’s total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: As a rule of thumb, a sub-source category would be significant if it accounts for 25-30% of emissions from the source category.

Emission Factor Equation: Equation 4.17 shows how to calculate the emission factor for CH_4 from manure management:

EQUATION 4.17

EMISSION FACTOR FROM MANURE MANAGEMENT

$$EF_i = VS_i \bullet 365 \text{ days/year} \bullet B_{o_i} \bullet 0.67 \text{ kg/m}^3 \bullet \Sigma_{(jk)} MCF_{jk} \bullet MS_{ijk}$$

Where:

EF_i = annual emission factor for defined livestock population *i*, in kg

VS_i = daily VS excreted for an animal within defined population *i*, in kg

B_{o_i} = maximum CH_4 producing capacity for manure produced by an animal within defined population *i*, m^3/kg of VS

MCF_{jk} = CH_4 conversion factors for each manure management system *j* by climate region *k*

MS_{ijk} = fraction of animal species/category *i*'s manure handled using manure system *j* in climate region *k*

4.3.1.3 CHOICE OF ACTIVITY DATA

There are two main types of activity data for estimating CH_4 emissions from manure management: (1) animal population data and (2) manure management system usage data.

The animal population data should be obtained using the approach described in the Livestock Population Characterisation section (see Section 4.1). As noted in the section, the *good practice* method for characterising livestock populations is to conduct a single characterisation that will provide the activity data for all emissions sources relying on livestock population data. It is important to note, however, that the level of disaggregation in the livestock population data required to estimate emissions from this source category may differ from those used for other sources, such as enteric fermentation. For example, for some livestock population species/categories, such as cattle, the 'Enhanced' characterisation required for the Tier 2 enteric fermentation estimate could be aggregated to broader categories that are sufficient for this source category.

Inventory agencies in countries with varied climatic conditions are encouraged to obtain population data for each major climatic zone. Such an effort will improve accuracy because CH_4 emissions from manure management systems can vary considerably depending on the climate. Ideally, the regional breakdown can be obtained from published national statistics. If regional data are not available, experts should be consulted regarding regional production (e.g. milk, meat, and wool) patterns or land distribution, which may provide the required information to estimate the regional animal distributions.

The best means of obtaining manure management system distribution data is to consult regularly published national statistics. If such statistics are unavailable, the preferred alternative is to conduct an independent survey of manure management system usage. If the resources are not available to conduct a survey, experts should be consulted to obtain an opinion of the system distribution. Chapter 6, Quantifying Uncertainties in Practice, Section 6.2.5, describes how to elicit expert judgement for uncertainty ranges. Similar expert elicitation protocols can be used to obtain manure management system distribution data.

For a regional emissions analysis, it is important that regional data for both population and manure management system usage is used. Additionally, information on climatic differences among regions within a country must be obtained so that the proper MCFs can be applied. If all of these data are not available at a regional level, a regional analysis will not be more accurate than a national-level emissions study.

4.3.1.4 COMPLETENESS

A complete inventory will include emissions estimates from all domesticated animal population manure sources in a country, regardless of the tier that is applied. The listed IPCC animal population categories are distinct and population data are generally available from national references or the FAO. Thus, inventory agencies should be able to develop an emissions estimate that encompasses all of the required animal population species.

4.3.1.5 DEVELOPING A CONSISTENT TIME SERIES

Developing a consistent time series for the Tier 1 method requires collecting and compiling animal population and manure management data during the time period. For the Tier 1 method, difficulties arise when:

- Animal population data are not available for the entire period;
- Animal population data over the entire period are not broken down into the animal species/categories recommended by IPCC;
- Changes in manure management practices over time affect CH_4 emissions.

Animal population data can be obtained by collecting aggregate historical data from FAO and using current data to break out historical population data into the animal groups. If significant changes in manure management practices have occurred over time, the Tier 1 method will not provide an accurate time series of emissions, and the Tier 2 method should be considered.

In addition to the data issues described for the Tier 1 method, developing a time series for the Tier 2 method requires the collection and compilation of country-specific manure management system data. Difficulties arise in the Tier 2 method when:

- Manure management system data are not available for some period during the time series;
- Manure management system data are not broken down into the systems recommended by IPCC;
- The Tier 2 method was not used throughout the time series.

The lack of reliable manure management system data can be addressed by extrapolating manure management system trends from a sample area or region to the entire country, if climatic conditions are similar (i.e. temperature and rainfall). If the emission estimation method has changed, historical data that are required by the current method should be collected and used to recalculate emissions for that period. If such data are not available, it may be appropriate to create a trend with recent data and use the trend to back-estimate management practices for the time series. Among other sources, publications and industry and university experts can be used to develop trends for the animal population and manure characteristics. Chapter 7, Methodological Choice and Recalculation, provides guidance on how to address these issues. Section 4.1 suggests approaches for the animal population aspects.

4.3.1.6 UNCERTAINTY ASSESSMENT

Expert judgement will, in the probable absence of extensive empirical data, be required to assess uncertainties for this source. Chapter 6, Quantifying Uncertainties in Practice, provides advice for obtaining expert judgements and combining them with other uncertainties.

Experts can estimate uncertainty by evaluating the various components of the emission estimate. The major sources of uncertainty are the accuracy of emission factors, manure management system distribution, and activity data. The default values (either Tier 1 or 2 method) may have a large uncertainty for an individual country, because they may not reflect the actual conditions within the country. Uncertainties can be reduced by developing and using a model that relates MCF and B_o values to different country/region specific factors.

TABLE 4.10

MCF VALUES FOR MANURE MANAGEMENT SYSTEMS DEFINED IN THE *IPCC GUIDELINES* (REVISIONS ARE NOTED IN ITALICS)

SYSTEM	DEFINITION	MCFs BY CLIMATE			COMMENTS
		Cool	Temperate	Warm	
Pasture/Range/ Paddock	The manure from pasture and range grazing animals is allowed to lie as is, and is not managed.	1%	1.5%	2%	
Daily Spread	*Dung and urine are collected by some means such as scraping. The collected waste is applied to fields.*	0.1%	0.5%	1%	
Solid Storage	*Dung and urine are excreted in a stall. The solids (with or without litter) are collected and stored in bulk for a long time (months) before disposal, with or without liquid runoff into a pit system.*	1%	1.5%	2%	
Dry lot	In dry climates animals may be kept on unpaved feedlots where the manure is allowed to dry until it is periodically removed. Upon removal the manure may be spread on fields.	1%	1.5%	5%	
Liquid/Slurry	*Dung and urine are collected and transported in liquid state to tanks for storage. Liquid may be stored for a long time (months). To facilitate handling water may be added.*	*39%*	*45%*	*72%*	When slurry tanks are used as fed-batch storage/digesters, MCF should be calculated according to formula 1.
Anaerobic Lagoon	Characterised by flush systems that use water to transport manure to lagoons. The manure resides in the lagoon for period from 30 days to over 200 days. The water from the lagoon may be recycled as flush water or used to irrigate and fertilise fields.	*0-100%*	*0-100%*	*0-100%*	Should be subdivided in different categories, considering % recovery of the biogas and flaring of the biogas . Calculation with formula 1.
Pit Storage below animal confinements	*Combined storage of dung and urine below animal confinements:* *<1 month* *>1 month*	*0* *39%*	*0* *45%*	*30%* *72%*	When pits used as fed-batch storage/digesters, MCF should be calculated according to formula 1. Note that the ambient temperature, not the stable temperature is to be used for determining the climatic conditions.
Anaerobic Digester	*The dung and urine in liquid/slurry are collected and anaerobically digested. CH4 may be burned flared or vented.*	0-100%	0-100%	0-100%	Should be subdivided in different categories, considering amount of recovery of the biogas, flaring of the biogas and storage after digestion.
Burned for Fuel	*The dung and urine are excreted on fields. The sun dried dung cakes are burned for fuel.*	*10%*	*10%*	*10%*	

Source: *IPCC Guidelines* and Judgement by Expert Group (see Co-chairs, Editors and Experts; CH_4 Emissions from Manure Management).

Formula 1:
$MCF = [\{CH_{4\ prod} - CH_{4\ used} - CH_{4\ flared} + MCF_{storage} * (B_o - CH_{4\ prod})\}/ B_o] *100\%$
Where:
$CH_{4\ prod}$ = methane production in digester , (l CH_4/gVS added). Note: When a gas tight coverage of the storage for digested manure is used, the gas production of the storage should be included.
$CH_{4\ used}$ = amount of methane gas used for energy, (l CH_4/gVS added)
$CH_{4\ flared}$ = amount of methane flared, (l CH_4/gVS added)
$MCF_{storage}$ = CH_4 emitted during storage of digested manure (%)
When a gas tight storage is included: $MCF_{storage} = 0$; otherwise $MCF_{storage}$ = MCF value for liquid storage

TABLE 4.11

MCF VALUES FOR MANURE MANAGEMENT SYSTEMS NOT SPECIFIED IN THE *IPCC GUIDELINES* (JUDGEMENT BY EXPERT GROUP)

Additional Systems	**Definition**	**MCFS BY CLIMATE**			**Comments**
		Cool	**Temperate**	**Warm**	
Cattle and Swine Deep Litter	Cattle/swine dung and urine are excreted on stall floor. The accumulated waste is removed after a long time.				
	<1 month	0	0	30%	MCF’s are similar to liquid/slurry; temperature dependant.
	>1 month	39%	45%	72%	
Composting - Intensive	Dung and urine are collected and placed in a vessel or tunnel, there is forced aeration of the waste.	0.5%	0.5%	0.5%	MCF’s are less than half of solid storage. Not temperature dependant.
Composting - Extensive	Dung and urine collected, stacked and regularly turned for aeration.	0.5%	1%	1.5%	MCF’s are slightly less than solid storage. Less temperature dependant.
Poultry manure with bedding	Manure is excreted on floor with bedding. Birds walk on waste.	1.5%	1.5%	1.5%	MCF’s are similar to solid storage but with generally constant warm temperatures.
Poultry manure without bedding	Manure is excreted on floor without bedding. Birds do not walk on waste.	1.5%	1.5%	1.5%	MCF’s are similar to dry lot at a warm climate.
Aerobic Treatment	Dung and urine are collected as a liquid. The waste undergoes forced aeration, or treated in aerobic pond or wetland systems to provide nitrification and denitrification.	0.1%	0.1%	0.1%	MCF’s are near zero. Aerobic treatment results in large accumulations of sludge. Sludge requires removal and has large VS values. It is important to identify the next management process for the sludge and estimate the emissions from that management process if significant.

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts; CH_4 Emissions from Manure Management).

4.3.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. To improve transparency, emission estimates from this source category should be reported along with the activity data and emission factors used to determine the estimates.

The following information should be documented:

- All activity data, including:
  - (i) Animal population data by species/category and by region if applicable;
  - (ii) Climatic conditions in regions if applicable;[5]
  - (iii) Manure management system data, by animal species/category and by region, if applicable.
- Activity data documentation, including:
  - (i) The sources of all activity data used in the calculations (i.e. complete citations for the statistical database from which data were collected), and in cases where activity data were not available directly from databases, the information and assumptions that were used to derive the activity data;
  - (ii) The frequency of data collection, and estimates of accuracy and precision.
- If the Tier 1 method is used, all default emission factors used in the emissions estimation for the specific animal population species/category.
- If the Tier 2 method is used, emission factor calculation components, including:
  - (i) VS and B_o values for all animal population types in inventory, whether country-specific, region-specific, or IPCC default.
  - (ii) MCF values for all manure management systems used, whether country-specific or IPCC default.
- Emission factors documentation, including:
  - (i) References for the emission factors that were used (IPCC default or otherwise).
  - (ii) The scientific basis of these emission factors and methods, including definition of input parameters and description of the process by which these emission factors and methods are derived, as well as describing sources and magnitudes of uncertainties. (In inventories, in which country- or region-specific emission factors were used or in which new methods other than those described in the *IPCC Guidelines* were used).

4.3.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to implement quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8, QA/QC, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source. The general QA/QC related to data processing, handling, and reporting, as outlined in Chapter 8, QA/QC, could be supplemented with procedures discussed below:

Activity data check

- The inventory agency should review data collection methods, checking the data to ensure they were collected and aggregated correctly. The data should be cross-checked with previous years to ensure the data are reasonable. Inventory agencies should document data collection methods, identify potential areas of bias, and evaluate the representativeness of the data.

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[5] e.g. average temperature during manure storage.

Review of emission factors

- If using defaults, the inventory agency should review the available default emission factor values and document the rationale for selecting specific values.
- If using the Tier 2 method (i.e. where country-specific emission factors by animal and manure management type are used to calculate emissions), the inventory agency should cross-check the country-specific factor parameters (i.e. VS excretion rates, $B_{o,}$ and MCF) against the IPCC defaults. Significant differences between country-specific parameters and default parameters should be explained and documented.
- If using the Tier 1 method (using default IPCC emission factors), the inventory agency should evaluate how well the default VS excretion rates and B_o values represent the defined animal population and manure characteristics of the country.
- Any available country-specific data should be used to verify relevant default components.
- Inventory agency should review the method used to determine the country- or region-specific VS and B_o values, particularly in terms of the standardised procedures previously described. A detailed description of the equations used to estimate emission factors should be reviewed as well, including the numbers used in each calculation and the source of any data collected.

External review

- If using the Tier 2 method, the inventory agency should conduct an expert peer review of the manure management practice assumptions by involving individuals with specific knowledge in disciplines associated with the parameters used to calculate factors (e.g. manure management practices and animal nutrition).
- If using the Tier 2 method, the inventory agency should provide a proper justification for country-specific emission factors via peer-reviewed documentation.

4.4 N_2O EMISSIONS FROM MANURE MANAGEMENT

4.4.1 Methodological issues

The nitrous oxide (N_2O) estimated in this section is the N_2O produced during the storage and treatment of manure before it is applied to land. The term 'manure' is used here collectively to include both dung and urine (i.e. the solids and the liquids) produced by livestock. The emission of N_2O from manure during storage and treatment depends on the nitrogen and carbon content of manure, and on the duration of the storage and type of treatment. The term 'manure management'[6] is used as a collective noun for all types of storage and treatment of manure. This chapter describes *good practice* for estimating N_2O emissions from manure management systems (MMS) using the method in the *IPCC Guidelines*. In the case of animals whose manure is unmanaged (i.e. animals grazing on pasture or grassland, animals that forage or are fed in paddocks, animals kept in pens around homes) the manure is not stored or treated but is deposited directly on land. This system of 'manure management' is referred to in the *IPCC Guidelines* as 'pasture, range, and paddock'. The N_2O emissions generated by manure in the system 'pasture, range, and paddock' occur directly and indirectly from the soil, and are therefore reported under the IPCC category 'agricultural soils'. However, because the estimation method for pasture, range, and paddock N_2O emissions is the same as that for other systems of manure management, pasture, range, and paddock is discussed in this section of the *good practice guidance*.

4.4.1.1 CHOICE OF METHOD

The *IPCC Guidelines* method for estimating N_2O emissions from manure management entails multiplying the total amount of N excretion (from all animal species/categories) in each type of manure management system by an emission factor for that type of manure management system. Emissions are then summed over all manure management systems. The level of detail being applied to the *good practice* method for estimating N_2O emissions from manure management systems will depend upon national circumstances. The decision tree in Figure 4.4, Decision Tree for N_2O Emissions from Manure Management, describes *good practice* in adapting the methods in the *IPCC Guidelines* to country-specific circumstances.

To estimate emissions from manure management systems, the animal population must first be divided into species/categories that reflect the varying amounts of manure produced per animal as well as the manner in which the manure is handled. Detailed information on how to characterise the livestock population for this source is provided in Section 4.1.

The following five steps are required to estimate N_2O emissions from manure management systems:

(i) Collect population data from livestock population characterisation;

(ii) Determine the annual average nitrogen excretion rate per head ($Nex_{(T)}$) for each defined livestock species/category T;

(iii) Determine the fraction of total annual excretion for each livestock species/category T that is managed in each manure management system S ($MS_{(T,S)}$);

(iv) Determine the N_2O emission factors for each manure management system S ($EF_{3(S)}$);

(v) For each manure management system type S, multiply its emission factor ($EF_{3(S)}$) by the total amount of nitrogen excretion (from all animal species/categories) in that system, to estimate N_2O emissions from that manure management system. Then sum over all manure management systems.

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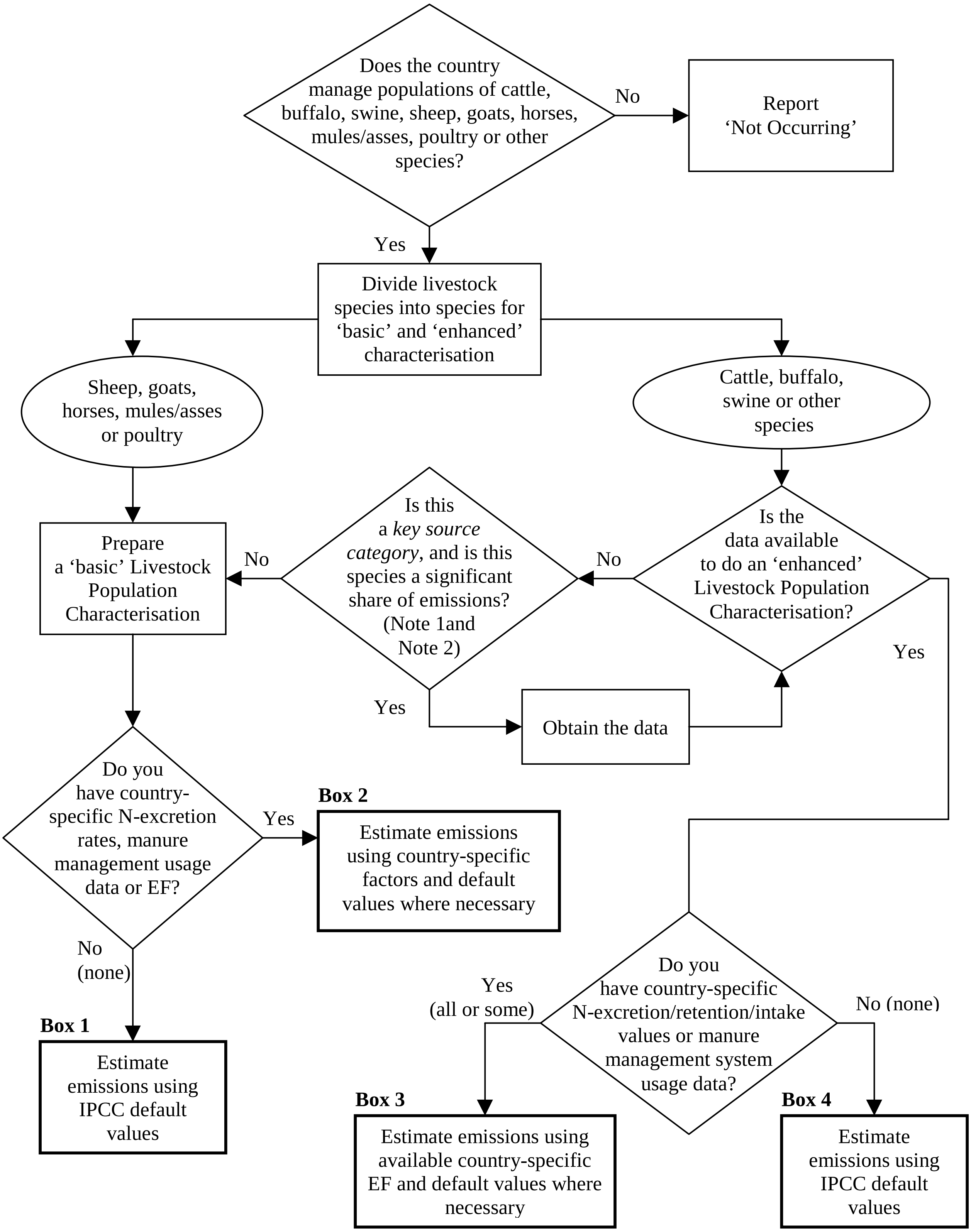
[6] Both the term 'manure management' and the term 'animal waste management' are used in the *IPCC Guidelines* to refer to animal manure that produces nitrous oxide. In this guidance, the term 'manure management' is used, so as to be consistent with Section 4.3 on CH_4 emissions from manure management.

Figure 4.4 Decision Tree for N_2O Emissions from Manure Management



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: As a rule of thumb, a sub-source category would be significant if it accounts for 25-30% of emissions from the source category.

The calculation of N_2O emissions from manure management is based on the following equation according to the *IPCC Guidelines*:

EQUATION 4.18

N_2O EMISSIONS FROM MANURE MANAGEMENT

$$(N_2O\text{-}N)_{(mm)} = \sum_{(S)} \{[\sum_{(T)} (N_{(T)} \bullet Nex_{(T)} \bullet MS_{(T,S)})] \bullet EF_{3(S)}\}$$

Where:

$(N_2O\text{-}N)_{(mm)}$ = N_2O-N emissions from manure management in the country (kg N_2O-N/yr)

$N_{(T)}$ = Number of head of livestock species/category *T* in the country

$Nex_{(T)}$ = Annual average N excretion per head of species/category *T* in the country (kg N/animal/yr)

$MS_{(T,S)}$ = Fraction of total annual excretion for each livestock species/category *T* that is managed in manure management system *S* in the country

$EF_{3(S)}$ = N_2O emission factor for manure management system *S* in the country (kg N_2O-N/kg N in manure management system *S*)

S = Manure management system

T = Species/category of livestock

Conversion of $(N_2O\text{-}N)_{(mm)}$ emissions to $N_2O_{(mm)}$ emissions for reporting purposes is performed by using the following equation:

$$N_2O_{(mm)} = (N_2O\text{-}N)_{(mm)} \bullet 44/28$$

4.4.1.2 CHOICE OF EMISSION FACTORS

The most accurate estimate will be obtained using country-specific emission factors that have been fully documented in peer reviewed publications. It is *good practice* to use country-specific emission factors that reflect the actual duration of storage and type of treatment of animal manure in each management system that is used. *Good practice* in the derivation of country-specific emission factors involves the measurement of emissions (per unit of manure N) from different management systems, taking into account variability in duration of storage and types of treatment. When defining types of treatment, conditions such as aeration and temperature should be taken into account. If inventory agencies use country-specific emission factors, they are encouraged to provide justification for these values via peer-reviewed documentation. If appropriate country-specific emission factors are unavailable, inventory agencies are encouraged to use the default emission factors. The *IPCC good practice* emission factors are presented in Table 4.12, Default Emission Factors for N_2O from Manure Management, and Table 4.13, Default Emission Factors for N_2O from Manure Management Systems not Specified in the *IPCC Guidelines*. These tables contain default emission factors, along with descriptions of the management systems, for several manure management systems that are not included in Table 4-22 of the Reference Manual of the *IPCC Guidelines*.

TABLE 4.12

DEFAULT EMISSION FACTORS FOR N_2O FROM MANURE MANAGEMENT

(ADDITIONAL SYSTEMS AND CHANGES TO THE *IPCC GUIDELINES* ARE NOTED IN ITALICS.)

System	Description	EF_3 (kg N_2O-N/kg Nitrogen excreted)	Uncertainty ranges of EF_3 [%]
Pasture/range/ paddock	*This manure is deposited directly on soils by livestock, i.e. it is unmanaged.*	0.02	-50%/ +100%
Daily Spread	*There is little or no storage or treatment of manure before it is applied to soils, so emissions during storage and treatment are assumed to be zero.*	0.0	Not Applicable
Solid storage[a]	Dung and urine (with or without litter) is collected but is stored in bulk for a long time (months) before disposal, with or without liquid runoff into a pit system.	0.02	-50%/ +100%
Dry lot	In dry climates animals may be kept on unpaved feedlots where the manure is allowed to dry until it is periodically removed. Upon removal the manure may be spread on fields.	0.02	-50%/ +100%
Liquid/Slurry	These systems are characterised by combined storage of dung and urine in tanks. To facilitate handling as a liquid, water may be added to the dung and urine.	0.001	-50%/ +100%
Anaerobic Lagoon	Anaerobic lagoon systems are characterised by flush systems that use water to transport manure to lagoons. The manure resides in the lagoon for periods from 30 days to over 200 days. The water from the lagoon may be recycled as flush water or used to irrigate and fertilise fields.	*0.001*	-50%/ +100%
Open pits below animal confinements	*Combined storage of dung and urine below animal confinements.*	*0.001*	-50%/ +100%
Anaerobic Digester	*Dung and urine is anaerobically digested to produce CH_4 gas for energy.*	*0.001*	-50%/ +100%
Burned for fuel[b]	Dung is collected and dried in cakes and burned for heating or cooking. *The urine N is deposited on pasture and paddock and must be treated in that category.*	*0.007* *0.02*	-50%/ +100%

[a] Quantitative data should be used to distinguish whether the system is judged to be a solid storage or liquid/slurry. The borderline between dry and liquid can be drawn at 20% dry matter content.

[b] The emissions associated with the burning of the dung are to be reported under the IPCC category 'fuel combustion' if the dung is used as fuel and under the IPCC category 'waste incineration,' if the dung is burned without energy recovery. Direct and indirect N_2O emissions associated with the urine deposited on agricultural soils are treated in Sections 4.7 and 4.8, respectively.

Source: *IPCC Guidelines* and Judgement by Expert Group (see Co-chairs, Editors and Experts; N_2O Emissions from Manure Management).

TABLE 4.13

DEFAULT EMISSION FACTORS FOR N_2O FROM MANURE MANAGEMENT SYSTEMS NOT SPECIFIED IN THE *IPCC GUIDELINES* (JUDGEMENT BY EXPERT GROUP)

Additional Systems	Definition	EF_3 (kg N_2O-N/kg nitrogen excreted)	Uncertainty Ranges of EF_3 (%)
Cattle and Swine Deep Litter	Cattle/swine dung and urine are excreted on stall floor. The accumulated waste is removed after a long time.		
	<1 month	0.005	-50%/+100%
	>1 month	0.02	-50%/+100%
Composting - Intensive	Dung and urine are collected and placed in a vessel or tunnel, there is forced aeration of the waste	0.02	-50%/+100%
Composting - Extensive	Dung and urine collected, stacked and regularly turned for aeration	0.02	-50%/+100%
Poultry manure with bedding	Manure is excreted on floor with bedding. Birds walk on waste.	0.02	-50%/+100%
Poultry manure without bedding	Manure is excreted on floor without bedding. Birds do not walk on waste	0.005	-50%/+100%
Aerobic Treatment	Dung and manure is collected as a liquid. The waste undergoes forced aeration, or is treated in aerobic ponds or wetland systems to provide nitrification and denitrification.	0.02	-50%/+100%

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts; N_2O Emissions from Manure Management).

4.4.1.3 CHOICE OF ACTIVITY DATA

There are three main types of activity data for estimating N_2O emissions from manure management systems: (1) livestock population data, (2) nitrogen excretion data for each animal species/category, and (3) manure management system usage data.

Livestock population data ($N_{(T)}$)

The livestock population data should be obtained using the approach described in the Livestock Population Characterisation (see Section 4.1). If using default nitrogen excretion rates to estimate N_2O emissions from manure management systems, a 'Basic' livestock population characterisation is sufficient. To estimate N_2O emissions from manure management using calculated nitrogen excretion rates, an 'Enhanced' characterisation must be performed. As noted in Section 4.1, *good practice* in characterising livestock populations is to conduct a single characterisation that will provide the activity data for all emissions sources that depend on livestock population data.

Annual average nitrogen excretion rates ($Nex_{(T)}$)

Accurate annual nitrogen excretion rates should be determined for each animal species/category defined by the livestock population characterisation. Country-specific rates may either be taken directly from documents or reports such as from the agricultural industry and scientific literature, or derived from information on animal nitrogen intake and retention (as explained below). In some situations, it may be appropriate to utilise excretion rates developed by other countries that have livestock with similar characteristics. If country-specific data cannot be collected or derived, or appropriate data are not available from another country, the IPCC default excretion rates should be used (see Table 4-20 in the Reference Manual of the *IPCC Guidelines*). In order to adjust the values for young animals, it is *good practice* to multiply the N excretion rates in Table 4-20 by the default adjustment factors shown in Table 4.14, Default Adjustment Factors for Table 4-20 in the *IPCC Guidelines*. When estimating the $Nex_{(T)}$ for animals whose manure is classified in the manure management system *burned for fuel* (Table 4.12, Default emission factors for N_2O from Manure Management), it should be kept in mind that the dung is burned and the urine stays in the field. As a rule of thumb, 50% of the nitrogen excreted is in the dung and 50% is in the urine. Therefore, these proportions of $Nex_{(T)}$ should be multiplied by the appropriate emission factors in Table 4.12 to obtain N_2O-N emissions for these sub-source categories. If the burned dung is used as fuel, then emissions are reported under the IPCC category *fuel combustion*, whereas if the dung is burned without energy recovery the emissions should be reported under the IPCC category *waste incineration*.

TABLE 4.14

DEFAULT ADJUSTMENT FACTORS FOR TABLE 4-20 IN THE *IPCC GUIDELINES* (REFERENCE MANUAL) WHEN ESTIMATING N EXCRETION RATES FOR YOUNG ANIMALS [a]

Animal Species/Category	Age Range (years)	Adjustment Factor
Non-Dairy Cattle	0 - 1	0.3
Non-Dairy Cattle	1 - 2	0.6
Dairy Cattle	0 - 1	0.3
Dairy Cattle	1 - 2	0.6
Poultry	0 - 0.25	0.5
Sheep	0 - 1	0.5
Swine	0 - 0.5	0.5

[a] The adjustment factor is 1 when the age of the animals exceeds the indicated age range.

Note: The category termed *Other Animals* in Table 4-20 of the *IPCC Guidelines*, Reference Manual, is not provided with adjustment factors.

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts; N_2O Emissions from Manure Management).

The annual amount of N excreted by each animal species/category depends on the total annual N intake and total annual N retention of the animal. Therefore, N excretion rates can be derived from N intake and N retention data. Annual N intake (i.e. the amount of N consumed by the animal annually) depends on the annual amount of feed digested by the animal, and the protein content of that feed. Total feed intake depends on the production level of the animal (e.g. growth rate, milk production, draft power). Annual N retention (i.e. the fraction of N intake that is retained by the animal for the production of meat, milk, and wool) is a measure of the animal's efficiency of production of animal protein from feed protein. Nitrogen intake and retention data for specific animal species/categories may be available from national statistics or from animal nutrition specialists. Nitrogen intake can also be calculated from data on feed and crude protein intake developed in the Livestock Population Characterisation Section (see Section 4.1). Default N retention values are provided in Table 4.15, Default Values for the Fraction of Nitrogen in Feed Taken in by Animals that is Retained by the Different Animal Species/Categories. Rates of annual N excretion for each animal species/category ($Nex_{(T)}$) are derived as follows:

EQUATION 4.19

ANNUAL N EXCRETION RATES

$$Nex_{(T)} = N_{intake(T)} \bullet (1 - N_{retention(T)})$$

Where:

($Nex_{(T)}$) = annual N excretion rates, kg N/animal-year

$N_{intake(T)}$ = The annual N intake per head of animal of species/category T, kg N/animal-year

$N_{retention(T)}$ = Fraction of annual N intake that is retained by animal of species/category T kg N retained/animal/year per kg N intake/animal/year

Note that annual nitrogen excretion data are also used for the calculation of direct and indirect N_2O emissions from agricultural soils (see Sections 4.7 and 4.8). The same rates of N excretion, and methods of derivation, that are used to estimate N_2O emissions from manure management should be used to estimate N_2O emissions from agricultural soils.

Manure management system usage data ($MS_{(T,S)}$)

The manure management system usage data used to estimate N_2O emissions from manure management should be the same as those that are used to estimate CH_4 emissions from manure management (see Section 4.3). If country-specific manure management system usage data are not available, default values from the *IPCC Guidelines* should be used. The IPCC default values for dairy cattle, non-dairy cattle, buffalo, and swine should be taken from Tables B-3 through B-6 of Appendix B of Section 4.2 (livestock) of the Agriculture Chapter of the Reference Manual. The IPCC default values for all other animal species/categories should be taken from Table 4-21 of the Agriculture Chapter of the Reference Manual.

TABLE 4.15

DEFAULT VALUES FOR THE FRACTION OF NITROGEN IN FEED TAKEN IN BY ANIMALS THAT IS RETAINED BY THE DIFFERENT ANIMAL SPECIES/CATEGORIES (FRACTION N-INTAKE RETAINED BY THE ANIMAL)

Animal category	$N_{retention(T)}$ **(kg N retained/animal/year per kg N intake/animal/year)**	**Uncertainty range [%]**
Dairy cattle	0.2	+/-50
Non dairy cattle	0.07	+/-50
Buffalo	0.07	+/-50
Sheep	0.1	+/-50
Goats	0.1	+/-50
Camels	0.07	+/-50
Swine	0.3	+/-50
Horses	0.07	+/-50
Poultry	0.3	+/-50

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts; N_2O Emissions from Manure Management).

4.4.1.4 UNCERTAINTY ASSESSMENT

Emission factors

There are large uncertainties associated with the default emission factors for this source category (see Tables 4.12 and 4.13). Accurate and well-designed emission measurements from well characterised types of manure and manure management systems can help to reduce these uncertainties. These measurements must account for temperature, moisture conditions, aeration, manure N content, metabolisable carbon, duration of storage, and other aspects of treatment.

Activity data – Livestock populations

See Section 4.1- Livestock Population Characterisation

Activity data - Nitrogen excretion rates

Uncertainty ranges for the default N excretion rates (see Table 4-20 in the *IPCC Guidelines*, Reference Manual), which are not provided in the *IPCC Guidelines*, are estimated at about +/–50% (Source: Judgement by Expert Group. See Co-chairs, Editors and Experts; N_2O Emissions from Manure Management). The uncertainty ranges for the default N retention values provided here are also +/–50% (see Table 4.15). If inventory agencies derive N excretion rates using accurate in-country statistics on N intake and N retention, the uncertainties associated with the N excretion rates may be as low as +/–25%.

Activity data – Manure management system usage

For some countries, the uncertainties associated with manure management system usage data are high. Although a well-defined classification scheme has been developed (see Tables 4.12 and 4.13), many inventory agencies only have limited, if any, quantitative data on the amounts of manure managed in different systems, beyond what is presented in Table 4-21 in the *IPCC Guidelines*, Reference Manual.

4.4.1.5 COMPLETENESS

A complete inventory should estimate N_2O emissions from all systems of manure management for all livestock species/categories. Countries are encouraged to utilise manure management definitions that are consistent with those in Tables 4.12 and 4.13. For more information regarding the completeness of livestock characterisation, see Section 4.1.

4.4.1.6 DEVELOPING A CONSISTENT TIME SERIES

Developing a consistent time series of emission estimates for this source category requires, at a minimum, the collection of an internally consistent time series of livestock population statistics. Guidance on the development of this time series is addressed in Section 4.1. In most countries, the other two activity data sets required for this source category (i.e. N excretion rates and manure management system usage data), as well as the manure management emission factors, will be kept constant for the entire time series. However, in some cases, there may be reasons to modify these values over time. For example, farmers may alter livestock feeding practices, or the entire livestock sector may undergo a change such that a greater fraction of manure from a certain livestock species/category is managed in wet systems rather than in dry systems, or a particular system of manure management may change such that a revised emission factor is warranted. These changes in practices may be due to the implementation of explicit greenhouse gas mitigation measures, or may be due to changing agricultural practices without regard to greenhouse gases. Regardless of the driver of change, the data and emission factors used to estimate emissions must reflect the change, and the data, methods, and results must be thoroughly documented. If activity data over a time series are affected by a change in farm practices or the implementation of greenhouse gas mitigation measures (e.g. annual N excretion rates decline due to policy measures implemented to decrease N_2O emissions through reductions in annual N intake), the inventory agency is encouraged to ensure that the activity data reflect these practices and that the inventory text thoroughly explains how the change in farm practices or implementation of mitigation measures has affected the time series of activity data or emission factors.

4.4.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. When country-specific emission factors, N excretion rates or manure management system usage data or both have been used, the derivation of or references for these data should be clearly documented and reported along with the inventory results under the appropriate IPCC source category.

N_2O emissions from different types of manure management systems have to be reported according to the *IPCC Guidelines*. Referring to the *IPCC Guidelines*, N_2O emissions from all types of manure management systems are to be reported under manure management, with two exceptions:

- Emissions from the manure management system for *pasture, range, and paddock* are to be reported under the IPCC source category *agricultural soils* because this manure is deposited directly on soils by the livestock.
- Emission from the manure management system *burned for fuel*, are to be reported under the IPCC category *fuel combustion* if the dung is used as fuel and under the IPCC category *waste incineration* if the dung is burned without energy recovery. It should be noted, however, if the urine nitrogen is not collected for burning it must be reported under N_2O emissions from *pasture, range, paddock* animals.

It must be kept in mind that after storage or treatment in any system of manure management, nearly all the manure will be applied to land. The emissions that subsequently arise from the application of the manure to soil are to be reported under *agricultural soils*. The methods for estimating these emissions are discussed in Sections 4.7 and 4.8.

4.4.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to implement quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates.

Additional quality control checks as outlined in Tier 2 procedures in Chapter 8, QA/QC, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source. The general QA/QC related to data processing, handling, and reporting, as outlined in Chapter 8, QA/QC, could be supplemented with procedures discussed below:

Review of emission factors

- If using country-specific emission factors, the inventory agency should compare them to the default factors, and differences noted. The development of country-specific emission factors should be explained and documented, and inventory agencies are encouraged to ensure that good practice methods have been used and the results have been peer-reviewed.

Activity data check

- If using country-specific data for $Nex_{(T)}$ and $MS_{(T,S)}$, the inventory agency should compare these values to the IPCC default values. Significant differences, data sources, and methods of data derivation, should be documented.

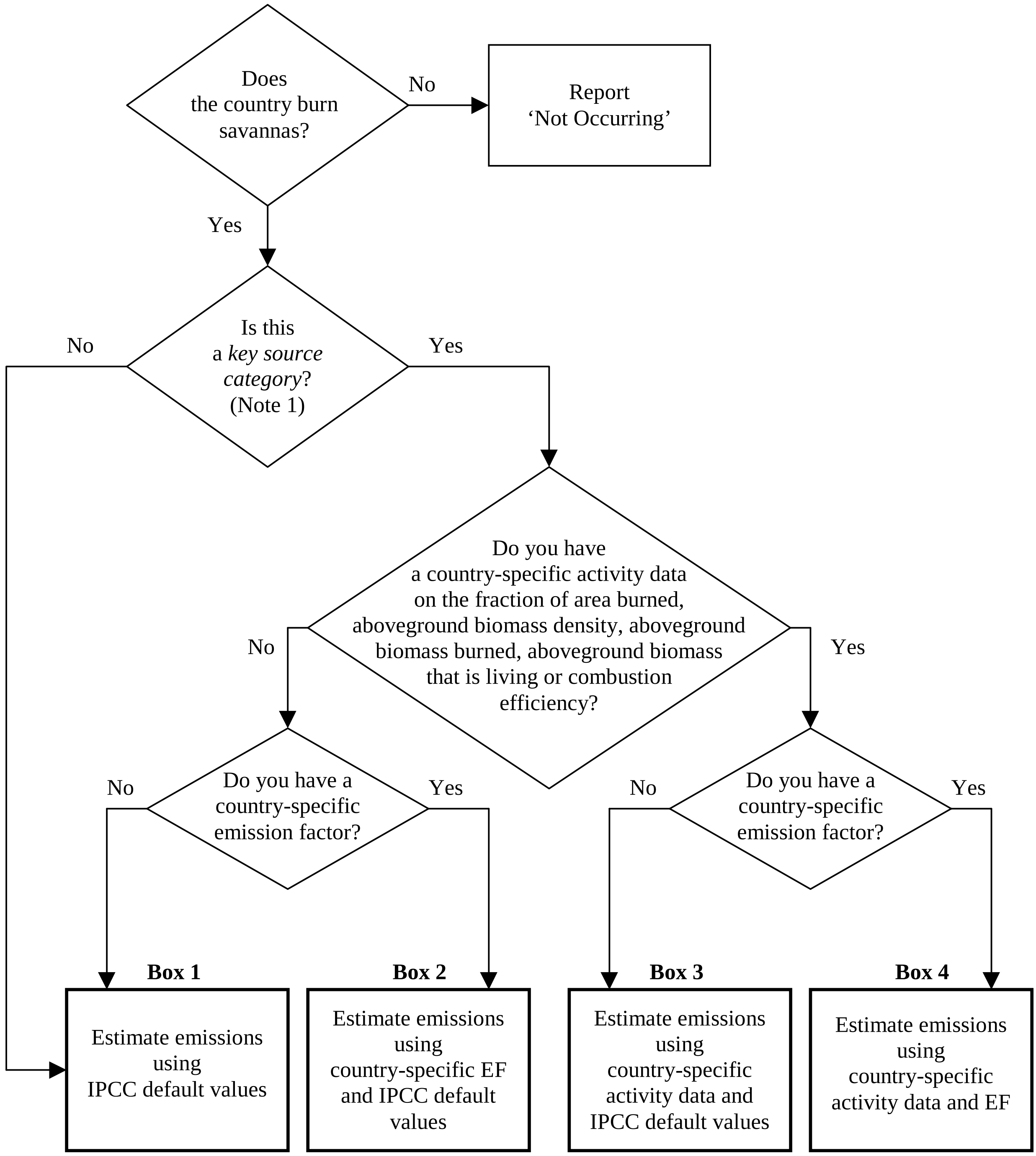
External review

- The inventory agency should utilise experts in manure management, animal nutrition, and GHG emissions to conduct expert peer review of the methods and data used.

4.5 CH_4 AND N_2O EMISSIONS FROM SAVANNA BURNING

At present, '*good practice*' for this source category is the application of the *IPCC Guidelines* following the suggested approach as set out in the decision tree in Figure 4.5, Decision Tree for CH_4 and N_2O Emissions from Savanna Burning. There is potential for further refinement of the method as indicated in Appendix 4A.1 at the end of this chapter. The appendix describes some of the details of a possible procedure for future revision of the methodology. At this time, the paucity of the data and size of uncertainties in many of the key parameters do not justify adoption of the material discussed in Appendix 4A.1 as *good practice*.

Figure 4.5 Decision Tree for CH_4 and N_2O Emissions from Savanna Burning

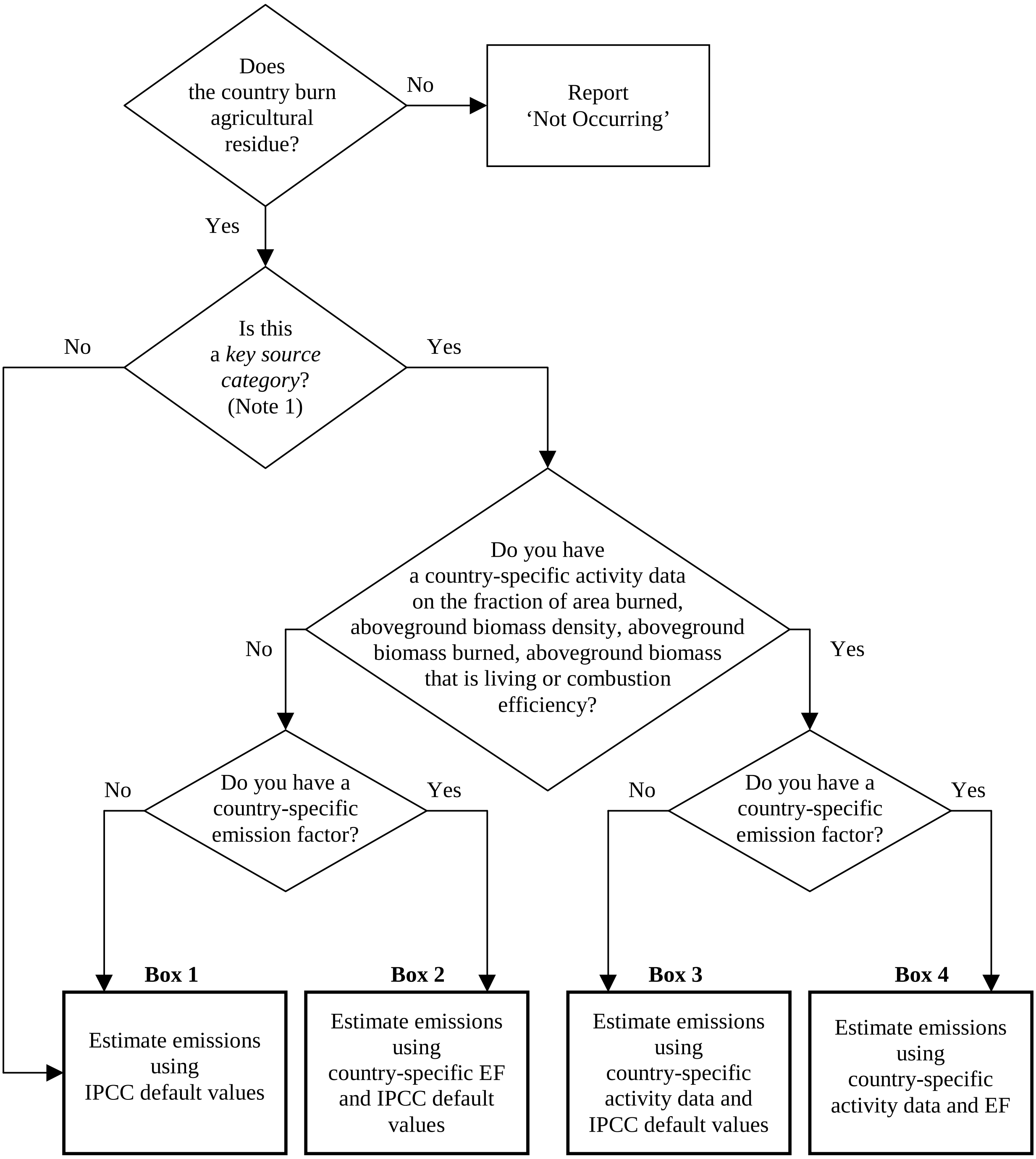


Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

4.6 CH_4 AND N_2O EMISSIONS FROM AGRICULTURAL RESIDUE BURNING

At present, '*good practice*' for this source category is the application of the *IPCC Guidelines* following the suggested approach as set out in the decision tree in Figure 4.6, Decision Tree for CH_4 and N_2O Emissions from Agricultural Residue Burning. There is potential for further refinement of the method as indicated in Appendix 4A.2 at the end of this chapter. The appendix describes some of the details of a possible procedure for future revision of the methodology. At this time, the paucity of the data and size of uncertainties in many of the key parameters do not justify adoption of the material discussed in Appendix 4A.2 as *good practice*.

Figure 4.6 Decision Tree for CH_4 and N_2O Emissions from Agricultural Residue Burning



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

4.7 DIRECT N_2O EMISSIONS FROM AGRICULTURAL SOILS

4.7.1 Methodological issues

Nitrous oxide (N_2O) is produced naturally in soils through the microbial processes of nitrification and denitrification. A number of agricultural activities add nitrogen to soils, increasing the amount of nitrogen (N) available for nitrification and denitrification, and ultimately the amount of N_2O emitted. The emissions of N_2O that result from anthropogenic N inputs occur through both a direct pathway (i.e. directly from the soils to which the N is added), and through two indirect pathways (i.e. through volatilisation as NH_3 and NO_x and subsequent redeposition, and through leaching and runoff). In the *IPCC Guidelines*, direct and indirect emissions of N_2O from agricultural soils are estimated separately.

The *IPCC Guidelines* method for estimating direct N_2O emissions from agricultural soils has two parts: (i) estimation of direct N_2O emissions due to N-inputs to soils (excluding N-inputs from animals on pasture, range, and paddock); and (ii) estimation of direct N_2O emissions from unmanaged animal manure (i.e. manure deposited by animals on pasture, range, and paddock).[7] This section discusses the first part of this method. The second part, estimation of direct N_2O emissions from pasture, range, and paddock manure, is covered in Section 4.4: N_2O Emissions from Manure Management.[8] Note, however, that direct N_2O emissions from pasture, range and paddock manure are to be reported in the agricultural soil category.

4.7.1.1 CHOICE OF METHOD

The approach described in the *IPCC Guidelines* for estimating direct N_2O emissions from agricultural soils due to applications of N and other cropping practices accounts for anthropogenic nitrogen (N) inputs from the application of: synthetic fertilisers (F_{SN}) and animal manure (F_{AM}); the cultivation of N-fixing crops (F_{BN}); incorporation of crop residues into soils (F_{CR}); and soil nitrogen mineralisation due to cultivation of organic soils[9] (i.e. histosols) (F_{OS}).[10] As the *IPCC Guidelines* treat indirect and direct emissions separately, the portion of applied synthetic fertiliser and animal manure N that volatilises after application is subtracted from the amounts applied, and the N_2O that is eventually emitted from this volatilised N is included as part of the indirect emissions (see Section 4.8).

The terms Tier 1a and Tier 1b have been used throughout the *IPCC Report on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (*Good Practice Report),* Subsections 4.7 and 4.8, to differentiate between the equations in the *IPCC Guidelines* (Tier 1a) and new equations (Tier 1b) presented here. The Tier 1b equations represent increased precision due to expansion of the terms in the equations. However, while Tier 1b equations may be preferred, the activity data needed to use them may not be available. In these cases, use of Tier 1a equations is appropriate. Estimating emissions using a combination of Tier 1a and Tier 1b equations for different sub-source categories, depending upon availability of activity data, is also acceptable. In some cases, there is no Tier 1b alternative because no refinement of the equation in the *IPCC Guidelines* was considered necessary.

The decision tree, Figure 4.7, Decision Tree for Direct N_2O Emissions from Agricultural Soils describes g*ood practice* in adapting the methods in the *IPCC Guidelines* to country-specific circumstances. The decision tree

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[7] As in Section 4.4, the term ‘manure’ is used here collectively to include both dung and urine.

[8] Even though animal manure deposited on pasture, range, and paddock is not managed, it is addressed in Section 4.4, because the method for estimating emissions from pasture, range, and paddock manure is the same as the method for estimating emissions from manure management systems.

[9] Organic soils are soils described as Histosols which are defined as: ‘Organic soils that have organic soil materials in more than half of the upper 80 cm, or that are of any thickness of overlying rock or fragmented materials that have interstices filled with organic soil materials.’ An organic soil material is defined as: ‘soil materials that are saturated with water and have 174 g kg^{-1} or more organic carbon if the mineral fraction has 500 g kg^{-1} or more clay, or 116 g kg^{-1} organic carbon if the mineral fraction has no clay, or has proportional intermediate contents, or if never saturated with water, have 203 g kg^{-1} or more organic carbon (SSSA, 1996).

[10] Histosols are soils containing an organic-rich surface layer at least 40 cm in thickness, with a minimum of 20% organic matter if the clay content is low, and a minimum of 30% organic matter where the clay content exceeds 50%.

describes how to choose the method of estimation. Both Tier 1a and Tier 1b are consistent with good practice, provided the emission factors and activity data are developed according to the guidance presented below.

In its most basic form, direct N_2O emissions from agricultural soils are estimated as follows:

EQUATION 4.20

DIRECT N_2O EMISSIONS FROM AGRICULTURAL SOILS (TIER 1a)

$$N_2O_{Direct}\text{-}N = [(F_{SN} + F_{AM} + F_{BN} + F_{CR}) \bullet EF_1] + (F_{OS} \bullet EF_2)$$

Where:

N_2O_{Direct}-N = Emission of N_2O in units of Nitrogen

F_{SN} = Annual amount of synthetic fertiliser nitrogen applied to soils adjusted to account for the amount that volatilises as NH_3 and NO_x

F_{AM} = Annual amount of animal manure nitrogen intentionally applied to soils adjusted to account for the amount that volatilises as NH_3 and NO_x

F_{BN} = Amount of nitrogen fixed by N-fixing crops cultivated annually

F_{CR} = Amount of nitrogen in crop residues returned to soils annually

F_{OS} = Area of organic soils cultivated annually

EF_1 = Emission factor for emissions from N inputs (kg N_2O-N/kg N input)

EF_2 = Emission factor for emissions from organic soil cultivation (kg N_2O-N/ha-yr)

Conversion of N_2O-N emissions to N_2O emissions for reporting purposes is performed by using the following equation:

$$N_2O = N_2O\text{-}N \bullet 44/28$$

The use of Equation 4.20 is considered Tier 1a. If more detailed emission factors are available to a country, further disaggregation of the terms in the equation can be undertaken, as shown in Equation 4.21 which is the Tier 1b equation. For example, if emission factors are available for the application of synthetic fertilisers and animal manure (F_{SN} and F_{AM}) under different conditions *i*, Equation 4.20 would be expanded as:

EQUATION 4.21

DIRECT N_2O EMISSIONS FROM AGRICULTURAL SOILS (TIER 1b)

$$N_2O_{Direct}\text{-}N = \Sigma_i \{[(F_{SN} + F_{AM})_i \bullet EF_i] + [(F_{BN} + F_{CR}) \bullet EF_1] + [F_{OS} \bullet EF_2]\}$$

Where:

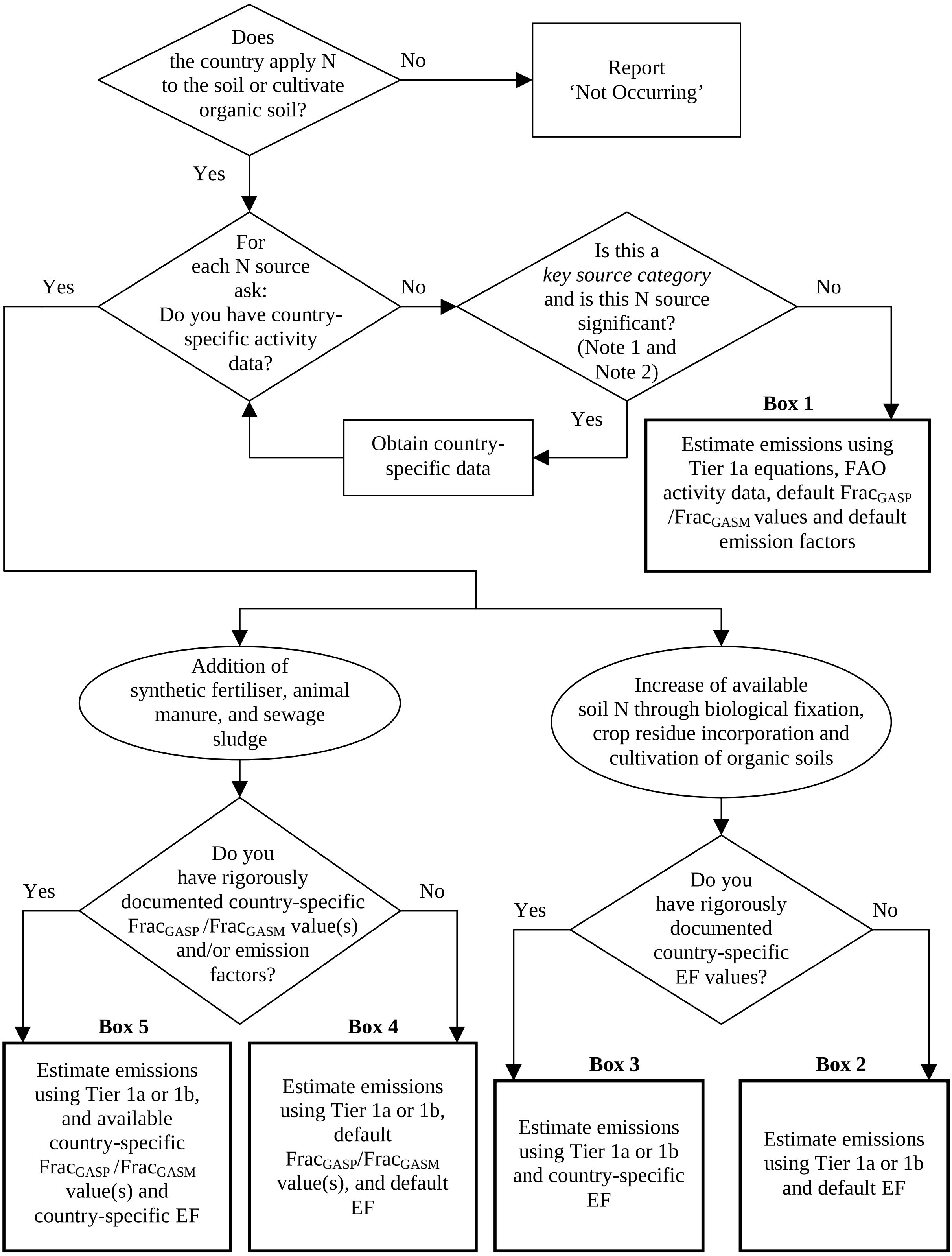
EF_i = Emission factors developed for N_2O emissions from synthetic fertiliser and animal manure application under different conditions *i*.

Conversion of N_2O-N emissions to N_2O emissions for reporting purposes is performed by using the following equation:

$$N_2O = N_2O\text{-}N \bullet 44/28$$

The Tier 1a approach can also be expanded to include other forms of N applied to all types of soils. For example, sewage sludge, an additional form of organic N, is often applied to soils as a soil amendment or dispose of the sludge. Sewage sludge nitrogen ($N_{SEWSLUDGE}$) can be included in this calculation if sufficient information is available. The sludge input should be measured in units of N and multiplied by EF_1 (i.e. in Equation 4.20, $N_{SEWSLUDGE}$ should be added to the first set of parentheses in Equation 4.21, it should be added inside the second set of parentheses).

Figure 4.7 Decision Tree for Direct N_2O Emissions from Agricultural Soils



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: As a rule of thumb, a sub-source category would be significant if it accounts for 25-30% of emissions from the source category.

Note that there are no default data for the new parameter $N_{SEWSLUDGE}$, or guidance on collecting such data. Therefore, this refinement should only be used if reliable country-specific data are available. The sewage sludge activity data used to estimate direct N_2O emissions should be the same as those used to estimate indirect N_2O emissions (see Section 4.8, Indirect N_2O Emissions from Nitrogen Used in Agriculture).

In order to apply either Equation 4.20 or 4.21, the amounts of various N inputs (F_{SN}, F_{AM}, F_{BN}, F_{CR}, F_{OS}) must be estimated. The *IPCC Guidelines* describe methods for how such calculations are to be made. In some cases, refinements in these methods are suggested for *good practice* in order to correct errors, ensure consistency between this source category and other agricultural source categories, and incorporate new information that has become available since the *IPCC Guidelines* were written. In addition, for some N inputs, detailed equations that describe how to implement the more disaggregated approaches are presented. Using a mix of aggregated and disaggregated equations to calculate the various N inputs is consistent with *good practice* in the derivation of each term in Equations 4.20 and 4.21 as described below.

Synthetic Fertiliser Nitrogen, Adjusted for Volatilisation (F_{SN}): The term $\underline{F_{SN}}$ refers to the annual amount of synthetic fertiliser nitrogen applied to soils after adjusting to account for the amount that volatilises. It is estimated by determining the total amount of synthetic fertiliser consumed annually (N_{FERT}), and then adjusting this amount by the fraction that volatilises as NH_3 and NO_x ($Frac_{GASF}$). The equation is thus:

EQUATION 4.22

N FROM SYNTHETIC FERTILISER APPLICATION

$$F_{SN} = N_{FERT} \bullet (1 - Frac_{GASF})$$

Animal Manure Nitrogen Used as Fertiliser, Adjusted for Volatilisation (F_{AM}): The term $\underline{F_{AM}}$ refers to the amount of animal manure nitrogen intentionally applied to soils after adjusting to account for the amount that volatilises. It is estimated by determining the total amount of animal manure nitrogen produced annually ($\sum_T(N_{(T)} \bullet Nex_{(T)})$) [11], and then adjusting this amount to account for the animal manure that is burned for fuel ($Frac_{FUEL-AM}$)[12], deposited onto soils by grazing livestock ($Frac_{PRP}$) and volatilised as NH_3 and NO_x ($Frac_{GASM}$). For this calculation, the equation presented in the *IPCC Guidelines* is replaced by:

EQUATION 4.23

N FROM ANIMAL MANURE APPLICATION

$$F_{AM} = \sum_T(N_{(T)} \bullet Nex_{(T)}) \bullet (1 - Frac_{GASM})[1 - (Frac_{FUEL-AM} + Frac_{PRP})]$$

Equation 4.23, however, may not be complete for all countries because animal manure may be used in ways other than as fuel. Since some countries use some of their animal manure for animal feed and for construction, a complete assessment should also determine the fractions of the animal manure (if any) that are used in this way ($Frac_{FEED-AM}$ and $Frac_{CNST-AM}$, respectively). Tier 1b can account for these uses and avoid overestimating emissions. It is assumed that all animal manure not used for another purpose will be applied to soils. The suggested *good practice* Tier 1b equation is thus:

EQUATION 4.24

N FROM ANIMAL MANURE APPLICATION (EXPANDED)

$$F_{AM} = \sum_T(N_{(T)} \bullet Nex_{(T)}) \bullet (1 - Frac_{GASM}) \bullet [1 - (Frac_{FUEL-AM} + Frac_{PRP} + Frac_{FEED-AM} + Frac_{CNST-AM})]$$

Note, however, that if the term $Frac_{PRP}$ includes fractions of animal manure used as fuel, feed, or construction, then whichever fractions are included in $Frac_{PRP}$ should not be included in Equation 4.24.

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[11] In this part of the *IPCC Guidelines*, the variable Nex is used for the total amount of animal manure produced. To be consistent with *good practice* in Section 4.4, this variable name has been revised to $\Sigma_T(N_{(T)} \bullet Nex_{(T)})$.

[12] In equations 4.23 and 4.24, the term used in the *IPCC Guidelines* ($Frac_{FUEL}$), has been renamed $Frac_{FUEL-AM}$, so as to distinguish it from the fraction of crops used as fuel ($Frac_{FUEL-CR}$) in Equation 4.29.

N fixed by Crops (F_{BN}): The approach presented in the *IPCC Guidelines* for estimating the amount of nitrogen fixed by N-fixing crops cultivated annually ($\underline{F_{BN}}$) is based on the assumption that the amount of N contained in the aboveground plant material (crop product plus residues) is a reasonable proxy for the total amount of N fixed by the crop. The *IPCC Guidelines* also assumes that the mass ratio of residue to product is 1 (i.e. the total aboveground plant biomass is 2 times the crop product). Therefore, the amount of fixed N is estimated by multiplying the seed yield of pulses and soybeans ($Crop_{BF}$) by a default value of 2 and then by the fraction of crop biomass that is nitrogen ($Frac_{NCRBF}$). The Tier 1a equation presented in the *IPCC Guidelines* is thus:

EQUATION 4.25

N FIXED BY CROPS (TIER 1A)

$$F_{BN} = 2 \bullet Crop_{BF} \bullet Frac_{NCRBF}$$

The approach suggested in the *IPCC Guidelines* can be modified in several ways to estimate more accurately the total mass of aboveground crop residue and product nitrogen. For example, Equation 4.25 uses a default value of 2 to convert $Crop_{BF}$ to total aboveground crop residue and product. This factor is too low for some pulses and soybeans, and may result in underestimating the total aboveground crop residue and product (see Table 4.16, Selected Crop Residue Statistics). As the ratio of aboveground biomass to crop product mass varies among crop types, more accurate estimates can be developed if crop specific values are used. Dry matter fractions also need to be incorporated into the equation so that adjustments are made for moisture contents. In addition, $Crop_{BF}$ should be defined so that it is representative of the products of all N-fixing crops, not just the seed yield of pulses and soybeans. In particular, N-fixing forage crops such as alfalfa should be included in the calculations. The approach is shown in Equation 4.26:

EQUATION 4.26

N FIXED BY CROPS (TIER 1b)

$$F_{BN} = \sum_i [Crop_{BF_i} \bullet (1 + Res_{BF_i}/Crop_{BF_i}) \bullet Frac_{DM_i} \bullet Frac_{NCRBF_i}]$$

Equation 4.26 introduces two new terms. The first, $Res_{BF_i}/Crop_{BF_i}$, represents the residue to crop product mass ratio specific to each crop type *i* (see Table 4.16). The second, $Frac_{DM_i}$, is the fraction of dry matter in the aboveground biomass of each crop type *i*. The term $[(1 + Res_{BF_i}/Crop_{BF_i}) \bullet Frac_{DM_i}]$ replaces the default value of '2' presented in the *IPCC Guidelines.* Note that it is assumed that the dry matter content of the residue and product are equal so only one dry matter variable is included in the equation. Countries may have dry matter contents specific to the product and the residue – these should be used if the additional effort is warranted by increased accuracy. Additionally, the variable $Crop_{BF}$ as currently defined in the *IPCC Guidelines* is the seed yield of pulses + soybeans in a country. However, this does not take into account crops such as alfalfa where the entire plant is harvested as product. Therefore, as mentioned above, $Crop_{BF}$ should be defined as the 'production of N-fixing crops.' In the case of N-fixing forage crops such as alfalfa, $Res_{BF_i}/Crop_{BF_i}$ will equal 0, and the equation 4.26 becomes:

EQUATION 4.27

N FIXED BY N-FIXING FORAGE CROPS

$$F_{BN} = \sum_i (Crop_{BF_i} \bullet Frac_{DM_i} \bullet Frac_{NCRBF_i})$$

Note that if inventory agencies use Equation 4.26 to estimate the amount of N fixed by N-fixing crops, and if any of the residues of these crops are burned in the field, they should use the same values for $Crop_{BF}$, $Res_{BF_i}/Crop_{BF_i}$, and $Frac_{DM_i}$ that are used in estimating emissions from agricultural residue burning. The values used for $Frac_{NCRBF_i}$ should also be consistent with N/C ratios used in estimating emissions from agricultural residue burning. *Good practice* default values for $Res_{BF_i}/Crop_{BF_i}$, $Frac_{DM_i}$, and $Frac_{NCRBF_i}$, for some crop types, are presented in Table 4.16. Inventory agencies may use these values if country-specific data are not available. If a default residue nitrogen content is needed for a crop type for which a value is not provided in Table 4.16, the non-crop specific default value listed in Table 4-19 of the Reference Manual of the *IPCC Guidelines* (0.03 kg N/kg dry matter) can be used.

TABLE 4.16
SELECTED CROP RESIDUE STATISTICS

Product	Residue/Crop Product Ratio	Dry Matter Fraction	Carbon Fraction	Nitrogen Fraction
Wheat	1.3	0.82-0.88	0.4853	0.0028
Barley	1.2	0.82-0.88	0.4567	0.0043
Maize	1.0	0.70-0.86	0.4709	0.0081
Oats	1.3	0.92		0.0070
Rye	1.6	0.90		0.0048
Rice	1.4	0.82-0.88	0.4144	0.0067
Millet	1.4	0.85-0.92		0.0070
Sorghum	1.4	0.91		0.0108
Peas	1.5	0.87		0.0142
Beans	2.1	0.82-0.89		
Soybeans	2.1	0.84-0.89		0.0230
Potatoes	0.4		0.4226	0.0110
Feedbeet	0.3		0.4072[a]	0.0228[a]
Sugarcane tops		0.32	0.4235	0.0040
Sugarcane leaves		0.83	0.4235	0.0040
Jerusalem artichoke	0.8			
Peanuts	1.0	0.86		0.0106

[a] These figures are for beet leaves.

Source: All data from Strehler and Stützle (1987), except sugarcane data (Turn *et al.*, 1997), dry matter and nitrogen fraction data for oats, rye, sorghum, peas, and peanuts (Cornell, 1994), and nitrogen fraction data for millet and soybeans (Barnard and Kristoferson, 1985).

N in Crop Residues Returned to Soils (F_{CR}): In the *IPCC Guidelines*, the amount of nitrogen returned to soils annually through incorporation of crop residues (F_{CR}) is estimated by determining the total amount of crop residue N produced (from both non-nitrogen-fixing crops and N-fixing crops), and adjusting it for the fraction that is burned in the field when residues are burned during or after harvest. The annual production of residue N is estimated by multiplying annual crop production of N-fixing crops ($Crop_{BF}$) and other crops ($Crop_O$) by their respective N contents ($Frac_{NCRBF}$ and $Frac_{NCRO}$), summing these two nitrogen values, multiplying by a default value of 2 (to yield total aboveground crop biomass), and then adjusting for the amount of total aboveground crop biomass that is removed from the field as product ($Frac_R$)[13] and burned ($Frac_{BURN}$). The Tier 1a equation presented in the *IPCC Guidelines* is thus:

EQUATION 4.28
N IN CROP RESIDUE RETURNED TO SOILS (TIER 1a)

$$F_{CR} = 2 \bullet (Crop_O \bullet Frac_{NCRO} + Crop_{BF} \bullet Frac_{NCRBF}) \bullet (1 - Frac_R) \bullet (1 - Frac_{BURN})$$

The Tier 1a approach can be modified in several ways to estimate more accurately the amount of crop residue nitrogen that is incorporated into soils:

- First, Equation 4.28 uses a default value of 2 to convert $Crop_O$ and $Crop_{BF}$ to total aboveground crop residue and product. As previously mentioned with F_{BN}, this factor is too low for some pulses and soybeans, and

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[13] The *IPCC Guidelines* define $Frac_R$ as the 'fraction of crop residue that is removed from the field as crop.' However, this variable, as it is currently used, is instead the 'fraction of total *aboveground crop biomass* that is removed from the field as crop.'

may result in underestimating the total aboveground crop residue and product. In addition, this factor of 2 is inconsistent with the default value for $Frac_R$ presented in the *IPCC Guidelines.* [14]

- Second, $Crop_{BF}$ should be defined so that it is representative of the products of all N-fixing crops, not just seed yield of pulses and soybeans.
- Third, dry matter fractions need to be incorporated into the equation so that adjustments are made for moisture contents.
- Fourth, the equation should be modified to account for additional uses of crop residues, specifically as fuel, construction material, and fodder. These modifications are shown in Equation 4.29:

EQUATION 4.29

N IN CROP RESIDUE RETURNED TO SOILS (TIER 1b)

$$F_{CR} = \sum_i [(Crop_{O_i} \bullet Res_{O_i}/Crop_{O_i} \bullet Frac_{DM_i} \bullet Frac_{NCRO_i}) \bullet (1 - Frac_{BURN_i} - Frac_{FUEL\text{-}CR_i} - Frac_{CNST\text{-}CR_i} - Frac_{FOD_i})] + \sum_j [(Crop_{BF_j} \bullet Res_{BF_j}/Crop_{BF_j} \bullet Frac_{DM_j} \bullet Frac_{NCRBF_j}) \bullet (1 - Frac_{BURN_j} - Frac_{FUEL\text{-}CR_j} - Frac_{CNST\text{-}CR_j} - Frac_{FOD_j})]$$

Equation 4.29 allows for available crop-specific values to be used for the following variables (i.e. each other crop type *i* and each nitrogen-fixing crop type *j*): (i) the residue to crop product mass ratio ($Res_{O_i}/Crop_{O_i}$ and $Res_{BF_j}/Crop_{BF_j}$); (ii) the dry matter content of the aboveground biomass ($Frac_{DM_i}$ and $Frac_{DM_j}$); (iii) the nitrogen content of the aboveground biomass ($Frac_{NCRO_i}$ and $Frac_{NCRBF_j}$); (iv) the fraction of residue burned in the field before and after harvest ($Frac_{BURN_i}$ and $Frac_{BURN_j}$); (v) the fraction of residue used as fuel ($Frac_{FUEL\text{-}CR_i}$ and $Frac_{FUEL\text{-}CR_j}$); (vi) the fraction of residue used for construction ($Frac_{CNST\text{-}CR_i}$ and $Frac_{CNST\text{-}CR_j}$); and (vii) the fraction of residue used as fodder ($Frac_{FOD_i}$ and $Frac_{FOD_j}$). *Good practice* default values for $Res_{O_i}/Crop_{O_i}$, $Frac_{DM_i}$, and $Frac_{NCRO_i}$, for some crop types, are presented in Table 4.16. Inventory agencies may use these values if country-specific data are not available. If a default residue nitrogen content is needed for a crop type for which a value is not provided in Table 4.16, the non-crop specific default values for N-fixing and Non-N-fixing crops that are listed in Table 4-19 of the Reference Manual of the *IPCC Guidelines* can be used (0.03 and 0.015 kg N/kg dry matter, respectively).

Area of organic soils harvested (F_{OS}): The *IPCC Guidelines* defines F_{OS} as the area (in hectares) of organic soils cultivated annually. This definition is applicable for both the Tier 1a and Tier 1b methods.

4.7.1.2 CHOICE OF EMISSION FACTORS

Two emission factors are needed to estimate direct N_2O emissions from agricultural soils. The first (EF_1) indicates the amount of N_2O emitted from the various nitrogen additions to soils, and the second (EF_2) estimates the amount of N_2O emitted from cultivation of organic soils.

Country-specific emission factors should be used where possible, in order to reflect the specific conditions of a country and the agricultural practices involved. Such emission factors should be based on measurements that are conducted frequently enough and over a long enough time period to reflect the variability of the underlying biogeochemical processes, given the selected measurement technique, and documented in refereed publications. *Good practice* in the derivation of country-specific emission factors is described in Box 4.1.

If country-specific emission factors are not available, emission factors from other countries with comparable management and climatic conditions are good alternatives. If this is not a key source category (see Chapter 7, Methodological Choice and Recalculation) or if the necessary resources are not available for deriving country- or region-specific emission factors, default emission factors may be used. It is anticipated that some inventory agencies will use a mix of default values and country-specific emission factors when the latter do not cover the

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[14] The *IPCC Guidelines* present a default value for $Frac_R$ of 0.45 that is not consistent with the default value presented for aboveground crop residue and product. If $Frac_R = 0.45$, then 55% of the residue plus crop product mass equals residue. However, if residue plus crop product mass equals 2 times the crop product, then 50% of the residue plus crop product mass equals residue.

full range of environmental and management conditions. If country-specific or other emission factors are used instead of defaults, their derivation must be clearly documented.

The *good practice* default emission factors are summarised in Table 4.17, Updated Default Emission Factors to Estimate Direct N2O Emissions from Agricultural Soils. The default value for EF_1 in the *IPCC Guidelines* is 1.25% of the nitrogen applied to soils. In many cases, this factor will be adequate. However, if synthetic fertilisers are applied to fields that are already receiving applications of organic manure, recent data indicate that higher N_2O losses may occur (Clayton *et al.*, 1997). At this time no recommendation to change the default is made because of the need for further corroborating evidence. Where this correction is needed, *good practice* requires use of a more detailed form of the basic equation presented in the *IPCC Guidelines* to ensure that the appropriate emission factors are applied to the various nitrogen inputs.

The default value for EF_2 presented in the *IPCC Guidelines* should be updated based on the results of more recent measurements. These measurements indicate that the emission factors for organic soils in mid-latitudes are higher than previously estimated (Klemedtsson *et al.*, 1999). These data suggest that a value of 8 rather than 5 is appropriate for EF_2 in mid-latitudes. Consistent with the approach taken in the *IPCC Guidelines*, in which mineralisation rates are assumed to be about 2 times greater in tropical climates than in temperate climates, the emission factor EF_2 for tropical climates should be 16.

TABLE 4.17
UPDATED DEFAULT EMISSION FACTORS TO ESTIMATE DIRECT N_2O EMISSIONS FROM AGRICULTURAL SOILS

Emission Factor	**IPCC Default Value** **(EF_1 in kg N_2O-N/kg N)** **(EF_2 in kg N_2O-N/ha-yr)**	**Updated Default Value** **(EF_1 in kg N_2O-N/kg N)** **(EF_2 in kg N_2O-N/ha-yr)**
EF_1 for F_{SN}	1.25%	No Change
EF_1 for F_{SN} when applied to fields already receiving organic fertiliser/animal manure (applied or grazing)	1.25%	No Change
EF_1 for F_{AM}	1.25%	No Change
EF_1 for F_{BN}	1.25%	No Change
EF_1 for F_{CR}	1.25%	No Change
EF_2 for Mid-Latitude Organic Soils	5	8
EF_2 for Tropical Organic Soils	10	16

Source: *IPCC Guidelines*, Klemedtsson *et al.* (1999), Clayton *et al.* (1997).

4.7.1.3 CHOICE OF ACTIVITY DATA

Several types of activity data are required to estimate direct N_2O emissions from soils. For the anthropogenic N inputs from application of synthetic fertilisers (F_{SN}) and animal manure (F_{AM}), as well as biological N-fixation by crops (F_{BN}), mineralisation of crop residues returned to soils (F_{CR}), and soil nitrogen mineralisation due to cultivation of organic soils (F_{OS}), the types and sources of the activity data and key considerations related to the application of more detailed country-and potentially crop-specific methods (now or in the future) are described below. Even if inventory agencies cannot currently prepare estimates based on country- or crop-specific emission factors , it is *good practice* to collect detailed activity data as far as possible. This will allow for a more accurate future revision of previously constructed inventories should country- or crop-specific emission factors become available.

F_{SN}: The inputs required for calculation of F_{SN} are N_{FERT} and $Frac_{GASF}$.

- Synthetic fertiliser consumption (N_{FERT}) data should be collected from official statistics (e.g. national bureaux of statistics) using yearly census data. Most inventory agencies may be able to readily obtain such data. If country-specific data are not available, data from the International Fertiliser Industry Association (IFA, Paris; www.fertiliser.org/stats.htm) on total fertiliser use by type and by crop, or from the Food and Agriculture Organisation of the United Nations (FAO; www.apps.fao.org) on synthetic fertiliser consumption can be used. It may be useful to compare national statistics to international databases such as those of the IFA and FAO. If possible, N_{FERT} data should be disaggregated by fertiliser type, crop type and climatic regime for major crops, if sufficient data are available.

- For the fraction of nitrogen that volatilises as NH_3 and NO_x from applied synthetic fertilisers ($Frac_{GASF}$), a fixed loss rate of 10% can be used in the (*IPCC Guidelines*, Table 4-19, Reference Manual). However, the loss rate can be highly variable, and depends on the type of synthetic fertiliser applied, the mode of application, and climate. The use of appropriately documented country-specific loss rates is encouraged.

F_{AM}: *Good practice* in developing the inputs for the calculation of F_{AM} using either the Tier 1a or Tier 1b equation has been summarised above. Regardless of how F_{AM} is estimated, it is suggested that the amount of animal manure applied and areas covered be disaggregated by crop type and climatic region if possible. This data may be useful in developing revised emission estimates if inventory methods are improved in the future.

- The total amount of nitrogen excreted by a country's animal population ($\Sigma_T(N_{(T)} \bullet Nex_{(T)})$) is calculated by determining the number of animals within a country by animal species/category ($N_{(T)}$) and multiplying by N excretion rates for each animal species/category ($Nex_{(T)}$). For *good practice*, the livestock population data should be developed following the approach described in Section 4.1, Livestock Population Characterisation, and must be consistent with the livestock characterisations used for other emission source categories. The N excretion rates for each animal species/category must also be consistent across source categories. The good practice approach for developing country-specific nitrogen excretion rates is described in Section 4.4: Estimating N_2O Emissions from Manure Management. If country-specific $\Sigma_T(N_{(T)} \bullet Nex_{(T)})$ rates are not available, default values from Table 4-20 in the *IPCC Guidelines* Reference Manual should be used.
- For the fraction of nitrogen that volatilises as NH_3 and NO_x from animal manure ($Frac_{GASM}$), a fixed loss rate of 20% is reported in the *IPCC Guidelines* Reference Manual Table 4-19. These losses are highly variable and depend on the type of animal manure, its storage, mode of application, and climate. Country-specific $Frac_{GASM}$ factors are encouraged for use if appropriately documented.
- The amounts of animal manure used for purposes other than fertiliser (represented by $Frac_{FUEL-AM}$, $Frac_{PRP}$, and if using the Tier 1b equation, $Frac_{CNST-AM}$ $Frac_{FEED-AM}$) can be obtained from official statistics or a survey of experts. The $Frac_{PRP}$ value used in this calculation must be consistent with the value used in calculating the N_2O emissions from grazing animals in the manure management section.

BOX 4.1
GOOD PRACTICE IN DERIVATION OF COUNTRY-SPECIFIC EMISSION FACTORS

In general, *good practice* requires the measurement of emissions by individual sub-source category (i.e. synthetic fertiliser (F_{SN}), animal manure (F_{AM}), biological N-fixation (F_{BN}), crop residue mineralisation (F_{CR}) and cultivation of organic soils (F_{OS})). For emission factors to be representative of environmental and management conditions within the country, measurements should be made in the major crop growing regions within a country, in all seasons, and if relevant, in different geographic and soil regions and under different management regimes. Appropriate selection of regions or regimes may enable a reduction in the number of sites that must be sampled to derive a reliable flux estimate. Maps or remote sensing data can provide a useful basis for delineation by utilising the variability of a system or landscape. Aggregation errors may occur if available measurements do not cover the actual range of environmental and soil management conditions, and inter-annual climatic variability. Validated, calibrated, and well-documented simulation models may be a useful tool to develop area-average emission factors on the basis of measurement data (Smith *et al.*, 1999).

Regarding measurement period and frequency, emission measurements should be taken over an entire year (including fallow periods), and preferably over a series of years, in order to reflect differences in weather conditions and inter-annual climatic variability. Measurements should be taken at least once per day following major disturbances that would cause emissions to increase above background levels (e.g. during and after rainfall events, ploughing, or fertiliser application). Less frequent measurements (once per day or less) are acceptable during periods when emissions are close to background levels. A good description of the measurement techniques that are available can be found in IAEA (1992).

To ensure accurate emission factors, it is *good practice* to monitor on representative sites those factors that may influence inter-annual variability of N_2O emissions. Such factors include fertiliser application, the previous crop, soil texture and drainage condition, soil temperature, and soil moisture. A complete list of factors that are involved in the regulation of N_2O formation, consumption, and exchange between soil and air can be found in Firestone and Davidson (1989). For N_2O emissions from organic soil cultivation, it can be assumed that the frequency of measurement need not be more detailed than that for mineral soils. The frequency of measurement should be consistent with the frequency of the disturbance event. Emissions are likely to be variable among geographic regions, especially among different cropping systems.

It is possible that N deposition from industrial sources might result in unrepresentative emission factors, but this is probably not a significant problem. In general, emission factors are determined by subtracting the emissions of a control plot (zero fertiliser) from the emissions of a fertilised plot. Since N deposition affects both plots, one would expect that N deposition is not included in the derived emission factor. Hence, the current default emission factor is most likely correct.

Note that the emission factors derived for both synthetic fertiliser and animal manure application should include corrections for volatilisation. In other words, the emission factor for these two sub-sources should represent the following: kg N_2O-N emitted / (kg N input- kg N volatilised)[15].

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[15] In words: kg N_2O (as N) emitted divided by (kg N input minus kg N volatilised).

F_{BN} and F_{CR}: The factors required for calculation of F_{BN} and F_{CR} using the Tier 1a method are $Crop_{BF}$, $Crop_O$, $Frac_{NCRBF}$, $Frac_{NCRO}$, $Frac_R$, and $Frac_{BURN}$:

- $Crop_{BF}$ and $Crop_O$, $Frac_{NCRBF}$, $Frac_{NCRO}$, $Frac_R$, and $Frac_{BURN}$: Data on the production of N-fixing crops ($Crop_{BF}$), as well as non-N-fixing crops ($Crop_O$), can generally be obtained from national statistics. If such data are not available, FAO publishes data on crop production (see the website: www.apps.fao.org). As previously mentioned, the definition of the term $Crop_{BF}$ should be modified from the definition provided in the *IPCC Guidelines*. It should be defined so that it represents the products of all N-fixing crops, not just the seed yield of pulses and soybeans. For the fraction of nitrogen in N-fixing crops ($Frac_{NCRBF}$), non-N-fixing crops ($Frac_{NCRO}$), and the fraction of residues burned in the field ($Frac_{BURN}$) some crop-specific default values are provided in the *Good Practice Report* Table 4.16, and non-crop specific values are provided in Table 4-19, Reference Manual of the *IPCC Guidelines*. The *IPCC Guidelines* definition of the term $Frac_R$ should be modified to the fraction of total aboveground biomass that is removed from the field as crop product. Also, as already discussed, the default value for $Frac_R$ provided in Table 4-19 in the Reference Manual of the *IPCC Guidelines* is inconsistent with the default value '2' in Equation 4.28. If Equation 4.28 is used, a value of 0.50 should be used for $Frac_R$. For the fractions of residues burned, the same values that are used in the agricultural residue burning calculations should be used here.

- Some additional inputs are required for calculation of F_{BN} and F_{CR} using the Tier 1b method. These are $Res_{BF}/Crop_{BF}$, $Res_O/Crop_O$, $Frac_{DM}$, $Frac_{FUEL}$, $Frac_{CNST}$, $Frac_{FOD}$. The data needed to determine the residue to crop product mass ratio for N-fixing ($Res_{BF}/Crop_{BF}$) and non-N-fixing ($Res_O/Crop_O$) crops can generally be obtained from national statistics. If possible, crop-specific values should be used because of the variability among crops. If such data are not available nationally, default $Res_{BF}/Crop_{BF}$ and $Res_O/Crop_O$ values from *Good Practice Report* Table 4.16 can be used. If available, the dry matter content of the aboveground biomass for both N-fixing and non-N-fixing crops ($Frac_{DM}$) should also be obtained from national statistics and should be specific to specific crop types. Alternatively, default values for dry matter residue in Table 4.16 can be used. For the fractions of residue used as fuel ($Frac_{FUEL}$), used in construction ($Frac_{CNST}$), and used as fodder ($Frac_{FOD}$), country-specific values should be used. The values used for $Frac_{FUEL}$ must be consistent with those used in the energy calculations.

  It should also be noted that in the *IPCC Guidelines'* method for incorporation of crop residues, the contribution from root biomass from the harvested crop is not accounted for. Ideally, both the aboveground and the root biomass should be accounted for to include nitrogen from the total plant, but the root biomass cannot readily be estimated. For N-fixing crops, the *IPCC Guidelines* method does not include root biomass because it is assumed that the N contained in the aboveground part of the plant (crop product + shoots) is a proxy for the N_2O emissions associated with the processes of nitrogen fixation in the roots and movement aboveground.

F_{OS}: The area (in hectares) of organic soils cultivated annually (F_{OS}) should be collected from official national statistics. If this source is not available, data from FAO can be used.

4.7.1.4 COMPLETENESS

Complete coverage for this source category requires estimation of emissions for all of the anthropogenic inputs and activities (F_{SN}, F_{AM}, F_{BN}, F_{CR}, and F_{OS}, $F_{SEWSLUDGE}$), if they occur. Experience has shown that none of these sub-categories are likely to be missed in inventories, although countries may have difficulty obtaining accurate statistics for all sub-categories, particularly the amounts of crop residues (by crop type) that are typically incorporated into soils, and the area of cultivated organic soils.

Currently, the IPCC method does not explicitly address several activities that may enhance N_2O emissions, including:

- Consumption of commercial and non-commercial organic fertilisers other than animal manure and crop residues and sewage sludge;
- Production of N-fixing forage crops such as alfalfa;
- Production of mixed grass and N-fixing forage;
- Use of cover crops (catch crops) sown as green manure to reduce leaching of N in post-harvest periods;
- Ploughing of pasture lands;
- Use of plastic sheeting on horticultural soils;

- N deposition onto agricultural land from industrial sources (see Box 1: *Good Practice* in Derivation of Country-specific Emission Factors).

These additional activities can be considered, if appropriate, and if national activity data for these activities are collected. Some of these activities can be readily included in national inventories based on available information. For the additional commercial and non-commercial organic fertilisers, the default emission factor used for applied N and default fraction of animal manure N volatilised may be used. For N-fixing forage crops, use of the *good practice* method for biological nitrogen fixation is suggested, using harvested crop dry matter as the measure of total aboveground biomass. For cover (catch) crops, the *good practice* method for crop residues is suggested. Further research will be required to develop the flux data that is needed to develop emission factors for mixed grass and legume pastures, ploughing of grasslands, and use of plastic sheeting on horticultural areas.

4.7.1.5 DEVELOPING A CONSISTENT TIME SERIES

Ideally, the same method should be used throughout the entire time series. However, it is likely that the detail and disaggregation of emissions estimates from this source category will improve over time. In cases where some historical data are missing, it may be necessary to derive the data using other references or data sets. For example, annual data of areas for cultivated organic soils may need to be derived by interpolation from a longer time series based upon long-term trends (e.g. from decadal statistics over a 20- or 30-year period). Estimates of the amounts of crop residue incorporated annually may also need to be derived based on expert judgement. For general good practice guidance on ensuring time series consistency (see Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2).

It is important that the methods used reflect the results of action taken to reduce emissions and the methods and results are thoroughly documented. If policy measures are implemented such that activity data are affected directly (e.g. increased efficiency of fertiliser use resulting in a decrease in fertiliser consumption), the effect of the policy measures on emissions will be transparent, assuming the activity data are carefully documented. In cases where policy measures have an indirect effect on activity data or emission factors (e.g. a change in animal population feed practices to improve animal productivity that results in a change in animal excretion per head), inventory input data should reflect these effects. The inventory text should thoroughly explain the effect of the policies on the input data.

4.7.1.6 UNCERTAINTY ASSESSMENT

Uncertainties in estimates of direct emissions of N_2O from agricultural soils are caused by uncertainties related to the emission factors and activity data, lack of coverage of measurements, spatial aggregation, and lack of information on specific on-farm practices. Additional uncertainty will be introduced in an inventory when emission measurements that are not representative of all conditions in a country are used. For *good practice* measurements of direct N_2O emissions from soils for a specific sub-category (Smith *et al.*, 1999), the associated uncertainty is expected to be about 25%. In general, the reliability of activity data will be higher than that of the emission factors. As an example, further uncertainties may be caused by missing information on observance of laws and regulations related to handling and application of fertiliser and manure, and changing management practices in farming. Generally it is difficult to obtain information on the actual observance of laws and possible emission reductions achieved as well as information on farming practices.

Recent data (Smith *et al*, 1999; Mosier and Kroeze, 1999) indicate that measured emission factors for N_2O from applied nitrogen have a skewed distribution which is nearer to log-normal than normal, with a range from the order of 0.1% to the order of 10%. The best estimate of the 95% confidence limit ranges from one-fifth to 5 times the default emission factor of 1.25%, i.e. from about 0.25% to 6%.

For histosols, the uncertainty range is 1 to 80 kg N_2O-N $ha^{-1}yr^{-1}$ for soils in mid-latitudes and 5 to >100 kg N_2O-N $ha^{-1}yr^{-1}$ in tropical histosols.

As uncertainties for this source category are caused by many different factors, the uncertainty needs to be estimated using expert judgement based on knowledge of various error components. Chapter 6, Quantifying Uncertainties in Practice, provides advice on quantifying uncertainties in practice, including application of Monte Carlo methods.

4.7.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. N_2O emissions from agricultural soils (direct-soils, direct-grazing animals, and indirect) are reported in aggregate under the IPCC category ‘Agriculture’. These three source categories should be listed separately in inventory reports. In addition, to improve the transparency of reporting, estimates of emissions from this source category should be reported by the following components:

- Synthetic fertiliser consumption;
- Animal manure applied to soils (other than that used as commercial fertiliser);
- Production of leguminous (N-fixing) crops;
- Crop residue incorporation;
- Organic soil cultivation.

If other components are included, such as commercial organic fertiliser, these should be reported separately as well. In addition to completing the reporting formats, the following additional information is necessary to document the estimate:

- **Activity data**: Sources of all activity data used in the calculations (i.e. complete citations for the statistical databases from which data were collected), and in cases when activity data were not available directly from databases, the information and assumptions that were used to derive the activity data. This documentation should include the frequency of data collection and estimation, and estimates of accuracy and precision.
- **Emission factors**: The sources of the emission factors that were used (specific IPCC default values or otherwise). In inventories in which country- or region-specific emission factors were used, or in which new methods (other than the default IPCC methods) were used, the scientific basis of these emission factors and methods should be completely described and documented. This includes defining the input parameters and describing the process by which these emission factors and methods are derived, as well as describing sources and magnitudes of uncertainties.
- **Emission results**: Significant fluctuations in emissions between years should be explained. A distinction should be made between changes in activity levels and changes in emission factors from year to year, and the reasons for these changes documented. If different emission factors are used for different years, the reasons for this should be explained and documented.

4.7.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to implement quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8, QA/QC, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category.

It is *good practice* to supplement the general QA/QC related to data processing, handling, and reporting, as outlined in Chapter 8, QA/QC, with source-specific category procedures discussed below. The persons who collect data are responsible for reviewing the data collection methods, checking the data to ensure that they are collected and aggregated or disaggregated correctly, and cross-checking the data with previous years to ensure that the data are reasonable. The basis for the estimates, whether statistical surveys or ‘desk estimates’, must be reviewed and described as part of the QC effort. Documentation is a crucial component of the review process because it enables reviewers to identify mistakes and suggest improvements.

Review of emission factors

- The inventory agency should review the default emission factors and document the rationale for setting specific values.
- If using country-specific factors, the inventory agency should compare them to the IPCC default emission factors, and, if accessible, the country-specific emission factors used by other countries with comparable

circumstances. Differences between country-specific factors and default or other country factors should be explained and documented.

Review of any direct measurements

- If using factors based on direct measurements, the inventory agency should review the measurements to ensure that they are representative of the actual range of environmental and soil management conditions, and inter-annual climatic variability, and were developed according to recognised standards (IAEA, 1992).
- The QA/QC protocol in effect at the sites should also be reviewed and the resulting estimates compared between sites and with default-based estimates.

Activity data check

- The inventory agency should compare country-specific data on synthetic fertiliser consumption with fertiliser usage data from the IFA and synthetic fertiliser consumption estimates from the FAO.
- The inventory agency should ensure that N excretion data are consistent with those used for the manure management systems source category.
- National crop production statistics should be compared to FAO crop production statistics.
- The inventory agency should ensure that the QA/QC described in Section 4.1 for livestock population characterisation has been implemented and that a consistent livestock population characterisation is used across sources.
- Country-specific values for various parameters should be compared to IPCC defaults.

External review

- The inventory agency should conduct expert (peer) review when first adopting or revising the method. Given the complexity and uniqueness of the parameters used in calculating country-specific factors for these categories, involve specialists in the field should be involved in such reviews.

4.8 INDIRECT N_2O EMISSIONS FROM NITROGEN USED IN AGRICULTURE

Nitrous oxide (N_2O) is produced naturally in soils and aquatic systems through the microbial processes of nitrification and denitrification. A number of agricultural and other anthropogenic activities add nitrogen (N) to soils and aquatic systems, increasing the amount of N available for nitrification and denitrification, and ultimately the amount of N_2O emitted. The emissions of N_2O that result from anthropogenic N inputs occur through a direct pathway (i.e. directly from the soils to which N is applied), and through a number of indirect pathways, including the leaching and runoff of applied N in aquatic systems, and the volatilisation of applied N as ammonia (NH_3) and oxides of nitrogen (NO_x) followed by deposition as ammonium (NH_4) and NO_x on soils and water.

4.8.1 Methodological issues

The *IPCC Guidelines* provide methods to estimate N_2O emissions from both direct and indirect pathways. This section provides *good practice guidance* on how to estimate indirect emissions of N_2O, while the direct pathway is covered in Section 4.7. Indirect emissions from both aquatic systems and agricultural soils are covered in Section 4.5.4 of the Reference Manual of the *IPCC Guidelines*. The method for estimating indirect N_2O emissions from human sewage, that is discharged into rivers or estuaries, is also presented in this section, although these emissions are reported under the Waste Sector.

4.8.1.1 CHOICE OF METHOD

The method in the *IPCC Guidelines* for estimating indirect N_2O emissions from N used in agriculture describes five separate pathways by which anthropogenic inputs of N become available for formation of N_2O:

- Atmospheric deposition on soils of NO_x and ammonium (NH_4)[16] with the sources of N including volatilisation of N inputs to soils, as well as combustion and industrial process sources;
- Leaching and runoff of N that is applied to, or deposited on, soils;
- Disposal of sewage N;
- Formation of N_2O in the atmosphere from NH_3 emissions originating from anthropogenic activities;
- Disposal of processing effluents from food processing and other operations.

Of these five sources, the *IPCC Guidelines* describe how to estimate emissions from: (i) that portion of the atmospheric deposition of NO_x and ammonium (NH_4) associated with the N from synthetic fertilisers and animal manure that have been applied to soils; (ii) that portion of the N from applied synthetic fertilisers and animal manure lost as leaching and runoff; and (iii) the discharge of sewage N into rivers or estuaries. However, there is no current method for estimating conversion of NH_3 to N_2O in the atmosphere. The basic equation shown in the *IPCC Guidelines* for estimating a country's indirect N_2O emissions ($N_2O_{indirect}$) (kg N/year) is:

EQUATION 4.30

INDIRECT N_2O EMISSIONS

$$N_2O_{indirect}\text{-}N = N_2O_{(G)} + N_2O_{(L)} + N_2O_{(S)}$$

Where:

$N_2O_{indirect}$-N = Emissions of N_2O in units of nitrogen

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[16] The *IPCC Guidelines* refer to 'atmospheric deposition of NO_x and NH_3', but the process actually entails the volatilisation of applied N (or direct gaseous emissions of N) as oxides of nitrogen (NO_x) and ammonia (NH_3), transformations of these gases within the atmosphere (or upon deposition) and subsequent deposition as NO_x, nitric acid (HNO_3), and particulate ammonium (NH_4). NO_x is often hydrolysed in the atmosphere or upon deposition to form HNO_3, while NH_3 gas generally combines with atmospheric nitric acid or sulphuric acid (H_2SO_4) to form ammonium nitrate and ammonium sulphate aerosols, and hence is transformed to particulate ammonium form (NH_4).

$N_2O_{(G)}$ = N_2O produced from volatilisation of applied synthetic fertiliser and animal manure N, and its subsequent atmospheric deposition as NO_x and NH_4 (kg N/yr)

$N_2O_{(L)}$ = N_2O produced from leaching and runoff of applied fertiliser and animal manure N (kg N/yr)

$N_2O_{(S)}$ = N_2O produced from discharge of human sewage N into rivers or estuaries (kg N/yr) [17]

Conversion of N_2O-N emissions to N_2O emissions for reporting purposes is performed by using the following equation:

$$N_2O = N_2O\text{-}N \bullet 44/28$$

To apply the estimation method, the amount of N_2O produced from each of these indirect pathways must be determined. *Good practice guidance* on how to apply the *IPCC Guidelines* is provided below in order to clarify the method, and ensure consistency and completeness between source categories. The choice of *good practice* method is illustrated by the decision tree in Figure 4.8, Decision Tree for Indirect N_2O Emissions from Nitrogen used in Agriculture.

The terms Tier 1a and Tier 1b are used throughout *Good Practice Report,* Subsections 4.7 and 4.8, to differentiate between the equations in the *IPCC Guidelines* (Tier 1a) and new equations (Tier 1b) presented here. The Tier 1b equations represent increased precision due to expansion of the terms in the equations. However, while Tier 1b equations may be preferred, the activity data needed to use them may not be available. In these cases, use of the Tier 1a equations is appropriate. Estimating emissions using a combination of Tier 1a and Tier 1b equations for different sub-source categories, depending upon availability of activity data, is also acceptable. In some cases, there is no Tier 1b alternative because no refinement of the equation in the *IPCC Guidelines* was considered necessary.

Atmospheric deposition of NO_x and NH_4 ($N_2O_{(G)}$): Atmospheric deposition of nitrogen compounds such as nitrogen oxides (NO_x) and ammonium (NH_4) fertilises soils and surface waters, which results in enhanced biogenic N_2O formation. According to the *IPCC Guidelines*, the amount of applied agricultural N that volatilises and subsequently deposits on nearby soils is equal to the total amount of synthetic fertiliser nitrogen applied to soils (N_{FERT}) plus the total amount of animal manure nitrogen excreted in the country ($\sum_T(N_{(T)} \bullet Nex_{(T)})$) multiplied by appropriate volatilisation factors.[18] The volatilised N is then multiplied by an emission factor for atmospheric deposition (EF_4) to estimate $N_2O_{(G)}$ emissions.

The equation in the *IPCC Guidelines* is thus:

EQUATION 4.31

N_2O FROM ATMOSPHERIC DEPOSITION OF N (TIER 1a)

$$N_2O_{(G)}\text{-}N = [(N_{FERT} \bullet Frac_{GASF}) + (\textstyle\sum_T(N_{(T)} \bullet Nex_{(T)}) \bullet Frac_{GASM})] \bullet EF_4$$

Where[19]:

$N_2O_{(G)}$ = N_2O produced from atmospheric deposition of N, kg N/yr

N_{FERT} = total amount of synthetic nitrogen fertiliser applied to soils, kg N/yr [20]

$\sum_T(N_{(T)} \bullet Nex_{(T)})$ = total amount of animal manure nitrogen excreted in a country, kg N/yr

$Frac_{GASF}$ = fraction of synthetic N fertiliser that volatilises as NH_3 and NO_x, kg NH_3-N and NO_x-N/kg of N input

$Frac_{GASM}$ = fraction of animal manure N that volatilises as NH_3 and NO_x, kg NH_3-N and NO_x-N/kg of N excreted

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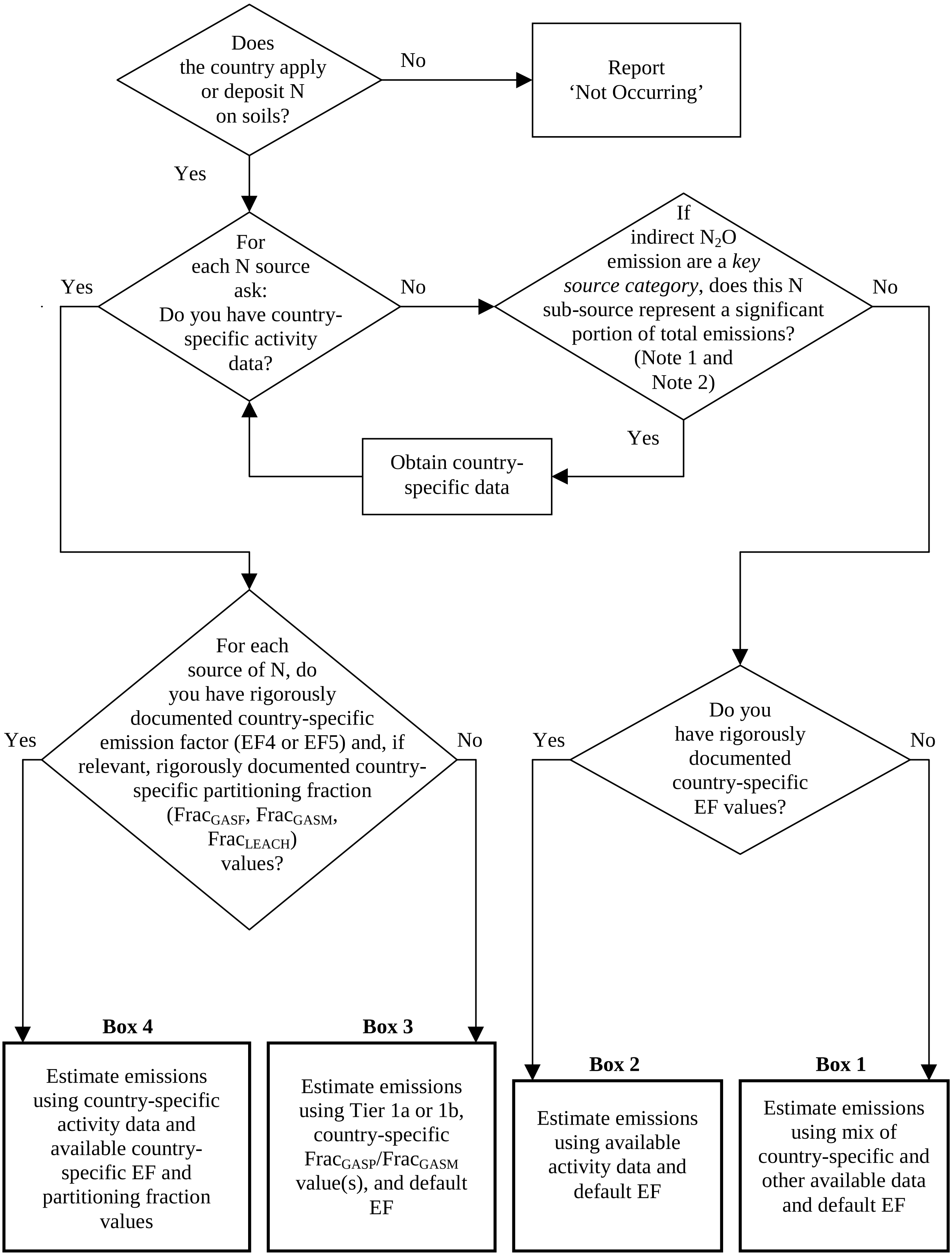
[17] Nitrous Oxide produced from human sewage ($N_2O_{(S)}$) is reported under the Waste sector.

[18] In this part of the *IPCC Guidelines*, the variable Nex is used for the total amount of animal manure produced. To be consistent with *Good Practice* in Section 4.4, this variable name has been revised to $\Sigma_T(N_{(T)} \bullet Nex_{(T)})$.

[19] Refer to Section 4.7 for more information on all of these terms except EF_4.

[20] The definition of N_{FERT} as total synthetic N fertiliser applied would cover application to forest soils.

Figure 4.8 Decision Tree for Indirect N_2O Emissions from Nitrogen Used in Agriculture



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: As a rule of thumb, a sub-source category would be significant if it accounts for 25-30% of emissions from the source category.

EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, kg N_2O-N/kg NH_3-N and NO_x-N emitted

Use of Equation 4.31 is consistent with *good practice*. If more detailed data are available, however, a more complete estimate can be prepared.

First, the activity data used to estimate $N_2O_{(G)}$ can be expanded to include other forms of N applied to *all* soils, rather than just synthetic fertilisers and animal manure applied to agricultural soils. For example, sewage sludge, an additional form of organic N, is often applied to soils as a soil amendment or to dispose of the sludge. Sewage sludge nitrogen ($N_{SEWSLUDGE}$) can be included in this calculation if sufficient information is available.[21] The sludge input should be measured in units of N and multiplied by the volatilization factor that is used for animal manure N, $Frac_{GASM}$. The resulting equation for estimating the amount of N_2O produced from atmospheric deposition, renamed $N_2O_{(G\text{-}SOIL)}$, is:

EQUATION 4.32

N2O FROM ATMOSPHERIC DEPOSITION OF N (TIER 1b)

$$N_2O_{(G\text{-}SOIL)}\text{-}N = \{(N_{FERT} \bullet Frac_{GASF}) + [\textstyle\sum_T(N_{(T)} \bullet Nex_{(T)}) + N_{SEWSLUDGE}\,] \bullet Frac_{GASM}\} \bullet EF_4$$

This equation will ensure a more complete accounting of the N_2O emissions from the volatilisation and re-deposition of N applied to soils. These emissions should be reported within the Agriculture Sector.

Second, other sources of N deposited on soils $N_2O_{(G\text{-}i)}$ can be accounted for. The estimation of $N_2O_{(G\text{-}i)}$, can be undertaken to the extent that data allow the inclusion of deposited N from other anthropogenic activities associated with agriculture that release NO_x and NH_3. This would include emissions of NO_x and NH_3 (in units of N) from prescribed burning of savannas and field burning of agricultural residues.[22]

Equation 4.33 shows the *good practice* approach for estimating N_2O emissions from these additional indirect sub-categories associated with agriculture. For each sub-category '*i*,' (i.e. prescribed burning of savannas and field burning of agricultural residues) the amount of N emitted as NO_x and NH_3 is multiplied by EF_4.

EQUATION 4.33

N2O FROM ADDITIONAL INDIRECT SUB-SOURCES

$$N_2O_{(G\text{-}i)}\text{-}N = (NO_{x\text{-}i} + NH_{3\text{-}i}) \bullet EF_4$$

Although the method for estimating these additional sub-categories of indirect emissions of N_2O is presented here, the estimates should be reported under the sector in which the originating activity is reported.

Leaching/runoff of applied or deposited nitrogen ($N_2O_{(L)}$): A large proportion of nitrogen is lost from agricultural soils through leaching and runoff. This nitrogen enters the groundwater, riparian areas and wetlands, rivers, and eventually the ocean, where it enhances biogenic production of N_2O. To estimate the amount of applied N that leaches or runs off (N_{LEACH}) using the method in the *IPCC Guidelines*, the total amount of synthetic fertiliser nitrogen (N_{FERT}) applied to the soils and the total amount of animal N excretion in the country ($\sum_T(N_{(T)} \bullet Nex_{(T)})$) are summed and then multiplied by the fraction of N input that is lost through leaching and runoff ($Frac_{LEACH}$). N_{LEACH} is then multiplied by the emission factor for leaching/runoff (EF_5) to obtain emissions of N_2O in units of N, $N_2O_{(L)}$. The equation in the *IPCC Guidelines* is thus:

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[21] Since there are no default data for the new parameter $N_{SEWSLUDGE}$, or guidance on collecting such data, this refinement should only be used if reliable country-specific data are available. Note that the sewage sludge activity data used to estimate indirect N_2O emissions should be the same as those used to estimate direct N_2O emissions (see Section 4.7).

[22] A complication in the estimation of N_2O emissions resulting from atmospheric deposition is that a significant fraction of NO_x and NH_3 may be deposited on the ocean, where EF_4 is probably not applicable and for which little information exists to define a more appropriate emission factor. This is particularly problematic for NO_x, which has a longer atmospheric lifetime than NH_3 and therefore is more likely to be transported far from its source (Smil, 1999). For the present, it is assumed that all NO_x and NH_3 are deposited on land.

EQUATION 4.34

DEPOSITED N FROM LEACHING/RUNOFF [23]

$$N_2O_{(L)}\text{-}N = [N_{FERT} + \sum_T(N_{(T)} \bullet Nex_{(T)})] \bullet Frac_{LEACH} \bullet EF_5$$

For *good practice*, this basic approach should be corrected so that it accounts for only the portion of animal manure N which is applied to soils (see Section 4.7).[24] As currently defined, the equation will overestimate N_2O emissions from this source because it does not reduce the total amount of animal manure N generated in a country ($\sum_T(N_{(T)} \bullet Nex_{(T)})$) by the amounts not applied to soil (i.e. the fractions used as fuel ($Frac_{FUEL\text{-}AM}$), feed ($Frac_{FEED\text{-}AM}$), and construction material ($Frac_{CNST\text{-}AM}$)). [25] The corrected equation is shown in Equation 4.35:

EQUATION 4.35

DEPOSITED N FROM LEACHING/RUNOFF (EXPANDED AS TO ANIMAL MANURE)

$$N_2O_{(L)}\text{-}N = N_{FERT} + \{\sum_T(N_{(T)} \bullet Nex_{(T)}) \bullet [1 - (Frac_{FUEL\text{-}AM} + Frac_{FEED\text{-}AM} + Frac_{CNST\text{-}AM})]\} \bullet Frac_{LEACH} \bullet EF_5$$

As with the estimation of $N_2O_{G\text{-}SOIL}$, if data are available the indirect emissions associated with the application of sewage sludge to soils should be included in the estimate (Tier 1b). In this case, the term $N_2O_{(L)}$ is renamed $N_2O_{L\text{-}SOIL}$ and the equation for estimating indirect N_2O emissions from leaching and runoff of N applied to soils is:

EQUATION 4.36

DEPOSITED N FROM LEACHING/RUNOFF (EXPANDED AS TO SEWAGE SLUDGE)

$$N_2O_{(L\text{-}SOIL)}\text{-}N = \left(N_{FERT} + \{\sum_T(N_{(T)} \bullet Nex_{(T)}) \bullet [1 - (Frac_{FUEL\text{-}AM} + Frac_{FEED\text{-}AM} + Frac_{CNST\text{-}AM})]\} + N_{SEWSLUDGE}\right) \bullet Frac_{LEACH} \bullet EF_5$$

Note that when estimating the animal manure N applied to soils, the calculation may need to be undertaken for each major animal species/category '*i*' because the fractions of animal manure used for fuel, feed, and construction may not be constant across all animal species/categories. In this case, Equation 4.36 should be rewritten as:

EQUATION 4.37

DEPOSITED N FROM LEACHING/RUNOFF (EXPANDED FOR MAJOR ANIMAL SPECIES/CATEGORIES)

$$N_2O_{(L\text{-}SOIL)}\text{-}N = \{N_{FERT} + \sum_i (N_{(EX)_i} \bullet [1 - (Frac_{(FUEL\text{-}AM)_i} + Frac_{(FEED\text{-}AM)_i} + Frac_{(CNST\text{-}AM)_i})] + N_{SEWSLUDGE}\} \bullet Frac_{LEACH} \bullet EF_5$$

The estimates derived from Equations 4.35, 4.36, and 4.37 should be reported as part of Agricultural Soil emissions within the Agriculture sector.

The term $N_2O_{(L)}$ can also be expanded to include other sources of N deposited on soils $N_2O_{(L\text{-}i)}$. If data allow, this should be undertaken to the extent that data allow the inclusion of deposition from other anthropogenic activities

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[23] Equation 4.34 combines the equations for N_{LEACH} and $N_2O_{(L)}$ from the *IPCC Guidelines*.

[24] This correction ensures that the estimates prepared for this source are consistent with those prepared for direct N_2O emissions from agricultural soils, as described in Section 4.7.

[25] Note that in Equation 4.35, the fraction of N volatilised from fertiliser and animal manure is not accounted for. This is not an oversight but rather reflects the method's assumption that such N is subject to leaching after it redeposits on soil.

associated with agriculture that release NO_x and NH_3. This would include emissions of NO_x and NH_3 (in units of N) from prescribed burning of savannas and field burning of agricultural residues.

Equation 4.38 shows the *good practice* approach for estimating N_2O emissions from these additional indirect sub-source categories. For each source '*i*' (i.e. prescribed burning of savannas and field burning of agricultural residues), the amount of N emitted as NO_x and NH_3 is multiplied by $Frac_{LEACH}$ and EF_5.

EQUATION 4.38

DEPOSITED N FROM LEACHING/RUNOFF (EXPANDED AS TO ADDITIONAL INDIRECT SUB-SOURCES)

$$N_2O_{(L\text{-}i)}\text{-}N = (NO_{x\text{-}i} + NH_{3\text{-}i}) \bullet Frac_{LEACH} \bullet EF_5$$

Although the method for estimating these additional sources of indirect emissions of N_2O is presented here, the estimates should be reported under the source category in which the originating activity is reported.

Human consumption followed by municipal sewage treatment ($N_2O_{(S)}$): Human consumption of food results in the production of sewage, that can be processed in septic systems or wastewater treatment facilities, and then may seep into groundwater systems, be disposed of directly on land, or be discharged into a water source (e.g. rivers and estuaries). N_2O can be produced during all of these processes through nitrification and denitrification of sewage nitrogen. The *IPCC Guidelines* assume that N_2O emissions associated with sewage treatment and land disposal are negligible, so that all sewage nitrogen enters rivers and estuaries, where it is available for nitrification and denitrification. The method also recognises that some sewage N may be applied to soil as sludge. To estimate total sewage nitrogen (N_{SEWAGE}) using the method in the *IPCC Guidelines*, [26] the annual per capita protein consumption (PROTEIN, in kg protein/person-year) is multiplied by the national population (Nr_{PEOPLE}) and the fraction of protein that is nitrogen ($Frac_{NPR}$). N_{SEWAGE} is then multiplied by the emission factor for indirect emissions from sewage treatment (EF_6) to obtain N_2O emissions (in units of N) from discharge of sewage ($N_2O_{(S)}$). The two equations presented in the *IPCC Guidelines* to calculate N_2O emissions from discharge of sewage are combined in the single *good practice* equation below:

EQUATION 4.39

N_2O EMISSIONS FROM DISCHARGE OF SEWAGE[27]

$$N_2O_{(S)}\text{-}N = PROTEIN \bullet Nr_{PEOPLE} \bullet Frac_{NPR} \bullet EF_6$$

It is *good practice* to use this basic approach, if a basic approach has also been used for estimating indirect emissions from the atmospheric deposition and leaching/runoff pathways (i.e. if Equations 4.31 and 4.35 have been used). If a more detailed estimate has been prepared for these other pathways, however, a more detailed approach should also be used for this sub-category. To avoid double-counting of sewage N in this case, N_{SEWAGE} should be decreased by the amount of sewage N that is applied to soils in the form of sewage sludge ($N_{SEWSLUDGE}$), and that has already been accounted for in estimating both $N_2O_{(G\text{-}SOIL)}$ and $N_2O_{(L\text{-}SOIL)}$. Therefore, the more detailed equation for estimating $N_2O_{(S)}$, is :

EQUATION 4.40

N_2O EMISSIONS FROM DISCHARGE OF SEWAGE (EXPANDED AS TO SEWAGE SLUDGE)

$$N_2O_{(S)}\text{-}N = [(PROTEIN \bullet N_{PEOPLE} \bullet Frac_{NPR}) - N_{SEWSLUDGE}] \bullet EF_6$$

These emissions should be reported under Domestic and Commercial Wastewater in Chapter 5, Waste (Section 5.2).

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[26] General guidance for estimating N_2O emissions from human sewage is provided in Section 6.4, Nitrous Oxide from Human Sewage, IPCC Guidelines, Vol. 3. For a detailed description of the proposed method, the reader is referred to Section 4.5.4 of the IPCC Guidelines, Reference Manual.

[27] Equation 4.39 combines the equations for N_{SEWAGE} and $N_2O_{(S)}$ from the *IPCC Guidelines*.

4.8.1.2 CHOICE OF EMISSION FACTORS

The method for estimating indirect N_2O emissions includes three emission factors: one associated with deposited nitrogen (EF_4), the second associated with nitrogen lost through leaching and runoff (EF_5), and the third associated with nitrogen in discharged sewage (EF_6).

Very little information exists, even on a global scale, for specifying EF_4, EF_5, and EF_6. Therefore, although the *IPCC Guidelines* normally encourages inventory agencies to substitute country-specific data for default emission factors, for this source category the default values should be used unless rigorously documented and peer-reviewed country-specific values have been developed. The following discussion summarises the default values and describes some refinements of them. For *good practice*, the IPCC default emission factors are presented in Table 4.18, Default Emission Factors for Estimating Indirect N_2O Emissions from N used in Agriculture.

- **Emission factor for deposited nitrogen (EF_4):** The default value for EF_4 is 0.01 kg N_2O-N/kg NH_4-N and NO_x-N deposited. Country-specific values for EF_4 should be used with great caution because of the special complexity of transboundary atmospheric transport. Although inventory agencies may have specific measurements of N deposition and associated N_2O flux, in many cases the deposited N may not have originated in their country. Similarly, some of the N that volatilises in their country may be transported to and deposited in another country, where different conditions that affect the fraction emitted as N_2O may prevail.
- **Emission factor for leaching and runoff (EF_5):** This value should be updated based on a recent re-examination of one of the factors from which it was derived. However, more research will be required before a new default value can be established.
- **Emission factor for discharged sewage effluent:** The default value for EF_6 is 0.01 kg N_2O-N/kg N. This value was derived by adding estimates of emission factors for rivers ($EF_{5\text{-}r}$ = 0.0075) and estuaries ($EF_{5\text{-}e}$ = 0.0025). Country-specific values of EF_6 must be used with great caution because of the complexity of this emission pathway.

TABLE 4.18
DEFAULT EMISSION FACTORS FOR ESTIMATING INDIRECT N_2O EMISSIONS FROM N USED IN AGRICULTURE

Emission Factor	IPCC Default Value
EF_4 (kg N_2O-N/kg NH_4-N & NO_x-N deposited)	0.01
EF_5 (kg N_2O-N/kg N leached & runoff)	0.025
EF_6 (kg N_2O-N/kg sewage N discharged sewage effluent)	0.01

Source: *IPCC Guidelines*, Reference Manual, Table 4-23.

4.8.1.3 CHOICE OF ACTIVITY DATA

Much of the activity data required to estimate indirect N_2O emissions, such as fertiliser consumption and livestock nitrogen excretion, will have been previously developed for estimating emissions from other source categories. Table 4.19, Data for Estimating Indirect N_2O, summarises the key activity data required, and describes where to obtain them. It is essential that the same data sets be used across source categories to ensure consistency in emission estimates.

As Table 4.19 shows, most of the activity data will be data developed for other source category estimates. *Good practice* in obtaining that data is described in the appropriate sections. The discussion below summarises *good practice* for developing the activity data:

- **Estimating NO_x and NH_3 emissions from new source categories included for good practice:** Emissions of NO_x and NH_3 resulting from savanna burning and agricultural residue burning are required to estimate indirect N_2O emissions from these activities. Estimation methods and default emission factors (or emission ratios) for estimating NO_x emissions are included for these sub-categories in the *IPCC Guidelines* under their respective sectors or sub-sectors. The same methods used to estimate NO_x emissions for each sub-category should be used to estimate NH_3 emissions, but the NO_x emission factors should be replaced with NH_3 emission factors. A default emission factor of 0.038 Gg NH_3-N/Gg fuel N (Crutzen and Andreae, 1990)[28] may be used to estimate NH_3 emissions from savanna burning and agricultural residue burning if country-specific emission factors are not available.

TABLE 4.19
DATA FOR ESTIMATING INDIRECT N_2O

Activity Data	How to Obtain
N_{FERT}	From estimate of N_{FERT} value collected for Direct N_2O Emissions from Agricultural Soils
$\sum_T(N_{(T)} \bullet N_{ex(T)})$	From estimate of $\sum_T(N_{(T)} \bullet N_{ex(T)})$ value collected for Direct N_2O Emissions from Agricultural Soils
$N_{SEWSLUDGE}$	From estimate of $N_{SEWSLUDGE}$ value collected for Direct N_2O Emissions from Agricultural Soils
PROTEIN	Food and Agricultural Organisation (FAO)
Nr_{PEOPLE}	Food and Agricultural Organisation (FAO)
$Frac_{NPR}$	See Table 4-24 in the *IPCC Guidelines* Reference Manual
$Frac_{LEACH}$	See Table 4-24 in the *IPCC Guidelines* Reference Manual
$Frac_{GASF}$	See Table 4-19 in the *IPCC Guidelines* Reference Manual
$Frac_{GASM}$	See Table 4-19 in the *IPCC Guidelines* Reference Manual
$Frac_{FUEL-AM}$	From estimate of $Frac_{FUEL-AM}$ value collected for Direct N_2O Emissions from Agricultural Soils
$Frac_{FEED-AM}$	From estimate of $Frac_{FEED-AM}$ value collected for Direct N_2O Emissions from Agricultural Soils
$Frac_{CNST-AM}$	From estimate of $Frac_{CNST-AM}$ value collected for Direct N_2O Emissions from Agricultural Soils

- **Partitioning fractions for volatilisation ($Frac_{GASF}$, $Frac_{GASM}$):** For the fraction of nitrogen that volatilises as NH_3 and NO_x from applied synthetic fertilisers ($Frac_{GASF}$) and animal manure and sewage sludge ($Frac_{GASM}$), default values of 10% and 20%, respectively, are presented in the *IPCC Guidelines*. Country-specific volatilisation fractions can be used with reasonable documentation.

- **Partitioning fraction for leaching ($Frac_{LEACH}$):** A default value of 30% is presented in the *IPCC Guidelines* for $Frac_{LEACH}$. Note, however, that this default value was largely based on mass balance studies comparing agricultural N inputs to N recovered in rivers. Agricultural practices (e.g. irrigation, frequent ploughing, and drainage tiles) can promote heavy leaching losses of N applied to agricultural soils. However, for N that is deposited *away* from agricultural land, a lower value of $Frac_{LEACH}$ may be more appropriate. Future revisions of the method may reflect this consideration. Due to difficulties in developing a reliable factor for this source category, inventory agencies should use caution and provide rigorous documentation if using a country-specific factor.

- **Partitioning fraction for nitrogen in protein ($Frac_{NPR}$):** A default values of 16% is presented in the *IPCC Guidelines* for the fraction of animal and plant protein that is nitrogen ($Frac_{NPR}$). This term is not highly variable, and therefore country-specific values are unnecessary.

4.8.1.4 COMPLETENESS

Complete coverage for indirect N_2O emissions from nitrogen used in agriculture requires estimation of emissions from all of the agricultural input activities (i.e. N_{FERT}, $\sum_T(N_{(T)} \bullet Nex_{(T)})$, and $N_{SEWSLUDGE}$). If data are available, $N_{SEWSLUDGE}$ application (on all soils) can also be included. Complete coverage for indirect N_2O emissions from human sewage requires estimation of emissions from the discharge of sewage N (i.e. N_{SEWAGE}, N_{SEWAGE} minus $N_{SEWSLUDGE}$).

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[28] Table 2 of Andreae and Crutzen (1990) is the basis for the NO_x and NH_3 emission factors associated with biomass burning. Note that this table also lists an emission factor of 0.034 mole RCN per mole total N in biomass, on par with the NH_3 emission factor. RCN is a form of nitrogen which is biologically available and therefore subject to microbial nitrification, denitrification, and N_2O production. Furthermore, Table 2 of Andreae and Crutzen (1990) only accounts for about 70% of biomass N, implying that combustion may yield additional, as yet unidentified forms of biologically available nitrogen. Thus by only accounting for NO_x and NH_3 emissions, the method likely underestimates the total amount of biologically available nitrogen released by biomass burning.

If data are available, the inventory should also include indirect N_2O emissions from savanna burning and agricultural residue burning. These emissions are based upon direct emissions of NO_x and NH_3 from these activities.

4.8.1.5 DEVELOPING A CONSISTENT TIME SERIES

Emission estimates over a time series should be made using the same method (in terms of level of detail). Inter-annual changes in $Frac_{GASF}$, $Frac_{GASM}$, $Frac_{LEACH}$, $Frac_{NPR}$, EF_4, EF_5, and EF_6 are not expected unless mitigation measures are undertaken. These factors should be changed only with the proper justification and documentation. If updated defaults for any of these variables become available through future research, inventory agencies may recalculate their historical emissions. For general *good practice* guidance on ensuring consistency in a time series, see Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2.

4.8.1.6 UNCERTAINTY ASSESSMENT

Information about emission factors (EF_4, EF_5, and EF_6), leaching and volatilisation fractions are sparse and highly variable. Expert judgement indicates that emission factor uncertainties are at least in order of magnitude and volatilisation fractions of about +/–50%. Uncertainties in activity data estimates should be taken from the corresponding direct emissions source categories. Chapter 6, Quantifying Uncertainties in Practice, provides advice on quantifying uncertainties in practice including combining expert judgements and empirical data into overall uncertainty estimates.

4.8.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. The worksheets in the *IPCC Guidelines* (Workbook) for calculating indirect N_2O from agricultural soils provide for transparent documentation of the default method of the *IPCC Guidelines*, and the data used to implement the method. However, to implement *good practice*, these worksheets should be expanded to incorporate the new variables that have been added to the deposition and leaching calculations (i.e. $N_{SEWSLUDGE}$, $Frac_{FUEL\text{-}AM}$, $Frac_{FEED\text{-}AM}$, and $Frac_{CNST\text{-}AM}$) and should be revised to reflect Equations 4.31 and 4.35 or 4.36.

The worksheets in the Workbook of the *IPCC Guidelines* used for calculating indirect N_2O from human sewage also provide for transparent documentation of the default method and the data used to implement the method. However, to implement the *good practice* approach, these worksheets must be expanded to incorporate the new variable that has been added to the calculation (i.e. $N_{SEWSLUDGE}$) and must be revised to reflect Equation 4.40.

To implement *good practice* for indirect N_2O emissions from savanna burning and agricultural residue burning, new worksheets must be developed for each of these sub-categories. The worksheet for indirect N_2O emissions from savanna burning and agricultural residue burning should reflect Equations 4.33 and 4.38.

The reporting tables in the Reporting Instructions are inadequate. Direct and indirect agricultural N_2O sources are reported together as one entry entitled ‘agricultural soils’ rather than separately. Furthermore, the title is a misnomer for indirect emissions, since a large fraction of these emissions occurs from aquatic systems. To improve the transparency of reporting, estimates of emissions from deposition and leaching should be reported separately. An explicit entry for indirect emissions from human sewage should be added in the Waste section. Entries for the new indirect N_2O sources (savanna burning and agricultural residue burning) should also be added to the reporting tables.

In addition to completing the reporting formats, the following additional information is necessary to document indirect N_2O emission estimates:

- **Activity data**: References for all activity data used in the calculations (i.e. complete citations for the statistical database from which data were collected), and in cases when activity data were not available directly from databases, the information and assumptions that were used to derive the activity data. This documentation should include the frequency of data collection and estimation, and estimates of accuracy and precision.
- **Emission factors**: References for the emission factors that were used (specific IPCC default values or otherwise). In inventories in which country- or region-specific emission factors were used, or in which new methods (other than the default IPCC methods) were used, the scientific basis of these emission factors or

methods should be completely described and documented. This includes defining the input parameters and describing the process by which these emission factors or methods are derived, as well as describing sources and magnitudes of uncertainties.

- **Emission results**: Significant fluctuations in emissions between years should be explained. A distinction should be made between changes in activity levels and changes in emission factors from year to year and the reasons for these changes documented. If different emission factors are used for different years, the reasons for this should be explained and documented.

4.8.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to implement quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8, QA/QC, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source.

It is *good practice* to supplement the general QA/QC related to data processing, handling and reporting, as outlined in Chapter 8, QA/QC, with source-specific procedures discussed below. The persons who collect data are responsible for reviewing the data collection methods, checking the data to ensure that they are collected and aggregated or disaggregated correctly, and cross-checking the data with previous years to ensure that the data are reasonable. The basis for the estimates, whether statistical surveys or ‘desk estimates’ must be reviewed and described as part of the QC effort. Documentation is a crucial component of the review process because it enables reviewers to identify mistakes and suggest improvements.

Review of emission factors

- The inventory agency should review the parameters, equations and calculations used to develop the emission factors. These QC steps are particularly important for subcategories in this source category because of the number of parameters that are used to construct the emission factors.
- If using country-specific factors, the inventory agency should compare them to the IPCC default factors. This is particularly important for the emission factors for deposited N and for discharged sewage, where caution should be used in developing country-specific factors.

Activity data check

- Since many of the activity parameters used for this source category are also used for other agricultural sources, it is critical to ensure that consistent values are being used.
- If using country-specific values for various parameters, (i.e. $Frac_{LEACH}$), the inventory agency should compare them to the IPCC defaults. Rigorous documentation of the development of country-specific values should also be maintained.

External review

- Agricultural specialists (particularly nitrogen cycle specialists) as well as agricultural industry and other stakeholders, should peer review the inventory estimates and all important parameters and emission factors.

4.9 CH_4 EMISSIONS FROM RICE PRODUCTION

4.9.1 Methodological issues

Anaerobic decomposition of organic material in flooded rice fields produces methane (CH_4), which escapes to the atmosphere primarily by transport through the rice plants. The annual amount emitted from an area of rice acreage is a function of rice cultivar, number and duration of crops grown, soil type and temperature, water management practices, and the use of fertilisers and other organic and inorganic amendments.

4.9.1.1 CHOICE OF METHOD

The *IPCC Guidelines* outline one method for estimating emissions from rice production, that uses annual harvested areas[29] and area-based seasonally integrated emission factors.[30] In its most simple form, the IPCC method can be implemented using national activity data (i.e. national total area harvested) and a single emission factor. However, the conditions under which rice is grown (e.g. water management practices, organic fertiliser use, soil type) may be highly variable within a country, and these conditions can affect seasonal CH_4 emissions significantly. The method can be modified to account for this variability in growing conditions by disaggregating national total harvested area into sub-units (e.g. harvested areas under different water management regimes), and multiplying the harvested area for each sub-unit by an emission factor that is representative of the conditions that define the sub-unit. With this disaggregated approach, total annual emissions are equal to the sum of emissions from each sub-unit of harvested area. Thus, the basic equation is as follows:

EQUATION 4.41

CH_4 EMISSIONS FROM RICE PRODUCTION

$$\text{Emissions from Rice Production (Tg/yr)} = \sum_i \sum_j \sum_k (EF_{ijk} \bullet A_{ijk} \bullet 10^{-12})$$

Where:

EF_{ijk} = a seasonally integrated emission factor for *i*, *j*, and *k* conditions, in g CH_4/m^2

A_{ijk} = annual harvested area for *i*, *j*, and *k* conditions, in m^2/yr

i, j, and k = represent different ecosystems, water management regimes, and other conditions under which CH_4 emissions from rice may vary (e.g. addition of organic amendments)

The different conditions that should be considered include rice ecosystem type, water management regime, type and amount of organic amendments, and soil type. The primary rice ecosystem types, and water management regimes in each ecosystem type, are listed in Table 4.20, IPCC Default CH_4 Emission Scaling Factors for Rice Ecosystems and Water Management Regimes Relative to Continuously Flooded Fields. If rice is produced in distinct regions within the country (e.g. district, province), the equation above should be applied to each region. National emissions are equal to the sum of the regional estimates. In addition, if more than one crop is harvested in a particular region during the year, and the conditions of cultivation (e.g. use of organic amendments) vary among cropping seasons, then for that region, emissions should be estimated for each cropping season, and then summed over all cropping seasons. In this case, the activity data are cultivated area, rather than harvested area.

If rice is a *key source category* (as defined in Chapter 7, Methodological Choice and Recalculation), inventory agencies are encouraged to:

- Implement the IPCC method at the most disaggregated level possible;

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[29] In case of multiple cropping during the same year, ‘harvested area’ is equal to the sum of the area cultivated for each cropping.

[30] An emission factor represents the total missions over an entire cropping season (from land preparation until harvest or post season drainage) per unit area. As in Appendix 4A.3, emission factors should be based on measurements over the entire period of flooding, and should account for fluxes of soil-entrapped methane that typically occur upon drainage.

- Incorporate as many of the characteristics (i, j, k, etc.,) that influence CH_4 emissions as possible;
- Develop country-specific emission factors to reflect the local impacts of these characteristics, preferably through collection of field data;
- Use emission factors and activity data at the same level of aggregation.

The decision tree in Figure 4.9, Decision Tree for CH_4 Emissions from Rice Production, guides inventory agencies through the process of applying the *good practice* IPCC approach. Implicit in this decision tree is a hierarchy of disaggregation in implementing the IPCC method. Within this hierarchy, the level of disaggregation utilised by an inventory agency will depend upon the availability of activity and emission factor data, as well as the importance of rice as a contributor to national greenhouse gas emissions. The specific steps and variables in this decision tree, and the logic behind it, are discussed in the text that follows the decision tree.

4.9.1.2 CHOICE OF EMISSION FACTORS

Ideally, inventory agencies will have seasonally integrated emission factors for each commonly occurring set of rice production conditions in the country developed from standardised field measurements. These local, measurement-based emission factors account for the specific mix of different conditions that influence CH_4 emissions in one area implicitly. The most important conditions that influence rice emissions are summarised in Box 4.2:

BOX 4.2
CONSIDERATIONS FOR RICE PRODUCTION EMISSION FACTOR DEVELOPMENT

The following rice production characteristics should be considered in developing emission factors:

Regional differences in rice cropping practices: If the country is large and has distinct agricultural regions, a separate set of measurements should be performed for each region.

Multiple crops: If more than one crop is harvested on a given area of land during the year, and the growing conditions vary among cropping seasons, emissions should be measured for each season.

Ecosystem type: At a minimum, separate measurements should be undertaken for each ecosystem (i.e. irrigated, rainfed, and deep water rice production).

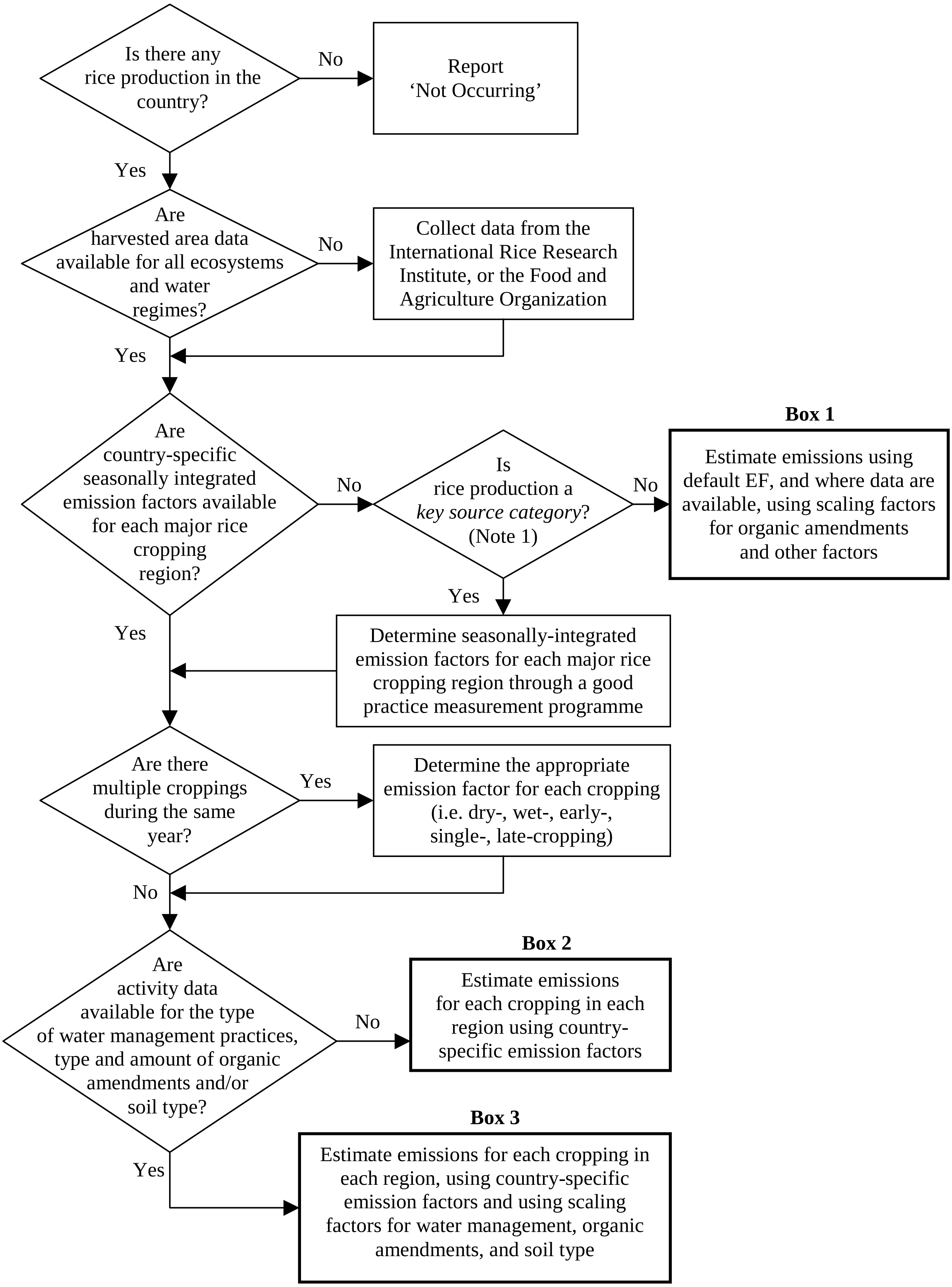
Water management regime: Each ecosystem should be broken down further to account for different water management practices (e.g. continuously flooded vs. intermittently flooded).

Addition of organic amendments: Measurements should be designed so that the effect of organic amendments (e.g. green manure, rice straw, animal manure, compost, weeds and other aquatic biomass, etc.) on CH_4 emissions can be quantified.

Soil type: Inventory agencies are encouraged to make every effort to undertake measurements on all major soil types under rice cultivation because of the significant influence that soil type can have on CH_4 emissions. Up to now the soil factor has not been taken into account in the *IPCC Guidelines* because data on harvested area by (major) soil type are not available from the standard activity data sources. However, with the recent developments of models to simulate CH_4 emissions from rice fields, deriving scaling factors for major soil types grown to rice will be feasible in the near future (e.g. Ding *et al.*, 1996, and Huang *et al.*, 1998). Combining measured or model-simulated soil type-specific scaling factors and a breakdown of rice acreage by soil type would further improve inventory accuracy if available.

Since some countries grow rice under a wide diversity of conditions, a complete set of local measurement-based emission factors may not be possible. In this case, inventory agencies are encouraged to first obtain a seasonally integrated emission factor for continuously flooded fields without organic amendments (EF_c), which is to be used as a starting point, and use scaling factors to adjust it to account for different conditions. The adjusted emission factors can then be determined using the following equation:

Figure 4.9 Decision Tree for CH_4 Emission from Rice Production



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

EQUATION 4.42
ADJUSTED SEASONALLY INTEGRATED EMISSION FACTOR

$$EF_i = EF_c \bullet SF_w \bullet SF_o \bullet SF_s$$

Where:

EF_i = Adjusted seasonally integrated emission factor for a particular harvested area

EF_c = Seasonally integrated emission factor for continuously flooded fields without organic amendments

SF_w = Scaling factor to account for the differences in ecosystem and water management regime (from Table 4.20)

SF_o = Scaling factors should vary for both types and amount of amendment applied. (from Table 4.21, Dose-Response Table for Non-Fermented Organic Amendments)

SF_s = Scaling factor for soil type, if available

The seasonally integrated emission factor for continuously flooded fields of major soil types without organic amendments should be determined through field measurements according to *good practice* procedures, as discussed in Appendix 4A.3. If data to determine EF_c are not yet available, the IPCC default of 20 g/m^2 may be used.

Scaling factors can be used to adjust the seasonally integrated emission factor for continuously flooded fields (EF_c) to account for the various conditions discussed in Box 4.2. In order, the three most important scaling factors are rice ecosystem/water management regime, organic amendments, and soil type. Country-specific scaling factors should only be used if they are based on well-researched and documented measurement data. If data to determine scaling factors are not yet available, IPCC defaults can be used.

Water management system: The main types of methane-emitting rice ecosystems are irrigated, rainfed and deep water. Within each ecosystem are water management systems, which affect the amount of CH_4 emitted during a cropping season. Table 4.20 provides IPCC default scaling factors for SF_w that can be used when country-specific data are unavailable. Scaling factors for additional ecosystem types and water management regimes can be applied only if country-specific data are available.

TABLE 4.20
IPCC DEFAULT CH_4 EMISSION SCALING FACTORS FOR RICE ECOSYSTEMS AND WATER MANAGEMENT REGIMES RELATIVE TO CONTINUOUSLY FLOODED FIELDS (WITHOUT ORGANIC AMENDMENTS)

Category	**Water Management Regime**		**Scaling Factor (SF_w)**
Upland	None		0
Lowland	Irrigated	Continuous Flooded	1.0
		Intermittently Flooded – Single Aeration	0.5 (0.2-0.7)
		Intermittently Flooded – Multiple Aeration	0.2 (0.1-0.3)
	Rainfed	Flood prone	0.8 (0.5-1.0)
		Drought prone	0.4 (0-0.5)
	Deep water	Water depth 50-100 cm	0.8 (0.6-1.0)
		Water depth > 100 cm	0.6 (0.5-0.8)

Source: *IPCC Guidelines*, Reference Manual, Table 4-12.

Organic amendments: *Good practice* is to develop a scaling factor (SF_o) that incorporates information on the type and amount of organic amendment applied (rice straw, animal manure, green manure, compost, and agricultural wastes). On an equal mass basis, more CH_4 is emitted from amendments containing higher amounts of easily decomposable carbon, and emissions also increase as more of each organic amendment is applied. Table 4.21 presents an approach to vary the scaling factor according to the amount of amendment applied.

Theoretically, the different amendments should be ranked according to the carbon content per unit of weight, but most often only information on the amount applied is available. In this case, the inventory agency should distinguish between fermented and non-fermented organic amendments. CH_4 emissions from fermented amendments (e.g. compost, residue of biogas pits) are significantly lower than non-fermented amendments because they contain much less easily decomposable carbon. Denier van der Gon and Neue (1995) empirically determined a reduction factor of six implying that the increase in CH_4 emission upon application of 12 t/ha compost is comparable to the increase upon application of 2 t/ha non-fermented organic amendment.

TABLE 4.21

DOSE-RESPONSE TABLE FOR NON-FERMENTED ORGANIC AMENDMENTS

Amount applied as dry matter (t/ha)	Scaling factor (SF_o)	Range
1-2	1.5	1-2
2-4	1.8	1.5-2.5
4-8	2.5	1.5-3.5
8-15	3.5	2-4.5
15+	4	3-5

Note: To use the table for fermented organic amendments, divide the amount applied by six.

Source: Derived from Denier van der Gon and Neue, 1995.

Soil types: In some cases emission data for different soil types are available and can be used to derive SF_s. The major motivation to incorporate soil type as a scaling factor is that both experiments and mechanistic knowledge confirm its importance. It is anticipated that in the near future simulation models will be capable of producing soil-specific scaling factors.

4.9.1.3 CHOICE OF ACTIVITY DATA

Activity data consist of rice production and harvested area statistics, which should be available from a national statistics agency. The activity data should be broken down by rice ecosystem or water management type. If these data are not available in-country, they can be downloaded from an FAO website: (http://www.fao.org/ag/agp/agpc/doc) or can be obtained from IRRI's World Rice Statistics (e.g. IRRI, 1995). Most likely, the accuracy of activity data will be high compared to the accuracy of the emission factor. However, for various reasons the area statistics may be biased and a check of the harvested area statistics for (parts of) the country with remotely sensed data is encouraged.

In addition to the essential activity data requested above, it is *good practice* to match data on organic amendments and soil types to the same level of disaggregation as the activity data. It may be necessary to complete a survey of cropping practices to obtain data on the type and amount of organic amendments applied.

4.9.1.4 COMPLETENESS

Complete coverage for this source category requires estimation of emissions from the following activities, where present:

- If soil submergence is not limited to the actual rice growing season, emissions outside of the rice growing season should be included (e.g. from a flooded fallow period);
- Other rice ecosystem categories, like swamp, inland-saline or tidal rice fields may be discriminated within each sub-category according to local emission measurements;
- If more than one rice crop is grown annually, these rice crops should be reported independently according to the local definition (e.g. early rice, late rice, wet season rice, dry season rice). The rice crops may fall into different categories with a different seasonally integrated emission factor and different correction factors for other modifiers like organic amendments.

4.9.1.5 DEVELOPING A CONSISTENT TIME SERIES

The emission estimation method should be applied consistently to every year in the time series, at the same level of disaggregation. If detailed activity level data are unavailable for earlier years, emissions for these years should be re-calculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3. If there have been significant changes in agricultural practices affecting CH_4 emissions over the times series, the rice estimation method should be implemented at a level of disaggregation which is sufficient to discern the effects of these changes. For example, various trends in (Asian) rice agriculture such as the adoption of new rice varieties, increasing use of inorganic fertiliser, improved water management, changing use of organic amendments, and direct seeding may lead to increases or decreases in overall emissions. To weigh the impact of these changes, it may be necessary to use model studies.

4.9.1.6 UNCERTAINTY ASSESSMENT

Table 4.22 presents a default emission factor, default scaling factors, and ranges for the default values. The range of emission factor, defined as the standard deviation about the mean, indicates the uncertainty associated with this default value for this source category. The uncertainty may be influenced by the following:

Natural Variability: The natural variability is a result of variations in natural controlling variables, such as annual climate variability, and variability within units that are assumed to be homogenous, such as spatial variability in a field or soil unit. For this source category, *good practice* should permit determination of uncertainties using standard statistical methods when enough experimental data are available. Studies to quantify some of this uncertainty are rare but available (e.g. for soil type induced variability). The variability found in such studies is assumed to be generally valid. For more detail, see Sass (1999).

Lack of activity data and documentation: Important activity data necessary to apply scaling factors (i.e. data on cultural practices and organic amendments) may not be available in current databases/statistics. Estimates of the fraction of rice farmers using a particular practice or amendment must then be based on expert judgement, and the range in the estimated fraction should also be based on expert judgement. As a default value for the uncertainty in the fraction estimate, ± 0.2 is proposed (e.g. the fraction of farmers using organic amendment estimated at 0.4, the uncertainty range being 0.2-0.6). Chapter 6, Quantifying Uncertainties in Practice, provides advice on quantifying uncertainties in practice including combining expert judgements and empirical data into overall uncertainty estimates.

TABLE 4.22
DEFAULT EMISSION FACTOR, DEFAULT SCALING FACTORS, AND RANGES FOR CH_4 EMISSIONS FROM RICE FIELD

Emission component	Default value	Ranges
Standard emission factor (EF)	20 g CH_4 m^{-2} $season^{-1}$	12-28 g CH_4 m^{-2} $season^{-1}$
Scaling factor water management SF_w	See Table 4.20	Table 4.20
Scaling factor organic amendments SF_o	2	1.5-5
Scaling factor soil types SF_s	1	0.1-2

Source: *IPCC Guidelines* and Judgement by Expert Group (see Co-chairs, Editors and Experts; CH4 Emissions from Rice Production).

4.9.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. It is *good practice* to document the emission estimate by reporting the information required to fill out the rice worksheet in the Workbook of the *IPCC Guidelines*. Inventory agencies that do not use the worksheets should provide comparable information. If the emission estimate is disaggregated by region, information on each region should be reported.

The following additional information should be reported, if available, to ensure transparency:

- Water management practices;
- The types and amounts of organic amendments used. (Incorporation of rice straw or residues of the previous (non-rice) crop should be considered an organic amendment, although it may be a normal production practice and not aimed at increasing nutrient levels as is the case with manure additions);
- Soil types used for rice agriculture;
- Number of rice crops grown annually;
- Most important rice cultivars grown.

When simple default emission factors are used to estimate CH_4 emissions, uncertainty can increase dramatically. Inventory agencies using country-specific emission factors should provide information on the origin and basis of the factor, compare it to other published emission factors, explain any significant differences, and attempt to place bounds on the uncertainty.

4.9.3 Inventory quality assessment/quality control (QA/QC)

It is *good practice* to implement quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and expert review of the emission estimates. Additional quality control checks as outlined in Tier 2 procedures in Chapter 8, QA/QC, and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source.

A detailed treatment on inventory QA/QC for field measurement is given by Sass (1999) and in Appendix 4A.3. Some important issues are highlighted and summarised below.

Compiling national emissions: It is, at present, not possible to cross-check emissions estimates from this source category through external measurements. However, the inventory agency should ensure that emission estimates undergo quality control by:

- Cross-referencing aggregated crop yield and reported field area statistics with national totals or other sources of crop yield/area data;
- Back-calculating national emission factors from aggregated emissions and other data;
- Cross-referencing reported national totals with default values and data from other countries.

APPENDIX 4A.1
CH_4 AND N_2O EMISSIONS FROM SAVANNA BURNING: BASIS FOR FUTURE METHODOLOGICAL DEVELOPMENT

4A.1.1 Methodological issues

In savanna regions burning is carried out every one to several years. The burning results in instantaneous emissions of carbon dioxide (CO_2). As the vegetation regenerates between burning cycles, however, the CO_2 released into the atmosphere is reabsorbed during the next vegetation growth period. For this reason, net CO_2 emissions from savanna burning are assumed to be zero. Savanna burning also releases other trace gases, including CH_4, CO, NMVOCs, N_2O and NO_x. In this chapter, only emissions of the direct greenhouse gases CH_4 and N_2O are discussed.

4A.1.1.1 CHOICE OF METHOD

The choice of method depends upon the availability of activity data and emission factors for CH_4 and N_2O. If an inventory agency does not have activity data and emission factors, the default values in the *IPCC Guidelines* may be used.

The current method requires a value for the living fraction of aboveground biomass in Table 4-12 of the Workbook of the *IPCC Guidelines*. In addition, Table 4-13 of the *IPCC Guidelines* requires values for oxidised fraction and carbon fraction in living and dead biomass for calculating the amount of carbon and nitrogen released from savanna burning. These parameters are difficult to measure in the field. Combustion efficiency can be used to depict the vegetation and combustion conditions, which ultimately determine the emission factors of CH_4 and N_2O. The combustion efficiency is defined as the molar ratio of emitted CO_2 concentrations to the sum of emitted CO and CO_2 concentrations from savanna fires. A column for combustion efficiency is included in Table 4.A1 of this document. The compiled combustion efficiency data are derived from the results of biomass burning experiments in different savanna ecosystems in tropical America and Africa. Therefore, in the proposed method the revised equation for computing the amount of CH_4 or N_2O emitted per year would be:

EQUATION 4.A1

CH_4 OR N_2O RELEASED FROM SAVANNA BURNING

$$\text{Amount of } CH_4 \text{ or } N_2O \text{ released} = \text{Amount of biomass burned (t dm)} \bullet \text{Emission factor of } CH_4 \text{ or } N_2O \text{ (kg/t dm)}$$

TABLE 4.A1

AMOUNT OF ABOVEGROUND BIOMASS BURNED

Region	Fraction of Total Savanna Burned Annually	Aboveground Biomass Density (t dm/ha)	Fraction of Biomass Actually Burned	Combustion Efficiency
Tropical America	0.50	6.6±1.8	0.85	0.95
Campo limpo[a.b]	0.3-1.0	7.1±0.5	1.0	0.96
Campo sujo[a.b]	0.3-1.0	7.3±0.5	0.97	
Campo cerrado[a.b]	0.3-1.0	8.6±0.8	0.72	0.94
Cerrado sensu stricto[a.b]	0.3-1.0	10.0±0.5	0.84	0.94
Tropical Africa	0.75	6.6±1.6	0.86	0.94
Sahel zone	0.05-0.15	0.5-2.5	0.95	
North Sudan zone	0.25-0.50	2-4	0.85	
South Sudan zone	0.25-0.50	3-6	0.85	
Guinea zone	0.60-0.80	4-8	0.90-1.0	
Moist Miombo[c,d,e]	0.5-1.0	8.9±2.7	0.74±0.04	0.92
Semiarid Miombo[c,e]	0.5-1.0	5.1±0.4	0.88±0.02	0.91
Moist Dambo[c,d,e]	0.5-1.0	3.0±0.5	0.99±0.01	0.95
Fallow Chitemene[c,e]	0.1	7.3±0.7	0.71±0.05	0.96
Semiarid Woodland (South Africa) [c,e]	0.25-0.5	4.6±2.8	0.85±0.11	0.93

[a]Kauffman *et al.* (1994), [b]Ward *et al.* (1992), [c]Shea *et al.* (1996), [d]Hoffa *et al.*(1999), [e]Ward *et al.* (1996).

For regions not specifically listed, data are contained in Table 4-14 of the *IPCC Guidelines*, Reference Manual (same as Table 4-12 of the Workbook of the *IPCC Guidelines.)* This table provides the basic ecological zones according to the available savanna statistics. Table 4.A1 above contains additional savanna data for four ecological zones in tropical America and five ecological zones in tropical Africa, based on the results of field experiments in Brazil, Zambia, and South Africa.

If an inventory agency has the necessary data for the fraction of savanna area burned annually, the aboveground biomass density, and the fraction of biomass actually burned in each ecological zone, the amount of biomass burned can be calculated at a disaggregated level.

It is desirable to develop the seasonal-dependent activity data and the emission factors of CH_4 and N_2O from savanna burning in various savanna ecosystems in each country if data are available. Fewer savanna areas and a smaller percentage of aboveground biomass are burned in the early dry season than in the late dry season. Therefore, as the dry season progresses in different savanna ecosystems, it is critical to monitor (i) the fraction of burned savanna area; (ii) the aboveground biomass density; (iii) the percentage of the aboveground biomass burned; and (iv) combustion efficiency.

4A.1.1.2 CHOICE OF EMISSION FACTORS

For savanna fires, there is a linear negative correlation between the CH_4 emission factor and the combustion efficiency. The emission factor is high for a fire of low combustion efficiency. The relationship is similar regardless of the climatic zone, the herbaceous species, or the amount of aboveground biomass.

Table 4.A2 lists different combustion efficiencies and associated CH_4 emission factors. Once the combustion efficiency of a savanna fire is determined according to the ecological zone and the burning period, the

corresponding emission CH_4 factor should be used to calculate the amount of CH_4 released per year from savanna burning.

TABLE 4.A2

COMBUSTION EFFICIENCY AND CORRESPONDING CH_4 EMISSION FACTOR

Combustion Efficiency	CH_4 Emission Factor (kg/t dm)
0.88	4.2
0.90	3.4
0.91	3.0
0.92	2.6
0.93	2.3
0.94	1.9
0.95	1.5
0.96	1.1

Source: Ward *et al.* (1996).

The emission of N_2O from biomass burning is linearly correlated with the emission of CO_2 and is dependent on the nitrogen content of the vegetation. The emission factor of N_2O is calculated by the equation:

EQUATION 4.A2

N_2O EMISSION FACTOR

$$\text{Emission factor of } N_2O \text{ (kg/t dm)} = \text{Emission factor of } CO_2 \text{ (kg/t dm)} \bullet 1/\text{Molecular weight of } CO_2 \bullet \text{Molar emission ratio of } N_2O \text{ to } CO_2 \bullet \text{Molecular weight of } N_2O$$

Equation 4.A2 is simplified to:

EQUATION 4.A3

N_2O EMISSION FACTOR

$$\text{Emission factor of } N_2O \text{ (kg/t dm)} = \text{Emission factor of } CO_2 \text{ (kg/t dm)} \bullet \text{Molar emission ratio of } N_2O \text{ to } CO_2$$

Since N_2O is not stable during storage of smoke samples, the molar emission ratio of N_2O to CO_2 has been derived from laboratory experiments in which different types of vegetation were burned (Hao *et al.*, 1991) and can be expressed by:

EQUATION 4.A4

MOLAR EMISSION RATIO OF N_2O TO CO_2

$$\text{Molar emission ratio of } N_2O \text{ to } CO_2 = 1.2 \bullet 10^{-5} + [3.3 \bullet 10^{-5} \bullet \text{Molar ratio of nitrogen to carbon (N/C) in the biomass}]$$

Emission factors for N_2O in several savanna ecosystems have been tabulated in Table 4.A3 on the basis of the results of field measurements of CO_2 emissions and the N/C ratios of the biomass. The default emission factors for N_2O in tropical America and Africa are calculated by averaging the emission factors for the continent. If an inventory agency has data on the N/C ratio in the biomass and assumes the emission factor for CO_2 to be 1700 kg/t dm, the emission factor for N_2O can be calculated by the two Equations 4.A3 and 4.A4 above.

TABLE 4.A3

EMISSION FACTORS OF N_2O IN VARIOUS SAVANNA ECOSYSTEMS

Region	Emission Factor of CO_2 (kg/t dm)	N/C Ratio in Biomass (%)	Emission Factor of N_2O (kg/t dm)
Tropical America	-	-	0.065
Campo limpo[a, b, c]	1745	0.60	0.055
Campo sujo[a, b, c]	1700	0.56	0.052
Campo cerrado[a, b, c]	1698	0.95	0.074
Cerrado sensu stricto[a, b, c]	1722	1.02	0.079
Tropical Africa	-	-	0.070
Moist Miombo[b, c, d]	1680	1.42	0.099
Semiarid Miombo[b, c, d]	1649	0.94	0.071
Moist Dambo[b, c, d]	1732	0.33	0.040
Fallow Chitemene[b, c, d]	1761	0.77	0.066
Semiarid Woodland	1699	0.98 ± 0.11	0.075

Source: [a]Ward *et al.* (1992), [b]Susott *et al.* (1996), [c]Hao *et al.* (1991), [d]Ward *et al.* (1996).

4A.1.1.3 CHOICE OF ACTIVITY DATA

The activity statistics for each savanna ecosystem include the following values: the savanna area; the fraction of savanna area burned; the aboveground biomass density; the fraction of aboveground biomass burned; and the carbon and nitrogen content in the biomass. Other parameters (i.e. the fraction of living and dead biomass burned and the carbon/nitrogen fraction of living and dead biomass) have been removed here because of the complexities of collecting these data in the field. Since the emission factor for CH_4 can decrease by 50-75% as the burning season progresses, it is strongly suggested that each inventory agency collect seasonal data on the fraction of savanna area burned, the aboveground biomass density, and the fraction of aboveground biomass burned in each savanna ecosystem from the early dry season to the late dry season.

4A.1.1.4 DEVELOPING A CONSISTENT TIME SERIES

Since there is a large degree of uncertainty in determining the burned area in each savanna ecosystem, it may be useful to take an average of at least three years to provide a base year estimate for identification of any trend in the emissions of CH_4 and N_2O from savanna burning. The methods for ensuring a consistent time series are described in Chapter 7, Methodological Choice and Recalculation.

4A.1.1.5 UNCERTAINTY ASSESSMENT

The uncertainty of the emission factor for CH_4 is about ±20%, based on the results of extensive field experiments in tropical America and Africa. The uncertainty of the N_2O emission factor is also about ±20%, based on extensive laboratory experiments. The uncertainty of the aboveground biomass density in a savanna ecosystem ranges from ±2% to ±60%. The larger uncertainty is probably due to the variation of the composition of aboveground biomass at different sites. The uncertainty of the fraction of biomass actually burned is less than ±10%. Presently, it is difficult to estimate the uncertainty for the fraction of savanna area burned each year, or the amount of burning in, for example, the early and late season.

4A.1.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. The reporting in the worksheets contained in the *IPCC Guidelines* is transparent, however, the most critical issue in reporting and documentation is that majority of the activity data (e.g. the percentage of savanna area burned, the aboveground biomass density, and the fraction of biomass actually burned) are not available or are difficult to collect in the field. There are also no standard methods of collecting the information on area burned and fraction of biomass actually burned, resulting in inconsistency among the reported data.

4A.1.3 Inventory quality assurance/quality control (QA/QC)

As mentioned above, there are large degrees of uncertainty in the activity data to compute the amount of biomass burned in savanna. Very limited data are available on the seasonal trends of the savanna areas burned, the aboveground biomass densities, and the fractions of aboveground biomass burned. The monitoring of the locations of active savanna fires and the mapping of burned areas in each country can be improved by using the satellite imagery available from various national and international agencies. In addition, standard methods have to be developed to measure the aboveground biomass density, the fraction of biomass burned, and the combustion efficiency in order to ensure the quality and consistency of the data.

APPENDIX 4A.2

CH_4 AND N_2O EMISSIONS FROM AGRICULTURAL RESIDUE BURNING: BASIS FOR FUTURE METHODOLOGICAL DEVELOPMENT

Although the burning of agricultural residues is not considered a net source of carbon dioxide because the carbon released to the atmosphere is reabsorbed during the next growing season, this burning is a source of net emissions of many trace gases including CH_4, CO_2, N_2O, and NO_x. It is important to note that some agricultural residues are removed from the fields and burned as a source of energy, especially in developing countries. Non-CO_2 emissions from this type of burning are dealt with in the Energy sector of the *IPCC Guidelines*. Crop residue burning must be properly allocated to these two components in order to avoid double counting. The following discussions are focused only on the direct greenhouse gases CH_4 and N_2O.

4A.2.1 Methodological issues

4A.2.1.1 CHOICE OF METHOD

The choice of method will depend on the availability of activity data and emission factors for CH_4 and N_2O in each country. Where available, country-specific activity data and emission factors for CH_4 and N_2O should be used. If a country does not have its own activity data and emission factors, the default values in the *IPCC Guidelines* may be used instead.

The largest degree of uncertainty in estimating the emission inventories of CH_4 and N_2O from agricultural residue burning is the fraction of agricultural residue burned in the field. The percentage of residue burned on-site must be based on a complete mass balance accounting of the residue. For substantial improvement in the emission estimates of CH_4 and N_2O, inventory agencies are encouraged to estimate local and regional practices that reflect: (i) the fraction of residue burned in the field; (ii) the fraction transported off the field and burned elsewhere (associated with processing); (iii) the fraction consumed by animals in the field; (iv) the fraction decayed in the field; and (v) the fraction used by other sectors (e.g. biofuel, domestic livestock feed, building materials, etc.). Currently, it is estimated that 10% of the total agricultural residue is burned in the field in developed countries and 25% in developing countries. These figures may be too high. *Good practice* suggests that an estimate of 10% may be more appropriate for developing countries.

4A.2.1.2 CHOICE OF EMISSION FACTORS

The CH_4 and N_2O emission factors in Table 4.16 of the Workbook of the *IPCC Guidelines* are generally reasonable. There are also insufficient data to update these emission factors as few field experiments have been conducted in the past five years that measure emissions produced by burning agricultural residue in the field. Emission factors, however, are probably dependent on weather conditions in the burning periods, as the emission factor of CH_4 from savanna burning decreases from the early dry season to the late dry season. If an inventory agency is conducting experiments to measure the CH_4 and N_2O emission factors from burning agricultural residue, the experiments should be carried out in the dry season and rainy season when crop residue is burned.

4A.2.1.3 CHOICE OF ACTIVITY DATA

The activity data for crop production can be obtained from either the country's data or the *FAO Production Yearbook* (U.N. Food and Agriculture Organisation). These statistical data are reasonably accurate. There are few data available to update residue/crop ratios, dry matter fractions, carbon fractions, and nitrogen to carbon ratios for different crop residue. When an inventory agency is compiling its activity data, it is necessary to collect monthly weather data and data on the amount of each crop residue burned after harvest. Weather conditions would influence the combustion efficiency (see Appendix 4A.1 of this chapter) and the CH_4 and N_2O emission factors.

4A.2.1.4 COMPLETENESS

The current method incorporates all the factors necessary to estimate the CH_4 and N_2O emissions from burning agricultural residue. Several crops are missing in Table 4.15 of the Workbook of the *IPCC Guidelines* (e.g. sugarcane and root crops such as cassava and yam). The ratio of residue to crop is 0.16 for sugarcane and 0.4 for root crops. It is important to account for the entire disposition of agricultural residue in the mass balance. Residue not being burned in the field will become a source of CH_4 or N_2O from microbial decomposition, domestic energy consumption, and domestic waste. These sources will have to be incorporated into the computation of CH_4 and N_2O emissions from other activities.

4A.2.1.5 DEVELOPING A CONSISTENT TIME SERIES

There are good prospects for developing the trend of CH_4 and N_2O emissions from agricultural residue burning because the statistics of agricultural production are compiled with reasonable accuracy. The weakness in the computation is estimating the percentage of residue burned in the field. Each inventory agency has to collect activity data on disposition of each crop residue, especially the percentage of residue burned on-site, after harvest.

4A.2.1.6 UNCERTAINTY ASSESSMENT

Crop production data, including cash crops and subsistence farming, are reasonably accurate, although it is difficult to determine the uncertainty. The uncertainties in CH_4 and N_2O emission factors for burning agricultural residue in the dry season are about ±20%. It is not known, however, about the emission factors in the rainy season. The fraction of agricultural residue burned in the field is probably the variable with the largest degree of uncertainty in estimating the amount of CH_4 and N_2O emitted from agricultural residue burning. Statistical data have to be compiled to account for the use of agricultural residue after harvest.

4A.2.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. Agricultural production data are easily accessible from each country or the *FAO Production Yearbook*. Weather conditions and the amount of each crop burned in the field during the dry season and rainy season have to be reported. It is necessary to measure and report the dry matter fraction, the carbon fraction, and the nitrogen to carbon ratio for each crop residue. It is also important to conduct field experiments that measure the CH_4 and N_2O emission factors in the dry and rainy season.

4A.2.3 Inventory quality assurance/quality control (QA/QC)

The quality of CH_4 and N_2O emissions estimates from agricultural residue burning will vary considerably from country to country, depending largely on the quality of the data on the percentage of the residue burned in the field. The qualities of other activity data and emission factors are reasonable and can be improved by collecting the data of the amount of residue burned during the dry season and rainy season. Crop production data can be verified by using commodity trade statistics.

APPENDIX 4A.3

CH_4 EMISSIONS FROM RICE PRODUCTION: MEASUREMENT, REPORTING, AND QA/QC OF FIELD DATA

Conducting Field Measurement: A standardised control rice plot with at least three replicate fields should be used to obtain standard regional and country emission factors. Plots are to be kept flooded from shortly before transplanting until maturity. The experimental plots should not have a recent history (i.e. five years) of added organic amendments to the soil other than recycled roots and perhaps short stubble. CH_4 flux measurements should be recorded at least twice per week over an entire flooded season. In areas where double or triple rice cropping is practised, data should be collected for all growing seasons. For a guideline for *good practice* standardised measurements for the irrigated rice ecosystem, see IGAC (1994). The nature of the instrumentation and the frequency of measurement will determine the associated uncertainty. For typical measurements, the associated uncertainty is expected to be at least 20%.

The accuracy and precision of CH_4 emission estimates increases with both the number of sites tested and the frequency and number of measurements at each site.

Other data, such as the location and extent of area that the measurement represents, soil data, and climate information, should be collected. Agronomic data such as rice yield and other crop production data are also important because these data can be used to determine if measurements are representative of typical agronomic conditions. In general, the various predictive models that have been recently published (e.g. Huang *et al.*, 1998) may aid in reporting CH_4 emission values. *Good practice* is to provide as much country- or region-specific detail as is feasible.

Reporting of Field Measurements: The minimum data set that should accompany flux measurements for (i) scaling factor determination, (ii) verification of inventory using models and, (iii) QA/QC consists of:

- Geographic data including site country and province, latitude and longitude, average elevation, and a short description of the location;
- A data log of agricultural events (e.g. time of organic input application, water management, weeding, etc.), method of crop establishment and dates of important plant events (e.g. transplanting, heading, harvest date);
- Air and soil temperature at 5 cm depth taken at the time of each flux measurement;
- Fertiliser types, application rates (including chemical amendments), and timing and mode of application;
- Soil types classified according to USDA Soil Taxonomy or FAO/UNESCO Soil Classification, at least on subgroup levels. General soil characteristics, including texture, should be measured;
- Water management (number of flooding days, drainage/drought events);
- Impact of organic amendment on emissions (type and amount of amendment should be documented);
- Rice cultivar used (name, crop duration, height, traditional or modern variety, specific traits);
- Plant parameters preferably for different growth stages (e.g. leaf area index, above ground biomass (straw and stubble), yield, harvest index).

Field Measurement QA/QC: Country scientists will usually determine field-level QA/QC procedures to establish country-specific emission factors. To ensure the comparability and inter-calibration of extended data sets used to establish country-specific emission factors, there are certain internationally determined procedures to obtain ‘standard emission factors’ that should be common to all monitoring programs (see IGAC (1994), Sass (1999)):

(i) CH_4 flux measurements should be recorded at least *twice per week* over an entire flooded season.

(ii) In areas where double rice cropping (or 5 rice crops in 2 years) is practised, data should be collected for all growing seasons.

(iii) Manual sampling of flux chambers may miss the large fluxes of soil-entrapped CH_4 upon drainage. In such cases, a correction should be made. If no specific data are available, an estimated 10-20% increase of seasonal emission can be applied.

(iv) Significance of pre-planting emissions should be discussed and, if appropriate, estimated or measured.

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WASTE

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5.1 CH_4 EMISSIONS FROM SOLID WASTE DISPOSAL SITES

5.1.1 Methodological issues

Methane (CH_4) is emitted during the anaerobic decomposition of organic waste disposed of in solid waste disposal sites (SWDS). Organic waste decomposes at a diminishing rate and takes many years to decompose completely.

5.1.1.1 CHOICE OF METHOD

The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (*IPCC Guidelines*) outline two methods to estimate CH_4 emissions from solid waste disposal sites, the default method (Tier 1) and the First Order Decay (FOD) method (Tier 2). The main difference between the two methods is that the FOD method produces a time-dependent emission profile that better reflects the true pattern of the degradation process over time, whereas the default method is based on the assumption that all potential CH_4 is released in the year the waste is disposed of. The default method will give a reasonable annual estimate of actual emissions if the amount and composition of deposited waste have been constant or slowly varying over a period of several decades. If the amount or composition of waste disposed of at SWDS is changing more rapidly over time, however, the IPCC default method will not provide an accurate trend. For example, if there is a reduction in the amount of carbon deposited at SWDS, the default method will underestimate emissions and overestimate reductions.

The choice of a *good practice* method will depend on national circumstances. The decision tree in Figure 5.1, Decision Tree for CH_4 Emissions from Solid Waste Disposal Sites, illustrates the process of choosing among methods. It is *good practice* to use the FOD method, if possible, because it more accurately reflects the emissions trend. The use of the FOD method requires data on current, as well as historic waste quantities, composition and disposal practices for several decades. It is *good practice* to estimate this historical data, if such data are unavailable, when this is a *key source category* (see Chapter 7, Methodological Choice and Recalculation) or if there have been significant changes in waste management practices.

The *IPCC Guidelines* do not provide default values or methods for the estimation of some key parameters needed to use the FOD method. These data are very dependent on country-specific conditions, and currently there are not enough data available to give reliable default values or methods for them. Inventory agencies are encouraged to obtain data from country-specific or regional research, because the inability of inventory agencies to use the FOD method where otherwise indicated by *good practice* would reduce comparability between national inventories. Inventory agencies selecting a method other than those described in the *IPCC Guidelines* should justify their selection based on comparable or increased accuracy and completeness of the emissions estimates.

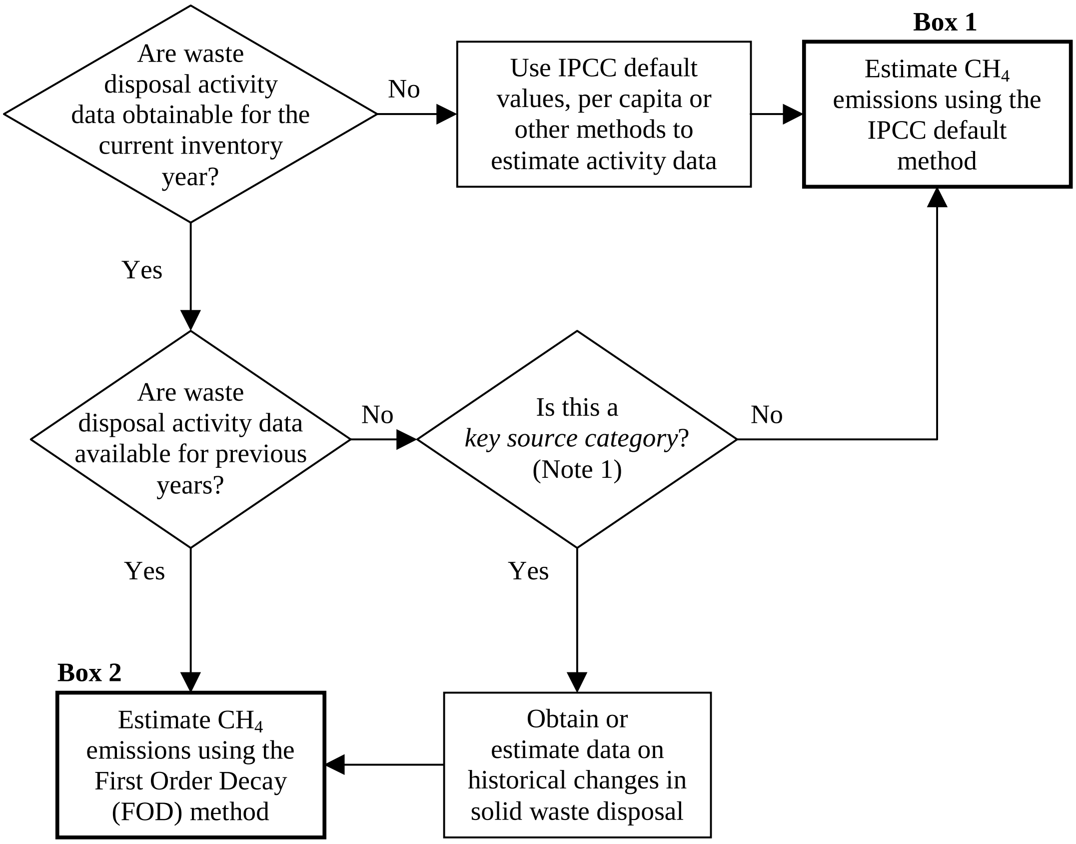
5.1.1.2 CHOICE OF EMISSION FACTORS AND ACTIVITY DATA

The discussion of *good practice* in the choice of activity data and emission factors is combined in this section, due to the unique character of the emission estimation methods.

First Order Decay (FOD) method – Tier 2

The *IPCC Guidelines* (pp 6.10-6.11, Reference Manual) present the FOD method in three equations. The first equation is to be used for an individual landfill, or possibly a group of specific landfills. A second equation, suitable for national and regional estimates, calculates emissions from all solid waste deposited in SWDS in one year. The purpose of the third equation is to estimate current annual emissions from waste disposal in current and previous years.

Figure 5.1 Decision Tree for CH_4 Emissions from Solid Waste Disposal Sites



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

The FOD method can be expressed equivalently by Equation 5.1 and Equation 5.2 below. Equation 5.1 is based on the derivative of the general FOD equation (see p 6.10, Reference Manual, *IPCC Guidelines*) with t replaced by t – x, representing a normalisation factor that corrects for the fact that the evaluation for a single year is a discrete time estimate rather than a continuous time estimate.

EQUATION 5.1

$$CH_4 \text{ generated in year t (Gg/yr)} = \sum_x [(A \bullet k \bullet MSW_T(x) \bullet MSW_F(x) \bullet L_0(x)) \bullet e^{-k(t-x)}]$$

for x = initial year to t

Where:

t = year of inventory

x = years for which input data should be added

$A = (1 - e^{-k}) / k$; normalisation factor which corrects the summation

k = Methane generation rate constant (1/yr)

$MSW_T(x)$ = Total municipal solid waste (MSW) generated in year x (Gg/yr)

$MSW_F(x)$ = Fraction of MSW disposed at SWDS in year x

$L_0(x)$ = Methane generation potential $[MCF(x) \bullet DOC(x) \bullet DOC_F \bullet F \bullet 16/12 \text{ (Gg } CH_4\text{/Gg waste)}]$

MCF (x) = Methane correction factor in year x (fraction)

DOC (x) = Degradable organic carbon (DOC) in year x (fraction) (Gg C/Gg waste)

DOC_F = Fraction of DOC dissimilated

F = Fraction by volume of CH_4 in landfill gas

16 / 12 = Conversion from C to CH_4

Sum the obtained results for all years (x).

EQUATION 5.2

$$CH_4 \text{ emitted in year t (Gg/yr)} = [CH_4 \text{ generated in year t} - R(t)] \bullet (1 - OX)$$

Where:

R(t) = Recovered CH_4 in inventory year t (Gg/yr)

OX = Oxidation factor (fraction)

Note that CH_4 recovered (R(t)) must be subtracted from the amount generated before applying the oxidation factor, because only landfill gas that is not captured is subject to oxidation in the upper layer of the landfill. In addition, the unit for the methane generation potential should be expressed by weight (Gg CH_4/Gg waste) and not volume (m^3/Mg waste) as currently written in the *IPCC Guidelines* in order to make the outcome of the default and FOD methods consistent.

The methane generation rate constant k that appears in the FOD method is related to the time taken for the DOC in waste to decay to half its initial mass (the 'half life' or $t_{½}$) as follows:

$$k = \ln 2 / t_{½}$$

The FOD method requires historical data on waste generation and management practices. In national inventories, it is usually necessary to include data for 3 to 5 half lives in order to achieve an acceptably accurate result. Changes in waste management practices (e.g. landfill covering/capping, leachate drainage improvement, compacting, and prohibition of hazardous waste disposal together with MSW) should also be taken into account when compiling historical data.

The value of k applicable to any single SWDS is determined by a large number of factors associated with the composition of the waste and the conditions at the site. Measurements from SWDS in the United States, the United Kingdom and the Netherlands support values for k in the range 0.03 to 0.2 per year (Oonk and Boom, 1995). The most rapid rates (k = 0.2, or a half life of about 3 years) are associated with high moisture conditions and rapidly degradable material such as food waste. The slower decay rates (k = 0.03, or a half life of about 23 years) are associated with dry site conditions and slowly degradable waste such as wood or paper. Inventory agencies are encouraged to establish k values or use their own k values if available and documented. In order to estimate k values, inventory agencies should determine the composition of waste disposed in SWDS over time and study the conditions at the site(s). If no data on types of waste are available, a k value of 0.05 (a half life of about 14 years) is suggested as a default value.

Inventory agencies can estimate historical waste disposal and composition data, assuming it to be proportional to population, or urban population in cases where there has been no organised waste collection or disposal in rural areas. Inventory agencies can use other relationships if better justified, and report the reasons for those choices.

Default method – Tier 1

The default method is based on the following equation:

EQUATION 5.3

$$CH_4 \text{ emissions (Gg/yr)} = [(MSW_T \bullet MSW_F \bullet L_0) - R] \bullet (1 - OX)$$

Where:

MSW_T = Total MSW generated (Gg/yr)

MSW_F = Fraction of MSW disposed at SWDS

L_0 = Methane generation potential [MCF • DOC • DOC_F • F • 16 / 12 (Gg CH_4/Gg waste)]

MCF = Methane correction factor (fraction)

DOC = Degradable organic carbon [fraction (Gg C/Gg MSW)]

DOC_F = Fraction DOC dissimilated

F = Fraction by volume of CH_4 in landfill gas

R = Recovered CH_4 (Gg/yr)

OX = Oxidation factor (fraction)

Note that all of the model parameters can change over time, depending upon waste disposal trends and waste management practices. *Good practice* is described below for each of the above model parameters.

Total municipal solid waste (MSW_T), and the fraction of MSW sent to SWDS (MSW_F)

The use of the term municipal solid waste (MSW) may not accurately describe the types of waste disposed of in SWDS. Inventory agencies should estimate the emissions from all types of solid waste material, including industrial waste, sludge, construction and demolition waste and municipal waste, disposed of at SWDS. Data on industrial waste may be difficult to obtain in many countries, but efforts to do so should be made. (Examples of industrial waste that can produce CH_4 when disposed of include agro-food industrial waste,[1] pulp and paper waste and sludge, and waste from wood processing.) In many countries, national estimates of total waste disposal may be available. National data are preferable, provided that inventory agencies document the data collection method including the number of sites surveyed and the type of survey undertaken. If national data are not available, inventory agencies can estimate data using default assumptions provided in Table 6-1, Reference Manual of the *IPCC Guidelines*. This table provides default MSW generation and disposal rates for many regions and countries. If no default values exist, inventory agencies can use expert judgement to estimate these parameters using the values for countries with similar conditions. (Elements of comparability that inventory agencies can consider are geography, population density, national income, and type and volume of industry.)

Methane correction factor (MCF)[2]

The methane correction factor (MCF) accounts for the fact that unmanaged SWDS produce less CH_4 from a given amount of waste than managed SWDS, because a larger fraction of waste decomposes aerobically in the top layers of unmanaged SWDS. The MCF in relation to solid waste management is specific to that area and should be interpreted as the 'waste management correction factor' that reflects the management aspect it encompasses. The term methane correction factor (MCF) in this context should not be confused with the methane conversion factor (MCF) referred to in the *IPCC Guidelines* for wastewater and livestock manure management emissions.

The *IPCC Guidelines* present default values for MCF, which are presented in Table 5.1 below.

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[1] Avoid double counting with the Agriculture Sector.

[2] Unmanaged SWDS cause serious local environmental and health problems, such as fire and explosion accidents, pollution of surrounding air and waters, and outbreaks of pests and infections. However, the *IPCC Guidelines* and this report on *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (*Good Practice Report*) are intended to address greenhouse gas aspects only.

TABLE 5.1
SWDS CLASSIFICATION AND METHANE CORRECTION FACTORS

Type of Site	**Methane Correction Factor (MCF) Default Values**
Managed [a]	1.0
Unmanaged – deep ($\geq$5 m waste)	0.8
Unmanaged – shallow (<5 m waste)	0.4
Uncategorised SWDS [b]	0.6

[a] Managed SWDS must have controlled placement of waste (i.e. waste directed to specific deposition areas, a degree of control of scavenging and a degree of control of fires) and will include some of the following: cover material, mechanical compacting or levelling of waste.
[b] The default value of 0.6 for uncategorised SWDS may be inappropriate for developing countries with a high percentage of unmanaged shallow sites, as it will probably lead to overestimation of emissions. Therefore, inventory agencies in developing countries are encouraged to use 0.4 as their MCF, unless they have documented data that indicates managed landfill practices in their country.

Source: Reference Manual of the *IPCC Guidelines.*

Degradable organic carbon (DOC)

Degradable organic carbon is the organic carbon that is accessible to biochemical decomposition, and should be expressed as Gg C per Gg waste. It is based on the composition of waste and can be calculated from a weighted average of the carbon content of various components of the waste stream. The following equation, as presented in the *IPCC Guidelines*, estimates DOC using default carbon content values:

EQUATION 5.4

$$DOC = (0.4 \bullet A) + (0.17 \bullet B) + (0.15 \bullet C) + (0.3 \bullet D)$$

Where:

A = Fraction of MSW that is paper and textiles

B = Fraction of MSW that is garden waste, park waste or other non-food organic putrescibles

C = Fraction of MSW that is food waste

D = Fraction of MSW that is wood or straw

The default carbon content values for these fractions can be found in the *IPCC Guidelines* (Table 6-3, Reference Manual).[3] The use of national values is encouraged if data are available. National values can be obtained by performing waste generation studies and sampling of different SWDS within a country. If national values are used, survey data and sampling results should be reported. In addition, it is important that inventory agencies exclude lignin from their DOC calculations if the default value (0.77) for DOC_F is used, as discussed below.

Fraction of degradable organic carbon dissimilated (DOC_F)

DOC_F is an estimate of the fraction of carbon that is ultimately degraded and released from SWDS, and reflects the fact that some organic carbon does not degrade, or degrades very slowly, when deposited in SWDS. The *IPCC Guidelines* provide a default value of 0.77 for DOC_F. Based on a review of recent literature, it appears that this default value may be an overestimate. It should only be used if lignin C is excluded from the DOC value. For example, experimental values in the order of 0.5-0.6 (including lignin C) have been used in the Netherlands (Oonk and Boom, 1995) and demonstrated to give reliable estimates of landfill gas generated and recovered in the Netherlands. It is also *good practice* to use a value of 0.5-0.6 (including lignin C) as the default. National values for DOC_F or values from similar countries can be used for DOC_F, but they should be based on well-documented research.

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[3] From Bingemer and Crutzen (1987).

Fraction of CH_4 in landfill gas (F)

Landfill gas consists mainly of CH_4 and carbon dioxide (CO_2). The CH_4 fraction F is usually taken to be 0.5, but can vary between 0.4 and 0.6, depending on several factors including waste composition (e.g. carbohydrate and cellulose). The concentration of CH_4 in recovered landfill gas may be lower than the actual value because of potential dilution by air, so F values estimated in this way will not necessarily be representative.

Methane recovery (R)

Methane recovery is the amount of CH_4 generated at SWDS that is recovered and burned in a flare or energy recovery device. CH_4 recovered and subsequently vented should not be subtracted from gross emissions. The default value for methane recovery is zero. This default should only be changed when references documenting the amount of methane recovery are available. Recovered gas volumes should be reported as CH_4 not as landfill gas, as landfill gas contains only a fraction of CH_4[4]. Reporting based on metering of all gas recovered for energy utilisation and flaring is consistent with *good practice*. The use of undocumented estimates of landfill gas recovery potential is not appropriate, as such estimates tend to overestimate the amount of recovery.

Oxidation factor (OX)

The oxidation factor (OX) reflects the amount of CH_4 from SWDS that is oxidised in the soil or other material covering the waste. If the oxidation factor is zero, no oxidation takes place, and if OX is 1 then 100% of CH_4 is oxidised. Studies show that sanitary landfills tend to have higher oxidation results than unmanaged dump sites. For example, the oxidation factor at sites covered with thick and well-aerated material may differ significantly from sites with no cover or where large amounts of CH_4 can escape through cracks in the cover.

The default oxidation factor in the *IPCC Guidelines* is zero. Results from field and laboratory give a wide range, but values higher than 0.1 are probably too high for national inventories. Field and laboratory CH_4 and CO_2 emissions concentrations and fluxes measurements should not be used directly. In general, these field and laboratory experiments determine CH_4 oxidation from uniform and homogeneous soil layers. In reality, only a fraction of the CH_4 generated will diffuse through such a homogeneous layer. Another fraction will escape through cracks or via lateral diffusion without being oxidised. Therefore, results from field and laboratory studies may lead to overestimations of oxidation in landfill cover soils.

Currently, most industrialised countries with well-managed SWDS use 0.1 for OX, which is a reasonable assumption based on available information. In developing countries with less elaborate management practices, the average value is probably closer to zero. The use of the oxidation value of 0.1 is justified for well-managed landfills, in other cases the use of an oxidation value different than zero should be clearly documented and referenced.

It is important to remember that any CH_4 that is recovered must be subtracted from the amount generated before applying an oxidation factor.

5.1.1.3 COMPLETENESS

Inventory agencies should make efforts to include emissions from non-MSW SWDS. These include industrial waste sites and sludge disposal sites as well as construction and demolition waste sites. As with MSW, the DOC must be assessed to evaluate the potential significance of the sub-source category. Industrial waste generation or disposal data may be hard to obtain, because they may be confidential or not reported. Usually, the non-MSW SWDS are less significant contributors to national CH_4 emissions than MSW SWDS.

Closed SWDS should not be a completeness issue, because both the FOD and the default methods use yearly waste disposal. Therefore, the waste that is present in a closed landfill should also have been accounted for.

5.1.1.4 DEVELOPING A CONSISTENT TIME SERIES

Given the differences in approach and expected results between the FOD and default methods, a time series should be developed using the same method (i.e. methods should not be mixed). Thus, if an inventory agency decides to move from the default to the FOD method, they need to recalculate the base year and the entire time series with the new approach. In this situation, inventory agencies will need to derive a time series of historical waste disposal data to support the FOD approach. The method of this derivation and number of years affected must be clearly described. To ensure consistency over time, it is *good practice* to recalculate emissions estimates using past and current methods to ensure that any trends in emissions are real and not caused by changes in the

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[4] CO_2 emissions from landfill gas recovery combustion are of biogenic origin and should not be included in national totals.

estimation methodologies. These recalculations should be carried out according to the guidance in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

Given the significance of this source category in many national inventories, and the limitations of the default method, inventory agencies should collect and maintain as much historical data as possible to enable future recalculations with more accurate methods. Inventory agencies should also take into account the time dependence of several parameters related to waste composition and landfill design.

5.1.1.5 UNCERTAINTY ASSESSMENT

Uncertainty estimates for MSW_T and MSW_F and the default model parameters are given in Table 5.2. The estimates are based on expert judgement. If an inventory agency uses national values for these factors, it should evaluate the uncertainty of these values consistent with the guidance provided in Chapter 6, Quantifying Uncertainties in Practice.

Some uncertainty information is available on the methane generation potential (L_0), which equals $MCF \bullet DOC \bullet DOC_F \bullet F \bullet 16 / 12$, and appears as a factor in the equations for both the default and the FOD methods. In the Netherlands, where high quality data are available, the uncertainty for CH_4 generation per tonne of waste is estimated to be approximately ±15% (Oonk and Boom, 1995). In countries with similar quality data, uncertainties in quantities of CH_4 generation per tonne of waste are expected to be of the same order. For countries with poor quality data on CH_4 generation per tonne of waste, the associated uncertainties could be of the order of ±50%. The basis for the uncertainty assessment should be well documented.

The data in Table 5.2, Estimates of Uncertainties Associated with the Default Parameters in the IPCC Default and FOD Methods for CH_4 emissions from SWDS, show that the overall uncertainty associated with estimating CH_4 emissions from SWDS is likely to be high, perhaps a factor of two, even when national data are well characterised. National data should be used where possible. Chapter 6, Quantifying Uncertainties in Practice, provides advice on quantifying uncertainties in practice. It includes eliciting and using expert judgements which in combination with empirical data can provide overall uncertainty estimates.

TABLE 5.2
ESTIMATES OF UNCERTAINTIES ASSOCIATED WITH THE DEFAULT PARAMETERS IN THE IPCC DEFAULT AND FOD METHODS FOR CH_4 EMISSIONS FROM SWDS [a]

Parameter	Uncertainty Range [b]
Total Municipal Solid Waste (MSW_T) and Fraction of MSW sent to SWDS (MSW_F)	Country-specific: >±10% (<–10%, >+10%. The absolute value of the uncertainty range is greater than 10%.) for countries with high quality data (e.g. weighing at all SWDS) For countries with poor quality data: more than a factor of two.
Degradable Organic Carbon (DOC) = 0.21 (maximal default value in the *IPCC Guidelines*)	–50%, +20%
Fraction of Degradable Organic Carbon Dissimilated (DOC_F) = 0.77	–30%, +0%
Methane Correction Factor (MCF)	
= 1	–10%, +0%
= 0.4	–30%, +30%
= 0.6	–50%, +60%
Fraction of CH_4 in Landfill Gas (F) = 0.5	–0%, +20%
Methane Recovery (R)	The uncertainty range will depend on how the amounts of CH_4 recovered and flared or utilised are estimated, but the uncertainty is likely to be relatively small compared to other uncertainties if metering is in place.
Oxidation Factor (OX)	Include OX in the uncertainty analysis if a value other than zero has been used for OX itself. In this case the justification for a non-zero value should include consideration of uncertainties, as specified in Section 5.1.1.2, Choice of Emission Factors and Activity Data.
Methane Generation Rate Constant (k) = 0.05	–40%, +300%

[a] The estimates are valid only for the default values given in the *IPCC Guidelines* or in the table, and are based on expert judgement.
[b] If the evaluation of additional data on the parameters provides data for the revision of the default values, the uncertainty range should also be changed. When country-specific values are used, they should be accompanied with appropriate uncertainty values.

Source*:* Judgement by Expert Group (see Co-chairs, Editors and Experts; CH_4 Emissions from Solid Waste Disposal).

5.1.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. Some examples of specific documentation and reporting relevant to this source category are provided below.

- If the FOD method is used, historical data and k values used should be documented.
- The distribution of waste to managed and unmanaged sites for the purpose of MCF should also be documented with supporting information.
- If methane recovery is reported, an inventory of known recovery facilities is desirable. Flaring and energy recovery should be documented separately from each other.
- Changes in parameters from year to year should be clearly explained and referenced.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

5.1.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in the Tier 2 procedures in Chapter 8 as well as quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Furthermore, transparency can be improved by the provision of clear documentation and explanations of work undertaken in the following areas:

Estimate of the emissions using different approaches

- If the emissions are estimated with the FOD method, inventory agencies should also estimate them with the IPCC default method. The results can be useful for cross-comparison with other countries. Inventory agencies should record the results of such comparisons for internal documentation, and investigate any discrepancies.

Review of emission factors

- Inventory agencies should cross-check country-specific values for estimation with the available IPCC values. The intent of this comparison is to see whether the national parameters used are considered reasonable relative to the IPCC default values, given similarities or differences between the national source category and the emission sources represented by the default.

Review of activity data

- Inventory agencies should compare country-specific data to IPCC default values for the following activity level parameters: MSW_T, MSW_F, and DOC. They should determine whether the national parameters are reasonable and ensure that errors in calculations have not occurred. If the values are very different, inventory agencies should characterise municipal solid waste separately from industrial solid waste.
- Where survey and sampling data are used to compile national values for solid waste activity data, QC procedures should include:
  - (i) Reviewing survey data collection methods, and checking the data to ensure they were collected and aggregated correctly. Inventory agencies should cross-check the data with previous years to ensure the data are reasonable.
  - (ii) Evaluating secondary data sources and referencing QA/QC activities associated with the secondary data preparation. This is particularly important for solid waste data, since most of these data are originally prepared for purposes other than greenhouse gas inventories.

Involvement of industry and government experts in review

- Inventory agencies should provide the opportunity for experts to review input parameters. For example, individuals with expertise in the country's solid waste management practices should review the characteristics of the solid waste stream and its disposal. Other experts should review the methane correction factors.

Verification of emissions

- Inventory agencies should compare national emission rates with those of similar countries that have comparable demographic and economic attributes. This comparison should be made with countries whose inventory agencies use the same landfill CH_4 estimation method. Inventory agencies should study significant discrepancies to determine if they represent errors in the calculation or actual differences.

5.2 EMISSIONS FROM WASTEWATER HANDLING

Handling of domestic and industrial wastewater under anaerobic conditions produces CH_4.[5] The methodological issues concerning CH_4 emissions from domestic and industrial wastewater handling systems are considered separately in this discussion because the types of activity data and emission factors needed for each sub-source category are different. Both wastewater systems are discussed in Section 5.2.2, Reporting and Documentation, and Section 5.2.3, Inventory Quality Assurance/Quality Control (QA/QC).

5.2.1 Methodological issues

5.2.1.1 DOMESTIC WASTEWATER

In developed countries, most domestic wastewater is handled in aerobic treatment facilities and lagoons. In developing countries, a small share of domestic wastewater is collected in sewer systems, with the remainder ending up in pits or latrines.

Some industrial wastewater may be discharged into municipal sewer lines where it combines with domestic wastewater.

CHOICE OF METHOD

The *IPCC Guidelines* describe a single method for calculating CH_4 emissions from domestic wastewater handling. Emissions are a function of the amount of waste generated and an emission factor that characterises the extent to which this waste generates CH_4. Any CH_4 that is recovered and flared or used for energy should be subtracted from total emissions. The simplified general equation is as follows:

EQUATION 5.5

$$\text{Emissions} = (\text{Total Organic Waste} \bullet \text{Emission Factor}) - \text{Methane Recovery}$$

Depending on the available activity data and emission factors, this method can be applied at various levels of disaggregation. The decision tree in Figure 5.2, Decision Tree for CH_4 Emissions from Domestic Wastewater Handling, describes how to determine the appropriate level of disaggregation in applying the IPCC method. Regardless of the level of disaggregation, the steps in *good practice* in inventory preparation for CH_4 from wastewater are as follows:

(i) Characterise the wastewater systems in the country;

(ii) Select the most suitable parameters;

(iii) Apply the IPCC method.

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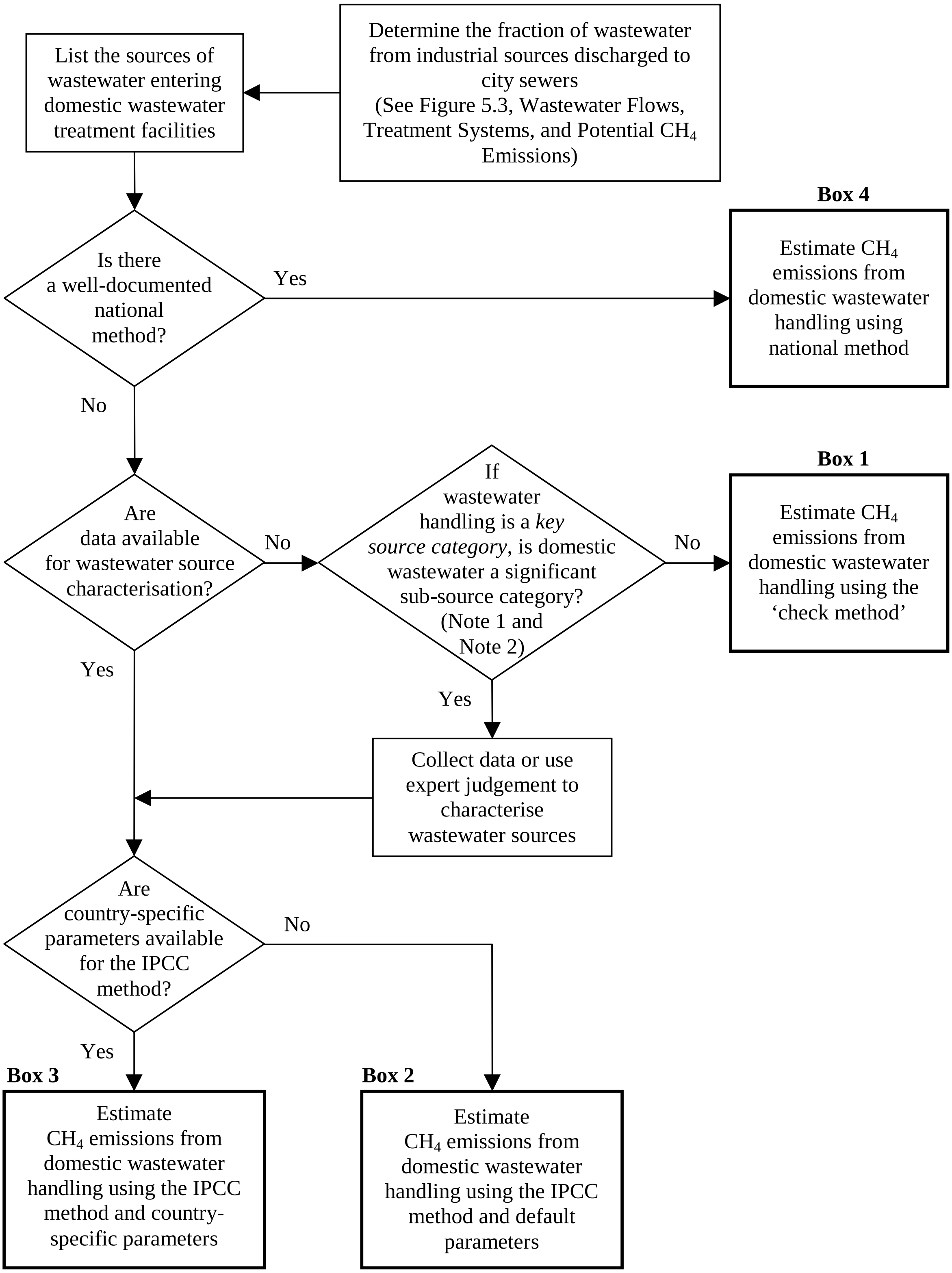
[5] *Good practice* methods for estimating indirect nitrous oxide (N_2O) emissions from sewage disposal were described with other indirect N_2O sources in Chapter 4, Agriculture, Section 4.8, Indirect N_2O Emissions from Nitrogen Used in Agriculture . Given the present state of data availability, the highly simplified method described in the *IPCC Guidelines* for direct N_2O emissions from wastewater disposal represents *good practice* as it stands. This is an area where future work is needed, however, to make possible the level of detail in the corresponding parts of the Agriculture Sector.

Figure 5.2 Decision Tree for CH_4 Emissions from Domestic Wastewater Handling



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: As a rule of thumb, a sub-source category would be significant if it accounts for 25-30% of emissions from the source category.

BOX 5.1
CHECK METHOD

Equation 5.6 presents a quick method to check national estimates. Default parameter values are included to enable a sample calculation to be made.

EQUATION 5.6

$$WM = P \bullet D \bullet SBF \bullet EF \bullet FTA \bullet 365 \bullet 10^{-12}$$

Where:

WM = Annual CH_4 emission per country, from domestic wastewater (Tg)

P = Population of country or urban population for some developing countries (person)

D = Organic load in biochemical oxygen demand per person (g BOD/person/day), overall default = 60 g BOD/person/day

SBF = Fraction of BOD that readily settles, default = 0.5

EF = Emission factor (g CH_4/g BOD), default = 0.6

FTA = Fraction of BOD in sludge that degrades anaerobically, default = 0.8

Over 50% of the BOD in domestic wastewater is associated with non-dissolved solids, much of which rapidly settle under a wide range of conditions. For example, a conventional settling tank typically removes 33% of suspended solids, whereas a figure of 50% is more appropriate to many longer-term processes such as lagoons, septic tanks, latrines, and ungraded sewers. This is SBF in the equation above. Furthermore, it is believed that in many countries a very large fraction of this settleable BOD will degrade anaerobically, resulting in the high FTA (0.8). The remaining parameters are as defined in the *IPCC Guidelines*.

For countries that are extensively sewered, employ exclusively aerobic processes, and whose sludge is treated by non-CH_4 producing procedures or by anaerobic digestion with combustion of CH_4, the FTA would be significantly lower or zero. In these cases, the full *IPCC Guidelines* method would be more accurate. For countries where data are unavailable to determine the percentage of population connected to the various treatment types in use or, more particularly, when there is a significant unsewered population, the full IPCC procedure can miss significant emissions and its results should be reviewed with results from the check method.

This method can be used to make a rough estimate of global CH_4 emissions from domestic wastewater. Setting the global population P to 6 billion and EF to 0.6, one will arrive at total WM of 32 Tg/yr. This is in the same range as the 29 Tg/yr global estimate in Doorn and Liles (1999).

CHOICE OF EMISSION FACTORS

The emission factor for each waste type is a function of the maximum methane producing potential of each waste type (B_o) and the weighted average of the methane conversion factors (MCFs) for the different wastewater treatment systems used in the country, as shown in Equation 5.7. The MCF indicates the extent to which the methane producing potential (B_o) is realised in each type of treatment method.

EQUATION 5.7

$$\text{Emission Factor} = B_o \bullet \text{Weighted Average of MCFs}$$

Where:

B_o = Maximum methane producing capacity (kg CH_4/kg BOD or kg CH_4/kg COD)

MCF = Methane conversion factor (fraction)

The derivation of each of these terms is described below.

Maximum methane producing capacity (B_o)

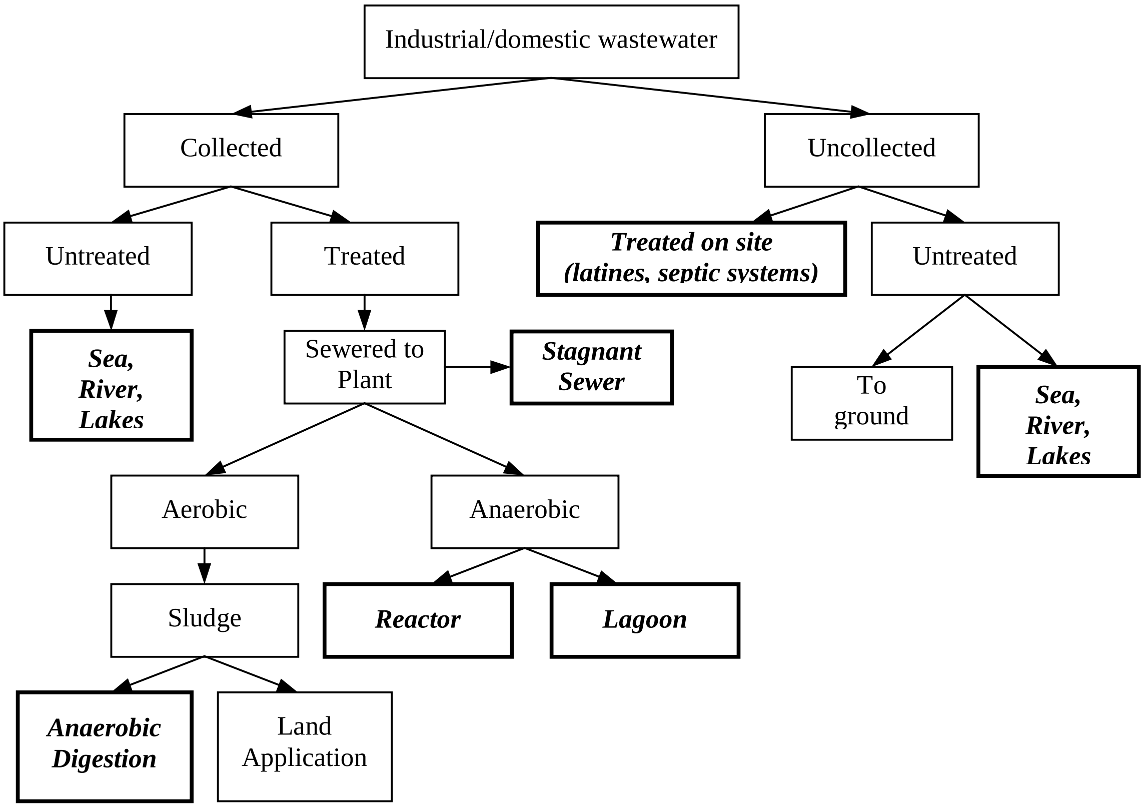
Good practice is to use country-specific data for B_o, expressed in terms of kg CH_4/kg BOD removed to be consistent with the activity data. If country-specific data are not available, a default value can be used. The *IPCC Guidelines* suggest a default value of 0.25 kg CH_4/kg COD (Chemical Oxygen Demand), based on a theoretical calculation. Comprehensive field test data (Doorn *et al*., 1997)[6] are in good agreement with the default value.

Note that degradable carbon in organic waste can be measured in terms of either BOD or COD. For typical domestic raw sewage, COD (mg/l) is 2 to 2.5 times higher than BOD (mg/l). Therefore, it is important to use emission factors that are consistent with the measure of degradable carbon being used. The *IPCC Guidelines* provide only one default value of B_o that has to be applied to both COD and BOD. This is not consistent with the observed differences between BOD and COD levels in raw sewage. Given the differences in the amount of BOD and COD in wastewater this can result in estimates of different emissions levels from the same amount of wastewater depending on which measure is used. To ensure that the resulting emission estimate from a given amount of wastewater is the same regardless of the measure of organic carbon is used, the COD-based value of B_o should be converted into a BOD-based value via up-scaling with a default factor of 2.5. Thus, it is *good practice* to use a default value of 0.25 kg CH_4/kg COD or a default value of 0.6 kg CH_4/kg BOD.

Weighted average of MCFs

The MCF is an estimate of the fraction of BOD or COD that will ultimately degrade anaerobically. The first step in determining the weighted MCF is to characterise the wastewater treatment systems in the country by producing a list of CH_4 emission sources. Figure 5.3 below presents a comprehensive picture of the flow of domestic and industrial wastewater through various treatment options. Those treatment options shown in bold are potential CH_4 sources.

Figure 5.3 Wastewater Flows, Treatment Systems, and Potential CH_4 Emissions



Note: Italic text in a bold frame box indicates areas with the potential for CH_4 emissions.

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[6] This reference indicated a representative value of 0.21 kg CH_4/kg COD.

In the *IPCC Guidelines*, the weighted MCF value is determined according to Equation 5.8:

EQUATION 5.8

$$\text{Weighted MCF}_i = \sum_X (WS_{ix} \bullet MCF_x)$$

Where:

WS_{ix} = Fraction of wastewater type i treated using wastewater handling system x

MCF_x = Methane conversion factors of each wastewater handling system x

The *IPCC Guidelines* propose a separate calculation for wastewater and for sludge removed from the wastewater. The distinction is inappropriate for most countries, however, because sludge is rarely collected separately. If sludge separation is practised and appropriate statistics are available, then these sub-source categories should be separated. Such separation will not affect the overall estimate unless there are country-specific B_o measurements for sludge and wastewater. Typically, the theoretical default B_o values for sludge and wastewater are the same. If default factors are being used, emissions from wastewater and sludge can be estimated together. In this case, summing across i terms becomes unnecessary. Where a separate estimate for emissions from sewage sludge is not made, the weighted MCF for primary treatment and aerobic secondary treatment may need to be greater than zero, reflecting the typical sludge processing routes for that country. Regardless of how sludge is treated, it is important that CH_4 emissions from biosolids (sludge) sent to landfills or used in agriculture are not included in this sector.

As mentioned above, the wastewater characterisation will determine the fraction of each wastewater type treated by a particular type of system. To determine the use of each type of treatment system, it is *good practice* to refer to national statistics (e.g. from regulatory authorities). If these data are not available, wastewater associations or international organisations such as the World Health Organization (WHO) may have data on system usage. Otherwise, consultation with sanitation experts can help and expert judgement can be applied (see Chapter 6, Quantifying Uncertainties in Practice, for general guidance on eliciting expert judgement). Urbanisation statistics may provide a useful tool (e.g. city sizes and income distribution), assuming that rural populations are less likely to have access to wastewater treatment in most countries.

If no national data are available, then Equation 5.8 can be modified as follows to incorporate the expert judgement of sanitation engineers and other experts:

EQUATION 5.9

Weighted MCF = Fraction of BOD that will ultimately degrade anaerobically

The determination of weighted MCF through expert judgement should be fully documented. Default data provided by the *IPCC Guidelines* can be used as a basis for expert judgement.

CHOICE OF ACTIVITY DATA

The activity data for this source category is the amount of organic waste in a country. Total Organic Waste (TOW) is a function of human population and waste generation per person, and is expressed in terms of biochemical oxygen demand (kg BOD/year):

EQUATION 5.10

$$TOW = P \bullet D_{dom}$$

Where:

TOW = Total organic waste (kg BOD/yr)

P = Human population (1000 persons)

D_{dom} = Degradable organic component (kg BOD/1000 persons/yr)

As mentioned previously, the degradable carbon in organic waste can be measured either as BOD or COD, and the COD-based value should be converted into a BOD-based value by multiplying by a default factor of 2.5. For domestic wastewater, BOD data are more likely to be available. The *IPCC Guidelines* provide default values for BOD for different regions in the world (see Table 6-5, Reference Manual of the *IPCC Guidelines*).

Total population statistics should be readily available from national statistics agencies or the United Nations. If significant amounts of waste in rural areas is expected to degrade aerobically, as is the case in some developing countries, then it is *good practice* to compute the estimate using only the urban population.

COMPLETENESS

The *IPCC Guidelines* present the main wastewater handling methods in developed and developing countries (see Table 6-4, Reference Manual of the *IPCC Guidelines*). This table mentions sources such as latrines, river discharge, sewer lines and septic tanks, but the current method does not allow for their inclusion. (See Doorn and Liles, 1999 for information on emissions from these sources.) A diagram such as Figure 5.3, Wastewater Flows, Treatment Systems, and Potential CH_4 Emissions, may be more useful than Table 6-4, Reference Manual of the *IPCC Guidelines*.

DEVELOPING A CONSISTENT TIME SERIES

Emissions from domestic wastewater handling should be calculated using the same method and data sets for every year in the time series. Where consistent data are unavailable for the same method for any years in the time series, these gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

UNCERTAINTY ASSESSMENT

Table 5.3 presents uncertainty ranges assigned to the parameters discussed in the text above.

TABLE 5.3
DEFAULT UNCERTAINTY RANGES FOR DOMESTIC WASTEWATER

Parameter	Uncertainty Range
Human Population	–5%, +5%
BOD/person	–30%, +30%
Maximum Methane Producing Capacity (B_o)	–30%, +30%
Fraction Treated Anaerobically	The uncertainty range should be determined by expert judgement, bearing in mind that this is a fraction and uncertainties cannot take it outside the range 0 to 1.

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts; CH_4 and N_2O Emissions from Wastewater Handling).

Chapter 6 provides advice on quantifying uncertainties in practice. It includes guidance on eliciting and using expert judgements which in combination with empirical data can provide overall uncertainty estimates.

5.2.1.2 INDUSTRIAL WASTEWATER

Industrial wastewater may be treated on site or released into domestic sewer systems. If it is released into the domestic sewer system, the emissions should be covered there. Therefore, this discussion deals with estimating CH_4 emissions from on-site industrial wastewater treatment.

CHOICE OF METHOD

The method for calculating emissions from industrial wastewater in the *IPCC Guidelines* is similar to the one used for domestic wastewater. The development of emission factors and activity data is more complex because there are many types of wastewater, and many different industries to track.

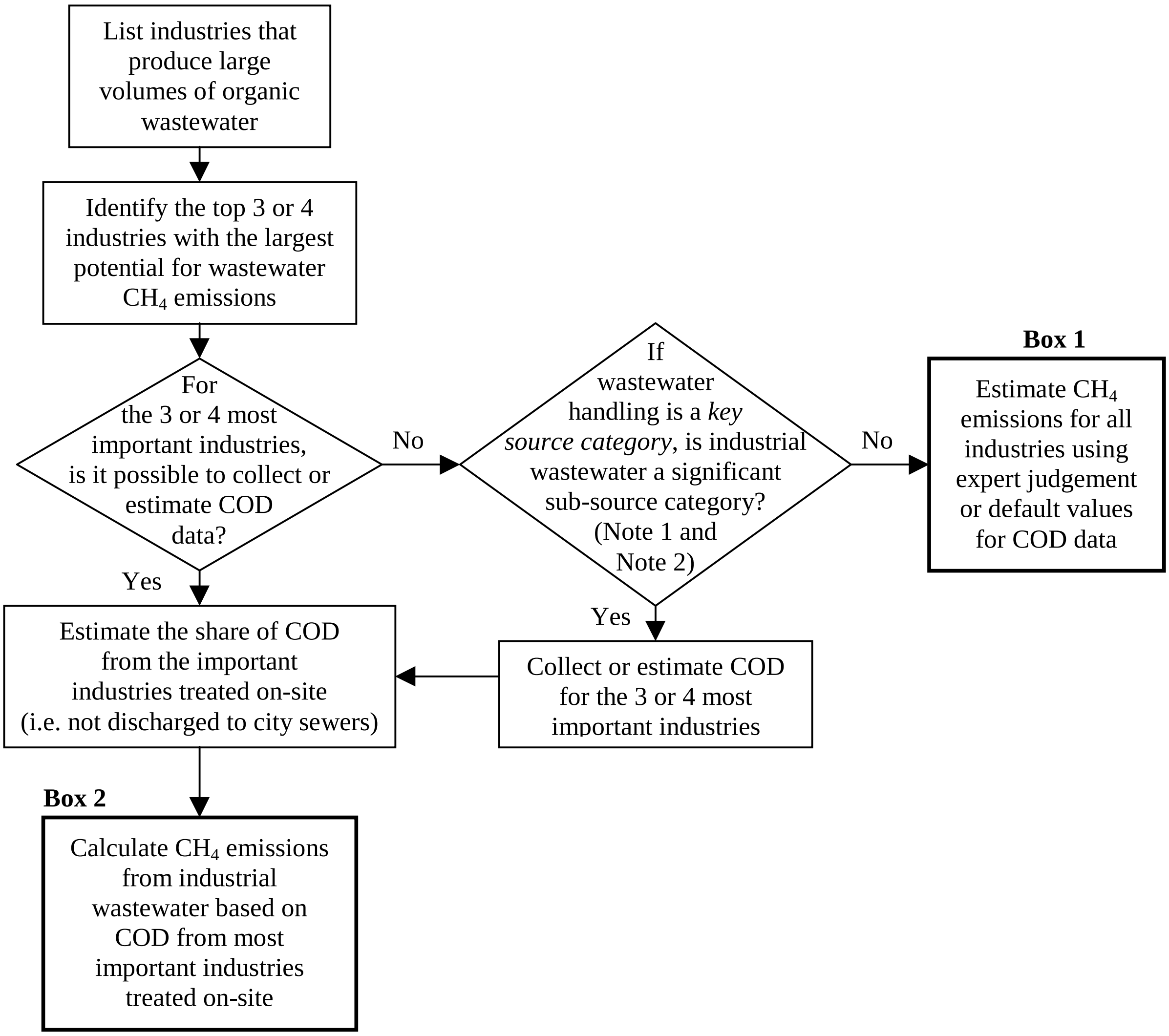
The most accurate estimates of emissions for this source category are based on measured data from point sources. Due to the high costs of measurements and the potentially large number of point sources, collecting comprehensive measurement data is very difficult. Therefore, it is suggested that inventory agencies use a top-down modified *IPCC Guidelines* approach. The decision tree in Figure 5.4 defines *good practice* in adapting the methods in the *IPCC Guidelines* to these country-specific circumstances.

CHOICE OF EMISSION FACTORS

There are significant differences in the CH_4 emitting potential of different types of industrial wastewater. To the extent possible, data should be collected to determine the maximum methane producing capacity (B_o) and the fraction of waste treated anaerobically (weighted MCF) in each industry. *Good practice* is to use country- and industry sector-specific data that may be available from government authorities, industrial organisations, or industrial experts. Currently, however, most inventory agencies will find detailed industry sector-specific data unavailable or incomplete. If no national data are available, it is *good practice* to use the IPCC COD-default factor for B_o (0.25 kg CH_4/kg COD).

In determining the fraction of waste treated anaerobically, expert judgement based on the advice of engineers and other experts should be used. A peer-reviewed survey of industry wastewater treatment practices is one useful technique for estimating these data. Surveys should be conducted frequently enough to account for major trends in industry practices (i.e. 3-5 years). Chapter 6, Quantifying Uncertainties in Practice, Section 6.2.5, Expert Judgement, describes how to elicit expert judgement for uncertainty ranges. Similar expert elicitation protocols can be used to obtain the necessary information for other types of data if published data and statistics are not available.

Figure 5.4 Decision Tree for CH_4 Emissions from Industrial Wastewater Handling



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Note 2: As a rule of thumb, a sub-source category would be significant if it accounts for 25-30% of emissions from the source category.

CHOICE OF ACTIVITY DATA

The first step in estimating the total industrial organic waste produced is to characterise by listing the industry sectors in the country which produce large volumes of organic wastewater. Since a limited number of industries are likely to produce most of the industrial wastewater (e.g. food processing, pulp and paper), it is *good practice* to focus on these industrial sectors. National statistics, regulatory agencies, wastewater treatment associations or industry associations can provide this information.

Next, the COD inputs for the top three or four identified major industrial sectors should be quantified. This may require some expert judgement. In some countries, COD and total water usage per sector data may be available directly from a regulatory agency. An alternative is to obtain data on industrial output and tonnes COD produced per tonne of product from the literature. The *IPCC Guidelines* present typical COD values for some industries. However, these values have been updated below (Table 5.4). Both sources are consistent with *good practice*, depending on national circumstances. For the remaining industries, an overall combined COD output should be assigned. Production data can be obtained from national statistics.

A significant fraction of industrial wastewater may be discharged into municipal sewers to be treated or disposed of with domestic wastewater. This fraction will likely have to be estimated by expert judgement and should be added to the domestic wastewater loading.

TABLE 5.4
INDUSTRIAL WASTEWATER DATA

Industry Type	Wastewater Generation (m^3/Mg)	Wastewater Generation Range (m^3/Mg)	BOD (g/l)	BOD Range (g/l)	COD (g/l)	COD Range (g/l)
Animal Feed	NA		NA		NA	
Alcohol Refining	24	16-32	NA	3-11	11	5-22
Beer & Malt	6.3	5.0-9.0	1.5	1-4	2.9	2-7
Coffee	NA		5.4	2-9	9	3-15
Coke	1.5	1.3-1.7	NA	0.1	0.1	
Dairy Products	7	3-10	2.4	1-4	2.7	1.5-5.2
Drugs & Medicines	NA		0.9		5.1	1-10
Explosives	NA		NA		NA	
Fish Processing	NA	8-18	1.5		2.5	
Meat & Poultry	13	8-18	2.5	2-3	4.1	2-7
Organic Chemicals	67	0-400	1.1	1-2	3	0.8-5
Paints	NA	1-10	NA		NA	1-10
Petroleum Refineries	0.6	0.3-1.2	0.4	1-8	1.0	0.4-1.6
Plastics & Resins	0.6	0.3-1.2	1.4	1-2	3.7	0.8-5
Pulp & Paper (combined)	162	85-240	0.4	0.3-8	9	1-15
Soap & Detergents	NA	1.0-5.0	NA	0.3-0.8	NA	0.5-1.2
Soft Drinks	NA	2.0	NA	1.0	NA	2.0
Starch Production	9	4-18	2.0	1-25	10	1.5-42
Sugar Refining	NA	4-18	NA	2-8	3.2	1-6
Textiles (natural)	172	100-185	0.4	0.3-0.8	0.9	0.8-1.6
Vegetable Oils	3.1	1.0-5.0	0.5	0.3-0.8	NA	0.5-1.2
Vegetables, Fruits & Juices	20	7-35	1.0	0.5-2	5.0	2-10
Wine & Vinegar	23	11-46	0.7	0.2-1.4	1.5	0.7-3.0

Notes: NA = Not Available.
When few data points are available, the range is assumed to be from –50 to +100%.

Source: Doorn *et al*. (1997).

COMPLETENESS

Industries may produce inventories that include emissions from on-site wastewater handling. It is *good practice* to use these estimates provided they are transparent and otherwise consistent with the QA/QC principles set out in Chapter 8, Quality Assurance and Quality Control. The national estimation method should be sufficiently disaggregated to allow recognition of the separate accounting of these emissions and hence avoid double counting.

DEVELOPING A CONSISTENT TIME SERIES

Emissions from industrial wastewater handling should be calculated using the same method and data sets for every year in the time series. Where consistent data are unavailable for the same method for any years in the time series, these gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

UNCERTAINTY ASSESSMENT

The uncertainty ranges in Table 5.5 were assigned to the parameters discussed in the text above.

TABLE 5.5
DEFAULT UNCERTAINTY RANGES FOR INDUSTRIAL WASTEWATER

Parameter	Uncertainty Range
Industrial Production	–25 %, +25%. Use expert judgement regarding the quality of data source to assign more accurate uncertainty range.
Wastewater/unit production COD/unit wastewater	These data can be very uncertain as the same sector might use different waste handling procedures in different countries. The product of the parameters should have less uncertainty. An uncertainty value can be attributed directly to kg COD/tonne of product. –50 %, +100% is suggested (i.e. a factor of 2).
Maximum Methane Producing Capacity (B_o)	–30%, +30%
Fraction Treated Anaerobically	The uncertainty range should be determined by expert judgement, bearing in mind that this is a fraction and uncertainties cannot take it outside the range 0 to 1.

Source*:* Judgement by Expert Group (see Co-chairs, Editors and Experts; CH_4 and N_2O Emissions from Wastewater Handling).

5.2.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. Some examples of specific documentation and reporting relevant to this source category are provided below.

The existing sectoral tables accompanied with a detailed inventory report provide good transparency for this source category. The tables necessarily separate industrial from domestic wastewater treatment. The inventory report should provide the remainder of the information on activity data, assumptions made and references, as text. It is particularly important to document the use of default data in developing parameter values. Two additional columns in the worksheet, one for comments and one for references (e.g. by number), should be provided by the inventory agency.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced (such as changes in default values for MCFs).

5.2.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in the Tier 2 procedures in Chapter 8 as well as quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Furthermore, transparency can be improved by the provision of clear documentation and explanations of work undertaken in the following areas:

Comparison of emissions estimate using different approaches

- For domestic wastewater, inventory agencies should cross-check the national estimate, as appropriate, with emissions estimated using IPCC defaults or the ‘check method’. This cross-check should be a standard QC practice wherever non-default parameters are used in the estimation method. Inventory agencies should record the results of such comparisons for internal documentation, and investigate any unexplainable discrepancies.

Review of emission factors

- For domestic wastewater, inventory agencies should compare country-specific values for B_o with the IPCC default value (0.25 kg CH_4/kg COD or 0.6 kg CH_4/kg BOD). Although there are no IPCC default values for the fraction of waste treated anaerobically, inventory agencies are encouraged to cross-check values for MCFs against those from other countries with similar wastewater handling practices.
- Inventory agencies should confirm the agreement between the units used for degradable carbon in the waste with the units for B_o. Both parameters should be based on the same units (either BOD or COD) in order to calculate emissions. This same consideration should be taken into account when comparing the emissions to the check method or to another country's emissions.
- For industrial wastewater, inventory agencies should cross-check values for MCFs against those from other national inventories with similar industrial wastewater characteristics.

Review of activity data

- For industrial wastewater, inventory agencies should review the secondary data sets (e.g. from national statistics, regulatory agencies, wastewater treatment associations or industry associations) used to estimate and rank industrial COD waste output. Some countries may have regulatory control over industrial discharges, in which cases significant QA/QC protocols may already be in place for the development of the wastewater characteristics on an industry basis.
- Inventory agencies should compare country-specific data (BOD in domestic wastewater or industry COD output) to IPCC default values. If inventory agencies use country-specific values, they should document why their country-specific or industry values differ from these default values.

Involvement of industry experts in the review

- In some countries, domestic wastewater treatment is highly scrutinised and regulated (especially in urban areas) and as such, there may be opportunities for expert peer review of the inputs to the emissions calculations. Peer review should involve experts that have knowledge of the particular input parameter. Expert peer review is particularly important to verify MCF values and other parameters where IPCC defaults are not available for cross-checks.
- For industrial wastewater, inventory agencies should involve industry experts that have knowledge of particular input parameters. For example, industry experts should review the characteristics of the industrial wastewater and its treatment with expertise in their specific industries. Expert peer review is particularly important to verify MCF values and other parameters where IPCC defaults are not available for cross-checks.

5.3 EMISSIONS FROM WASTE INCINERATION

5.3.1 Methodological issues

Incineration of waste produces emissions of CO_2, CH_4 and N_2O. Emissions of CH_4 are not likely to be significant because of the combustion conditions in incinerators (e.g. high temperatures and long residence times). Normally, emissions of CO_2 from waste incineration are significantly greater than N_2O emissions. Currently, waste incineration is more common in developed countries, although it is common for both developed and developing countries to incinerate clinical waste.

The methodology described here applies to incineration with and without energy recovery. Emissions from waste incineration without energy recovery have to be reported in the Waste Sector, while emissions from incineration with energy recovery should be reported in the Energy Sector.

Consistent with the *IPCC Guidelines*, only CO_2 emissions resulting from the incineration of carbon in waste of fossil origin (e.g. plastics, certain textiles, rubber, liquid solvents, and waste oil) should be included in emissions estimates. The carbon fraction that is derived from biomass materials (e.g. paper, food waste, and wooden material) is not included.

5.3.1.1 CHOICE OF METHOD

The choice of a *good practice* method will depend on national circumstances. The decision trees in Figures 5.5, Decision Tree for CO_2 Emissions from Waste Incineration, and 5.6, Decision Tree for N_2O Emissions from Waste Incineration, define *good practice* in adapting the methods in the *IPCC Guidelines* to these country-specific circumstances. Figures 5.5 and 5.6 describe respectively the choice of method to estimate CO_2 emissions and N_2O emissions.

The most accurate emissions estimates can be developed by determining the emissions for each type of waste (e.g. municipal solid waste (MSW), sewage sludge, clinical waste, and hazardous waste).

The methods for estimating CO_2 and N_2O from waste incineration differ because of the different factors that influence emission levels. For this reason, they are discussed separately below.

Estimating CO_2 emissions

The *IPCC Guidelines* describe one method for estimating CO_2 emissions from waste incineration. As shown in Equation 5.11, the activity data are the waste inputs into the incinerator, and the emission factor is based on the carbon content of the waste that is of fossil origin only. The most accurate CO_2 emissions estimates results from disaggregating the activity data into different waste types (e.g. municipal solid waste, sewage sludge, clinical waste, and hazardous waste). The burn out efficiency of combustion should also be included in the calculation.

EQUATION 5.11

$$CO_2 \text{ emissions (Gg/yr)} = \sum_i \left(IW_i \bullet CCW_i \bullet FCF_i \bullet EF_i \bullet 44 / 12 \right)$$

Where:

i = MSW: municipal solid waste

HW: hazardous waste

CW: clinical waste

SS: sewage sludge

IW_i = Amount of incinerated waste of type i (Gg/yr)

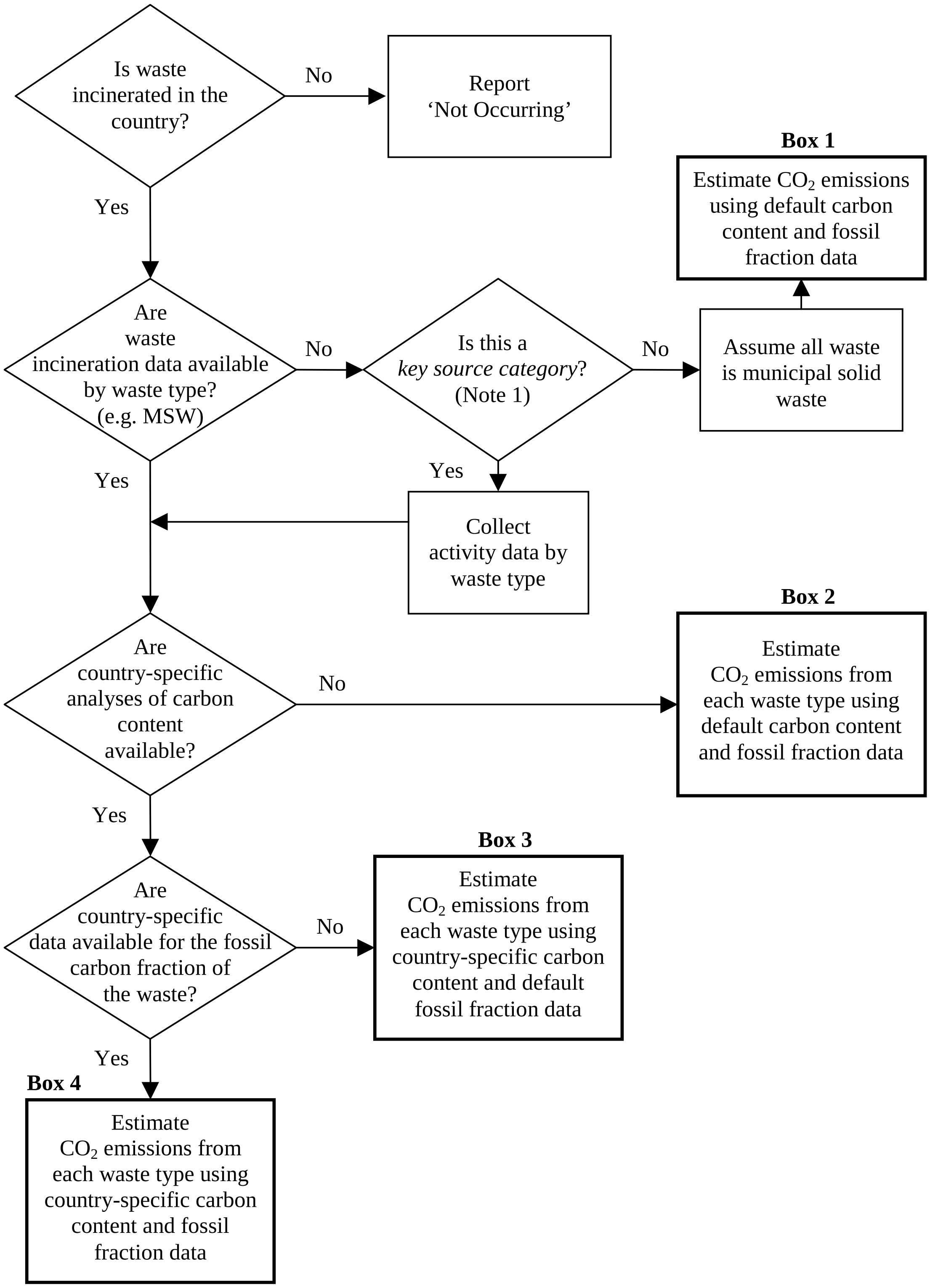
CCW_i = Fraction of carbon content in waste of type i

FCF_i = Fraction of fossil carbon in waste of type i

EF_i = Burn out efficiency of combustion of incinerators for waste of type i (fraction)

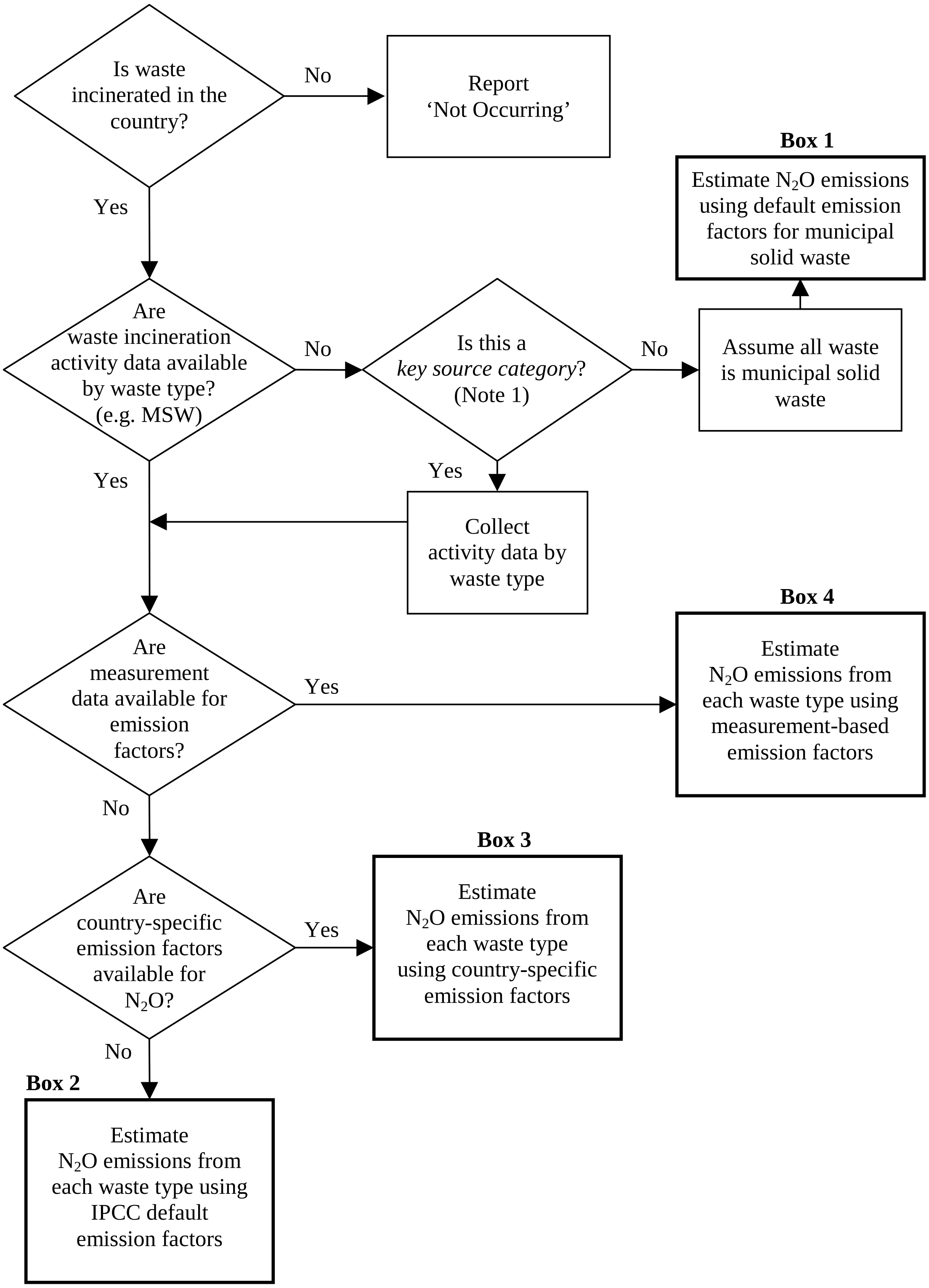
44 / 12 = Conversion from C to CO_2

Figure 5.5 Decision Tree for CO_2 Emissions from Waste Incineration



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

Figure 5.6 Decision Tree for N_2O Emissions from Waste Incineration



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

The decision tree in Figure 5.5 can be used to estimate CO_2 emissions for each incineration plant as well as for estimating emissions from all plants. The best results will be obtained if emissions are determined for each plant, and then summed.

Estimating N_2O emissions

The calculation of N_2O emissions is based on waste input to the incinerators and an emission factor:

EQUATION 5.12

$$N_2O \text{ emissions (Gg/yr)} = \sum_i (IW_i \bullet EF_i) \bullet 10^{-6}$$

Where:

IW_i = Amount of incinerated waste of type i (Gg/yr)

EF_i = Aggregate N_2O emission factor for waste type i (kg N_2O/Gg)

Or

EQUATION 5.13

$$N_2O \text{ emissions (Gg/yr)} = \sum_i (IW_i \bullet EC_i \bullet FGV_i) \bullet 10^{-9}$$

Where:

IW_i = Amount of incinerated waste of type i (Gg/yr)

EC_i = N_2O emission concentration in flue gas from waste of type i (mg N_2O/m^3)

FGV_i = Flue gas volume by amount of incinerated waste of type i (m^3/Mg)

Figure 5.6 provides a general decision tree for the estimation of N_2O emissions from waste incineration. The decision tree can also be used for estimation of other gases (e.g. NO_x). The best results will be obtained if N_2O emissions are determined for each plant based on the plant-specific monitoring data, and then summed.

5.3.1.2 CHOICE OF EMISSION FACTORS AND ACTIVITY DATA

CO_2 emissions

CO_2 is not normally directly monitored in exhaust gases. It can be calculated from the total carbon content of the waste. This is commonly undertaken in most countries. CO_2 emissions can also be estimated using default data for the carbon content (see Table 5.6, Default Data for Estimation of CO_2 Emissions from Waste Incineration). However, where the carbon content of the waste is not known but the inventory agency has well-documented measured data on CO_2 emissions from waste incineration, these data can be used to obtain the country-specific carbon content of the waste.

It can be difficult to differentiate between the biogenic and the fossil part of waste going for incineration. Data to determine the fractions can be gathered from the waste analysis available in many countries. However, actual data on the origin of waste is often lacking and may not be up to date.

The fractions of fossil and biogenic carbon are likely to change considerably in the future because of recent waste legislation adopted in many countries (e.g. Japan, Norway, and the USA). The legislation will influence the total waste flow incinerated as well as the fossil carbon content of the incinerated waste. It is uncertain how new legislation will influence the fossil carbon content, and limited current data are available as the changes are still occurring.

The fraction of fossil carbon will differ for different types of waste. The carbon in MSW and clinical waste is of both biogenic and fossil origin (default data are provided in Table 5.6). In sewage sludge the fossil carbon usually can be neglected (only traces of detergents and other chemicals). The carbon in hazardous waste is usually of fossil origin (default data are provided in Table 5.6).

It is *good practice* to assume that the composition of incinerated MSW is the same as the composition of MSW generated in the country. However, if a certain fraction of MSW is incinerated separately, the carbon content for these streams must be determined specifically.

TABLE 5.6
DEFAULT DATA FOR ESTIMATION OF CO_2 EMISSIONS FROM WASTE INCINERATION

	MSW	Sewage Sludge	Clinical Waste	Hazardous Waste
C Content of Waste	33-50% of waste (wet) default: 40%	10-40% of sludge (dry matter) default: 30%	50-70% of waste (dry matter) [a] default: 60%:	1-95% of waste (wet) default: 50%
Fossil Carbon as % of Total Carbon	30-50% default: 40%	0%	30-50% default: 40% more information is needed	90-100% [b] default: 90%
Efficiency of Combustion [c]	95-99% default: 95%	95%	50-99.5% default: 95%	95–99.5% default: 99.5%

[a] Clinical waste contains mainly paper and plastics. The carbon content can be estimated from the following factors: C-content of paper: 50% and C-content of plastics: 75-85%.
[b] The fossil carbon may be reduced if it includes carbon from packaging material and similar materials.
[c] Depends on plant design, maintenance and age.

Source: Judgement by Expert Group (see Co-chairs, Editors and Experts; Emissions from Waste Incineration).

N_2O emissions

Where practical, N_2O emission factors should be derived from emission measurements. Continuous emission monitoring is technically feasible, but not necessary for *good practice*. Periodic measurements should be conducted sufficiently often to account for the variability of N_2O generation (i.e. due to variable waste composition), and different types of incinerator operating conditions (e.g. combustion temperature). Chapter 8, Quality Assurance and Quality Control, Section 8.7.1.3, Direct Emission Measurements, provides further advice on representativeness. Where measurement data are not available, other reliable means of developing emission factors should be used (see Figure 5.6, Decision Tree for N_2O Emissions from Waste Incineration).

Emission factors for N_2O differ with facility type and type of waste. Emission factors for fluidised-bed plants are higher than from plants with grate firing systems. Emission factors for MSW are lower than for sewage sludge. Ranges of N_2O emission factors reflect abatement techniques (the injection of ammonia or urea as used in some NOx abatement technologies may increase emissions of N_2O), temperature, and the occupancy time of the waste in the incinerator.

If site-specific N_2O emission factors are not available, default factors can be used (see Table 5.7, Emission Factors for N_2O from Waste Incineration).

Many countries that use waste incineration should have plant-specific data for the amount of waste incinerated.

For hazardous waste and clinical waste, the activity data may be more difficult to obtain since waste incinerated in some of these plants (e.g. on-site incinerators in chemical and pharmaceutical industry) may not be included in waste statistics. For these waste types, plant-specific data may not be available, but overall data for total waste incinerated may be available from waste regulators.

Categorisation of waste types varies across countries (e.g. in Japan sewage sludge is included in industrial waste) as well as within countries (e.g. on a municipal or regional level). Therefore comparability of waste types may be difficult. Where possible, waste should be categorised as above to facilitate consistency and comparability.

5.3.1.3 COMPLETENESS

Completeness depends on the reporting of waste types and amounts burned. If the method is implemented at the facility-level and then summed across facilities, it is *good practice* to ensure that all waste incineration plants are included. Inventory agencies should make efforts to report all waste types arising in their country.

It should be noted that there are possibilities of double counting CO_2 emissions because waste is often incinerated in facilities with energy recovery capabilities. Also, waste can be used as substitute fuel in industrial plants other than waste incineration plants (e.g. in cement and brick kilns and blast furnaces). In order to avoid double counting, the emissions from such processes should be reported under ‘other fuels’ in the Energy Sector, not within the waste disposal source category.

TABLE 5.7
EMISSION FACTORS FOR N_2O FROM WASTE INCINERATION

Incineration Plant Type	**MSW** **kg N_2O/Gg waste (dry)**	**Sewage Sludge** **kg N_2O/Gg sewage sludge (dry matter)**	**Clinical Waste** **kg N_2O/Gg waste (dry)**	**Hazardous Waste (from industry)** **kg N_2O/Gg waste (dry)**
Hearth or grate	5.5-66 (Germany) average 5.5-11 highest value 30 (UK) 40-150 (Japan: wet)	400 (Japan: wet)	NA	NA
Rotating	NA	NA	NA	210-240 (Germany)
Fluidised bed	240-660 (Japan: wet)	800 (Germany) 100-1500 (UK) 300-1530 (Japan: wet)	NA	NA

Note: NA = Not Available.

Source:
Germany: Johnke (1999),
United Kingdom: Environment Agency (1999),
Japan: Yasuda (1993).

5.3.1.4 DEVELOPING A CONSISTENT TIME SERIES

Emissions from waste incineration should be calculated using the same method and data sets for every year in the time series. Where consistent data are unavailable for the same method for any years in the time series, these gaps should be recalculated according to the guidance provided in Chapter 7, Methodological Choice and Recalculation, Section 7.3.2.2, Alternative Recalculation Techniques.

5.3.1.5 UNCERTAINTY ASSESSMENT

Tables 5.6 and 5.7 provide default ranges for CO_2 and N_2O emissions estimates, but inventory agencies should assign country-specific uncertainties to the emission factors, especially if they used monitored data.

More recent information will have a lower uncertainty because it reflects changing practices, technical developments, or changing fractions (biogenic and fossil) of incinerated waste. In many developed countries, uncertainties on the amount of incinerated waste are estimated around 5%, but the uncertainty could be higher for some wastes, such as clinical waste.

The major uncertainty for CO_2 is the estimation of the fossil carbon fraction. There is a high level of uncertainty related to the separation of biogenic and fossil carbon fraction.

Direct measurement or monitoring of emissions of N_2O has less uncertainty. For continuous and periodic emission monitoring, uncertainty depends on the accuracy of measurement instruments. For periodic measurement, uncertainty will also depend on the sampling frequency.

If default values for the N_2O emission factors are used, uncertainty ranges have been estimated to be as high as 100%.

Chapter 6 provides advice on quantifying uncertainties in practice. It includes eliciting and using expert judgements which in combination with empirical data can provide overall uncertainty estimates.

5.3.2 Reporting and documentation

It is *good practice* to document and archive all information required to produce the national emissions inventory estimates as outlined in Chapter 8, Quality Assurance and Quality Control, Section 8.10.1, Internal Documentation and Archiving. Some examples of specific documentation and reporting relevant to this source category are provided below.

It is not practical to include all documentation in the national inventory report. However, the inventory should include summaries of methods used and references to source data such that the reported emissions estimates are transparent and steps in their calculation may be retraced.

Some countries use different categorisation schemes for waste at the local or regional level. In this case, the inventory agency should review consistency with the IPCC categorisation scheme and provide a rationale on how it transformed the data to fit in the IPCC categories. Inventory agencies should clearly indicate the waste types included in the waste estimates.

Inventory agencies should also include information on how they obtained the carbon content, the fossil carbon fraction, and the N_2O emission factors.

Many incineration plants produce electricity and heat. Combustion of waste for energy purposes should be reported under the Energy Sector of the *IPCC Guidelines* (CO_2 from stationary combustion). Waste should be reported as ‘other fuel’ in the Energy Sector. These emissions should not be reported in the Waste Sector of the *IPCC Guidelines* so as to avoid double counting.

Sometimes gas, oil, or other fuels are used as support fuel to start the incineration process or maintain the temperature. Consumption of support fuel for this purpose should not be reported under waste incineration but instead included in the Energy Sector. Support fuels normally account for less than 3% of total calorific input, but they can be more important with the incineration of hazardous waste.

5.3.3 Inventory quality assurance/quality control (QA/QC)

It is *good practice* to conduct quality control checks as outlined in Chapter 8, Quality Assurance and Quality Control, Table 8.1, Tier 1 General Inventory Level QC Procedures, and an expert review of the emissions estimates. Additional quality control checks as outlined in the Tier 2 procedures in Chapter 8 and quality assurance procedures may also be applicable, particularly if higher tier methods are used to determine emissions from this source category. Inventory agencies are encouraged to use higher tier QA/QC for *key source categories* as identified in Chapter 7, Methodological Choice and Recalculation.

Furthermore, transparency can be improved by the provision of clear documentation and explanations of work undertaken in the following areas:

Review of direct emission measurements

- Where direct measurement data are available, inventory agencies should confirm that internationally recognised standard methods were used for measurements. If the measurement practices fail this criterion, then the use of these emissions data should be carefully evaluated.
- Where emissions are measured directly, inventory agencies should compare plant-level factors among plants, and also to IPCC defaults. They should review any significant difference between factors.

Review of emission factors

- Inventory agencies should compare country-specific or plant-specific values of the carbon content of waste, the fossil carbon as fraction of total carbon, and the efficiency of combustion for the incinerator to the default values in Table 5.6.
- Inventory agencies should review the QC procedures associated with the waste incineration data and analysis used to develop site-specific emission factors. If there is insufficient QC, the uncertainty of the national estimates should be assessed and the use of those data may need to be evaluated.

Involvement of experts in the peer review

- Expert peer review should be directed at the characterisations of waste fuel and situations where default data are not used. This is particularly true for hazardous and clinical waste, because these wastes are often not quantified on a plant basis and can vary significantly from plant to plant.

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6

QUANTIFYING UNCERTAINTIES IN PRACTICE

CO-CHAIRS, EDITORS AND EXPERTS

Co-chairs of the Expert Meeting on Cross-sectoral Methodologies for Uncertainty Estimation and Inventory Quality

Taka Hiraishi (Japan) and Buruhani Nyenzi (Tanzania)

REVIEW EDITOR

Richard Odingo (Kenya)

Expert Group on Quantifying Uncertainties in Practice

CO-CHAIRS

Jim Penman (UK) and Semere Habetsion (Eritrea)

AUTHORS OF BACKGROUND PAPERS

Kay Abel (Australia), Simon Eggleston (UK) and Tinus Pullus (Netherlands)

CONTRIBUTORS

Simon Eggleston (UK), Christopher Frey (USA), Kari Gronfors (Finland), Niklas Höhne (UNFCCC Secretariat), Charles Jubb (Australia), Katarina Mareckova (Slovak Republic), Jeroen Meijer (IPCC-NGGIP/TSU), Frank Neitzert (Canada), Todd Ngara (Zimbabwe), Tinus Pulles (Netherlands), Emmanuel Rivière (France), Arthur Rypinski (USA), Martiros Tsarukyan (Armenia), and Peter Zhou (Botswana)

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6 QUANTIFYING UNCERTAINTIES IN PRACTICE

6.1 OVERVIEW

This chapter describes *good practice* in estimating and reporting uncertainties associated with both annual estimates of emissions, and emission trends over time. It identifies types of uncertainty from the viewpoint of the inventory practitioner and shows how to obtain expert judgements in a consistent manner. It provides two tiers for combining source category uncertainties into an uncertainty estimate for total national emissions, and presents an example of the application of the Tier 1 method.

The chapter is consistent with source-specific *good practice guidance* described in Chapters 2 to 5, the general principles discussed in Annex 1, Conceptual Basis for Uncertainty Analysis, and the chapters on methodological choice (Chapter 7, Methodological Choice and Recalculation) and QA/QC (Chapter 8, Quality Assurance and Quality Control).

Uncertainty estimates are an essential element of a complete emissions inventory. Uncertainty information is not intended to dispute the validity of the inventory estimates, but to help prioritise efforts to improve the accuracy of inventories in the future and guide decisions on methodological choice, as indicated in Chapter 7, Methodological Choice and Recalculation. Inventory practitioners understand that for most countries and source categories, greenhouse gas emissions estimates are reasonably accurate. However, national inventories prepared pursuant to the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (*IPCC Guidelines*) will typically contain a wide range of emission estimates, varying from carefully measured and demonstrably complete data on emissions of certain engineered chemicals, to order-of-magnitude estimates of highly variable nitrous oxide (N_2O) fluxes from soils and waterways.

Inventory estimates can be used for a range of purposes. For some purposes, only the national total matters, while for others, the detail by greenhouse gas and source category is important. In order to match the data to the intended purpose, users must be able to understand the actual reliability of both the total estimate and its component parts. For this reason, the methods used to communicate uncertainty must be practical, scientifically defensible, robust enough to be applicable to a range of source categories, methods and national circumstances, and presented in ways comprehensible to non-specialist inventory users.

There are many reasons that actual emissions and sinks may differ from the number calculated in a national inventory. These reasons are discussed at greater length in Annex 1. Some sources of uncertainty (i.e. sampling error or limitations on instrument accuracy) may generate well-defined, easily characterised estimates of the range of potential error. However, other sources of uncertainty may be much more difficult to characterise. This chapter describes how to account for both well-defined statistical uncertainties and less specific information characterising other forms of uncertainty, and how to combine this information into a characterisation of the uncertainty of both the total inventory and its components.

Ideally, emissions estimates and uncertainty ranges would both be derived from source-specific measured data. Since it is not practical to measure every emission source in this way, estimates are often based on the known characteristics of typical sources taken to be representative of the population. This introduces additional uncertainties, because it must be assumed that the population of these sources behave, on average, like the sources that have been measured. Sometimes enough will be known about these typical sources to determine their uncertainty distributions empirically. In practice, however, expert judgement will often be necessary to define the uncertainty ranges.

The pragmatic approach to producing quantitative uncertainty estimates in this situation is to use the best available estimates; a combination of the available measured data and expert judgement. The methods proposed in this chapter can therefore be used with the source category-specific uncertainty ranges discussed in Chapters 2 to 5, and also allow for new empirical data to be incorporated as they become available. This chapter also describes methods for eliciting expert judgement in a way that minimises the risk of bias, and it discusses how to combine uncertainties in emission factors and activity data to estimate source category and total uncertainties in inventories, as well as uncertainties in the trend.

The chapter uses two main statistical concepts – the probability density function and confidence limits – that are defined formally in Annex 3, the Glossary, and discussed in more detail in Annex 1, Conceptual Basis for

Uncertainty Analysis. Briefly, the probability density function describes the range and relative likelihood of possible values. Confidence limits give the range within which the underlying value of an uncertain quantity is thought to lie for a specified probability. This range is called the confidence interval. The *IPCC Guidelines* suggest the use of a 95% confidence interval which is the interval that has a 95% probability of containing the unknown true value.

The analysis of uncertainty presented in this chapter does not consider the uncertainties in Global Warming Potentials (GWPs). For reporting, the GWP values adopted at the Third Session of the UNFCCC Conference of the Parties become in effect fixed weighting factors. However, it should be kept in mind that GWP values actually have significant uncertainties associated with them and that an overall assessment of total equivalent emissions should take this fact into account.

6.2 IDENTIFYING UNCERTAINTIES

The estimated uncertainty of emissions from individual sources (e.g. power plants, motor vehicles, dairy cattle) is either a function of instrument characteristics, calibration and sampling frequency of direct measurements, or (more often) a combination of the uncertainties in the emission factors for typical sources and the corresponding activity data. The uncertainties in the emission factors and activity data should be described using probability density functions. Where data are available to do so, the shape of the probability density function should be determined empirically. Otherwise, expert judgement will be necessary, following the rules set out in Section 6.2.5, Expert Judgement, below. Sections 6.2.1 to 6.2.4 (below) give examples of typical situations that can arise under different circumstances of data availability. These subsections are ranked in order of their desirability in producing uncertainty assessments.

Uncertainties are affected by choice of estimation algorithm, and this is reflected in *good practice*, where higher tier methods (provided they are well implemented) should usually be associated with lower uncertainties. In general, uncertainties related to model choice will be reflected in the uncertainty ranges derived for use in the context of the model selected.

6.2.1 Uncertainties associated with continuous monitoring of emissions

Continuous monitoring of emissions, though comparatively rare, is usually consistent with source category-specific *good practice*. In this case, the probability density function, and therefore the uncertainty in emissions including 95% confidence limits, can be determined directly. Representative sampling requires that the equipment used to make the measurements be installed and operated according to the principles and references set out in Chapter 8 on QA/QC issues. Provided this is done, it is unlikely that there will be correlation of errors between years. Therefore, the probability density function of the difference in emissions between two years (the trend uncertainty) will be simply related to the probability density functions of the annual emissions. Assuming both probability density functions are normal, the probability density function of the difference in emissions will also be normal with:

EQUATION 6.1

$$\text{mean} = \mu_1 - \mu_2$$

EQUATION 6.2

$$\text{standard deviation} = (\sigma_1^2 + \sigma_2^2)^{1/2}$$

where μ_1 and μ_2 are the mean values of the emissions in years t_1 and t_2, and σ_1 and σ_2 are the standard deviations of the probability density functions of the emissions in year t_1 and t_2. The 95% confidence limits (this time of the mean or the difference in the means) will be given by plus or minus approximately two standard deviations.[1]

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[1] For sample sizes less than about 30, a Student *t* distribution should be used to estimate confidence intervals.

6.2.2 Uncertainties associated with direct determination of emission factors

In some cases, periodic emission measurements may be available at a site. If these measurements can be linked to representative activity data, which of course is crucial, then it is possible to determine a site-specific emission factor, together with an associated probability density function to represent annual emissions.

This can be a complex task. To achieve representativeness it may be necessary to partition (or stratify) the data to reflect typical operating conditions. For example:

- *Start-up and shut down can give different emission rates relative to activity data.* In this case, the data should be partitioned, with separate emission factors and probability density functions derived for steady state, start-up and shut down conditions.
- *Emission factors can depend on load.* In this case, the total emissions estimation and uncertainty analysis may need to be stratified to take account of load, expressed, for example, as percentage of full capacity. This could be done by regression analysis and scatter plots of the emission rate against likely controlling variables (e.g. emissions *versus* load) with load becoming part of the activity data needed.
- *Measurements taken for another purpose may not be representative.* For example, methane measurements made for safety reasons at coal mines and landfills may not reflect total emissions. In such cases, the ratio between the measured data and total emissions should be estimated for the uncertainty analysis.

If the data sample size is large enough, standard statistical goodness-of-fit tests can be used, in combination with expert judgement, to help in deciding which probability density function to use for describing variability in the data (partitioned if necessary) and how to parameterise it. However, in many cases, the number of measurements from which to make an inference regarding uncertainty will be small. Typically, as long as there are three or more data points, and as long as the data are a random representative sample of the quantity of interest, it is possible to apply statistical techniques to estimate the values of the parameters of many two-parameter distributions (e.g. normal, lognormal) that can be used to describe variability in the data set (Cullen and Frey, 1999, pp. 116-117). With small sample sizes, there will be large uncertainties regarding the parameter estimates that should be reflected in the quantification of uncertainty for use in the emissions inventory. Furthermore, it is typically not possible to rely on statistical methods to differentiate goodness-of-fit of alternative parametric distributions when sample sizes are very small (Cullen and Frey, 1999, pp. 158-159). Therefore, considerable judgement is required in selecting an appropriate parametric distribution to fit to a very small data set. In situations where the coefficient of variation is less than approximately 0.3, a normal distribution may be a reasonable assumption (Robinson, 1989). When the coefficient of variation is large and the quantity is non-negative, then a positively skewed distribution such as a lognormal one may be appropriate. Guidance on the selection of distributions is provided in Annex 1, Conceptual Basis for Uncertainty Analysis, and the use of expert judgements in this context is outlined in Section 6.2.5, Expert Judgement, below.

6.2.3 Uncertainties associated with emission factors from published references

When site-specific data are unavailable, *good practice* will usually be to develop emission estimates using emission factors drawn from references consistent with the *IPCC Guidelines* and the source category-specific *good practice guidance* described in Chapters 2 to 5. These factors will have been measured under particular circumstances that are judged to be typical. There will be uncertainties associated with the original measurements, as well as with the use of the factors in circumstances other than those associated with the original measurements. It is a key function of *good practice guidance* for each source category to guide the choice of emission factors to minimise this second source of uncertainty to the extent possible. The source category-specific guidance also indicates, wherever possible, the uncertainty ranges likely to be associated with using these factors.

Where such emission factors are used, the associated uncertainties should be estimated from:

- *Original research including country-specific data.* For measurement-based emission factors, the data from the original measurement programme may enable an assessment of the uncertainty and possibly the probability density function. Well-designed measurement programmes will provide sample data that cover the range of types of plants and their maintenance, size and age, so that the factors and their uncertainties can be used directly. In other cases, expert judgement will be needed to extrapolate from the measurements to the full population of plants in that particular source/sink category.

- *Good practice guidance.* For most emission factors, source category-specific *good practice guidance* provides default uncertainty estimates that should be used in the absence of other information. Unless clear evidence to the contrary is available, the probability density functions are assumed to be normal. However, the inventory agency should evaluate the representativeness of the default for its own situation. If the default is judged to be unrepresentative and the source category is important to the inventory, improved assumptions based upon expert judgement should be developed.

An emission factor that over or underestimates emissions in the base year will probably do so in subsequent years. Therefore, uncertainties due to emission factors will tend to be correlated over time.

6.2.4 Uncertainties associated with activity data

Activity data are often more closely linked to economic activity than are emission factors. There are often well established price incentives and fiscal requirements for accurate accounting of economic activity. Activity data therefore tend to have lower uncertainties and a lower correlation between years. Activity data are often collected and published regularly by national statistical agencies. It is possible that these agencies have already assessed the uncertainties associated with their data as part of their data collection procedures. These uncertainties can be used to construct probability density functions. This information will not necessarily have been published, so it is *good practice* to contact the statistical agencies directly. Since economic activity data are not usually collected for the purpose of estimating greenhouse gas emissions, the applicability of the data should be assessed before using them.

Examples of generic and specific questions that may arise on coverage, representativeness and repeatability from year to year are:

- *Interpretation of statistical differences.* Statistical differences in energy balance usually represent a difference between amount of reported primary fuels and amount of fuels identified in the categories ‘final consumption’ and ‘in transformation’. They can give an indication of the size of the uncertainties of the data, especially where long time series are considered.
- *Interpretation of energy balances.* Production, use and import/export data should be consistent. If not, this may give an indication of the uncertainties.
- *Cross-checks.* It may be possible to compare two types of activity data that apply to the same source to provide an indication of uncertainty ranges. For example, the sum of vehicle fuel use should be commensurate with the sum by vehicle type of the product of vehicle-km times fuel consumption efficiency.
- *Vehicle numbers and types.* Some countries maintain detailed vehicle registration databases with data on vehicles by type, age, fuel type and emission control technology, all of which can be important for a detailed bottom-up inventory of methane (CH_4) and nitrous oxide (N_2O) emissions from such vehicles. Others do not have such detailed information and this will tend to increase the uncertainty.
- *Smuggling of fuel across borders.* This can be significant and may introduce bias into the activity data. Apparent consumption and the sum of the sectoral fuel use may be compared as a cross-check.
- *Biomass fuels.* Where formal markets for these fuels do not exist, consumption estimates may be much less accurate than for fuels in general.
- *Livestock population data.* Accuracy will depend on the extent and reliability of national census and survey methods and there may be different accounting conventions for animals that do not live for a whole year.

Inventory agencies may also undertake dedicated research to collect additional activity data, consistent with *good practice* in the prioritisation of efforts toward *key source categories* (i.e. those source categories with a significant influence on a country’s total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both, as described in Chapter 7, Methodological Choice and Recalculation).

Probability density functions associated with activity data can be difficult to assess. The procedures outlined in this chapter should be applied to the available information, in accordance with the advice on interpreting expert judgements in the following section.

6.2.5 Expert judgement

Estimates of uncertainty in emission factors or direct emission measurements will need to be based on expert judgement when empirical data are lacking. Estimates of uncertainty in activity data will often be based on expert judgement, informed wherever possible by cross-checks like those described in the previous section.

Experts are people who have special skills or knowledge in a particular field. A judgement is the forming of an estimate or conclusion from information presented to or available to the expert. It is important to select appropriate experts with respect to the emission inventory inputs for which uncertainty estimates are needed.

The goal of expert judgement here is to develop a probability density function, taking into account relevant information such as:

- Is the emission source similar to other sources? How is the uncertainty likely to compare?
- How well is the emission process understood? Have all possible emission sources been identified?
- Are there physical limits on how much the emission factor can vary? Unless the process is reversible it cannot emit less than zero, and this may constrain a very wide uncertainty range. Mass balance considerations or other process data may place an upper limit on emissions.
- Are the emissions consistent with atmospheric concentrations? Emissions are reflected in atmospheric concentrations at site-specific and larger scales and again this may limit the possible emission rates.

A degree of expert judgement is required even when applying classical statistical techniques to data sets, since one must judge whether the data are a representative random sample and, if so, what methods to use to analyse the data. This may require both technical and statistical judgement. Interpretation is especially needed for data sets that are small, highly skewed or censored.[2] The formal methods for obtaining data from experts are known as *expert elicitation*.

POSSIBLE BIASES IN EXPERT ELICITATION

Wherever possible, expert judgement regarding uncertainty should be elicited using an appropriate protocol. Once experts are identified, elicitation protocols should be designed to overcome the biases that can be introduced by the rules of thumb (sometimes called *heuristics*) that experts use when formulating judgements about uncertainty.

The most common unconscious biases introduced by rules of thumb are:

- *Availability bias.* This is basing judgements on outcomes that are more easily remembered.
- *Representativeness bias.* This is basing judgements on limited data and experience without fully considering other relevant evidence.
- *Anchoring and adjustment bias.* This is fixating on a particular value in a range and making insufficient adjustments away from it in constructing an uncertainty estimate.

To counteract the first two potential sources of biases, elicitation protocols should include a review of relevant evidence. In order to counteract the third potential source of bias, it is important to ask the expert to make judgements regarding extreme values first, before asking for judgements regarding central values of a distribution. When an expert gives too narrow a range of values, that is said to be ‘overconfidence’. Experts often systematically underestimate uncertainties according to Morgan and Henrion (1990). It is desirable to avoid overconfidence so as not to underestimate the true uncertainty.

There is also the possibility of more conscious biases:

- *Motivational bias* is a desire by an expert to influence an outcome or to avoid contradicting prior positions on an issue.
- *Expert bias* arises from an unqualified expert’s desire to appear as a true expert in the field. This would typically lead to overconfident estimates of uncertainty.

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[2] In these cases it may be helpful to consider a numerical method, such as the bootstrap, for characterising sampling distributions. Methods for characterising sampling distributions for the mean are described by Cullen and Frey (1999), Frey and Rhodes (1996), and Frey and Burmaster (1999).

- *Managerial bias* is a situation in which an expert makes judgements that achieve organisational goals, rather than judgements that reflect the actual state of knowledge regarding an inventory input.
- *Selection bias* occurs when the inventory agency selects the expert who tells it what it wants to hear.

The best way to avoid these biases is to be careful in the selection of experts.

Expert judgements can be elicited from individuals or groups. Groups can be useful for sharing knowledge and hence could be part of the motivation, structuring, and conditioning steps of the elicitation. However, group dynamics may introduce other biases. Thus, it is usually preferable to elicit judgement on an individual basis.

A PROTOCOL FOR EXPERT ELICITATION

An example of a well-known protocol for expert elicitation is the Stanford/SRI protocol. Its five steps are described below, and an example of its use is presented in Box 6.1, A Brief Example of Detailed Expert Judgement.

- *Motivating*: Establish a rapport with the expert, and describe the context of the elicitation. Explain the elicitation method to be used and the reason it was designed that way. The elicitor should also try to explain the most commonly occurring biases to the expert, and to identify possible biases in the expert.
- *Structuring*: Clearly define the quantities for which judgements are to be sought, including, for example, the year and country, the emission source category, the averaging time to be used (one year), the focus on uncertainty in the mean value of emission factors, and the structure of the emission inventory model. Clearly identify conditioning factors and assumptions (e.g. emissions should be for typical conditions averaged over a one-year period).
- *Conditioning*: Work with the expert to identify all relevant data, models, and theory pertaining to the quantity for which judgements about uncertainty are required.
- *Encoding*: Request the expert’s judgement regarding uncertainty. The next section on encoding describes some alternative methods to use.
- *Verification*: Analyse the expert’s response and provide the expert with feedback as to what has been concluded regarding his or her judgement. Is what has been encoded really what the expert meant? Are there inconsistencies in the expert’s judgement?

METHODS FOR ENCODING EXPERT JUDGEMENTS

The method to be used in the encoding step should depend upon the expert’s familiarity with probability distributions. Some commonly used methods are:

- *Fixed Value*: Estimate the probability of being higher (or lower) than an arbitrary value and repeat, typically three or five times. For example, what is the probability that an emission factor would be less than 100?
- *Fixed Probability*: Estimate the value associated with a specified probability of being higher (or lower). For example, what is the emission factor such that there is only a 2.5 percent probability (or 1 in 40 chance) that the emission factor could be lower (or higher) than that value.
- *Interval Methods*: This method focuses on the median and the quartiles. For example, the expert would be asked to choose a value of the emission factor such that it is equally likely that the true emission factor would be higher or lower than that value. This yields the median. Then the expert would divide the lower range into two bins such that he or she felt it to be equally likely (25 percent probability) that the emission factor could be in either bin, and this would be repeated for the other end of the distribution. Finally, either fixed probability or fixed value methods could be used to get judgements for extreme values.
- *Graphing*: The expert draws his/her own distributions. This should be used cautiously because some experts are overconfident about their knowledge of probability distributions.

BOX 6.1

A BRIEF EXAMPLE OF DETAILED EXPERT JUDGEMENT

Suppose that the inventory agency has identified an expert regarding emissions of methane from power plants, and wish to obtain her judgement regarding the uncertainty in annual average emissions for this source category. As part of the motivation step, the elicitor has explained to the expert the general purpose of the analysis and the expert elicitation protocol to be used. In the structuring step, the elicitor works with the expert to set up the specific elicitation protocol. For example, although all the inventory agency may want is an annual average uncertainty estimate, the expert may tell the elicitor that she prefers to provide judgements separately for start-up, part load, and full load operation of the plant, and that these three judgements should be weighted in order to come up with the combined uncertainty for an annual average. After structuring the problem, the elicitor then reviews the expert information relevant to the assessment, such as measurements that may have been made on similar types of power plants or other combustion sources. In the elicitation step, the elicitor might ask the expert for an upper value such that there is only a one in 40 chance (2.5 percent probability) of obtaining a higher value. After getting the value, the elicitor asks the expert to explain the logical basis for this estimate, such as the scenario of operation at the plant that might lead to such a high emission rate. Then the process might be repeated for the lower end of the range, and perhaps for the median, 25th percentile, and 75th percentile. A mixture of fixed value and fixed probability questions might be used. The elicitor should plot these on a graph so that any inconsistencies can be identified and corrected during the time available with the expert. In the verification step, the elicitor would make sure that the expert is comfortable that their judgement has been well represented. The elicitor might also see how the expert would react to the possibility of values outside of the interval for which judgements were provided, so as to ensure that the expert is not being overconfident.

Sometimes the only available expert judgement will consist of a range, perhaps quoted together with a most likely value. Under these circumstances the following rules apply:

- Where experts only provide an upper and a lower limiting value, assume the probability density function is uniform and that the range corresponds to the 95% confidence interval.
- Where experts also provide a most likely value, assume a triangular probability density function using the most likely values as the mode and assuming that the upper and lower limiting values each exclude 2.5% of the population. The distribution need not be symmetrical.

Some other sources of information on expert elicitation include Spetzler and von Holstein (1975), Morgan and Henrion (1990), Merkhofer (1987), Hora and Iman (1989), and NCRP (1996).

The subjective nature of expert judgement increases the need for quality assurance and quality control procedures to improve comparability of uncertainty estimates between countries. Therefore expert judgements should be documented as part of the national archiving process, and inventory agencies are encouraged to review expert judgements, particularly for *key source categories*. Documentation should include:

- Reference number for judgement;
- Date;
- Person(s) involved and affiliation;
- The quantity being judged;
- The logical basis for judgement, including any data taken into consideration;
- The resultant probability distribution, or the range and most likely value and the probability distribution subsequently inferred;
- Identification of any external reviewers;
- Results of any external review;
- Approval by inventory agency, specifying date and person.

6.3 METHODS FOR COMBINING UNCERTAINTIES

Once the uncertainties in the source categories have been determined, they may be combined to provide uncertainty estimates for the entire inventory in any year and the uncertainty in the overall inventory trend over time.

The error propagation equation, as discussed more extensively in Annex 1 of this report, and in Annex I of the *IPCC Guidelines* (Reporting Instructions), yields two convenient rules for combining uncorrelated uncertainties under addition and multiplication:

- *Rule A:* Where uncertain quantities are to be combined by addition, the standard deviation of the sum will be the square root of the sum of the squares of the standard deviations of the quantities that are added with the standard deviations all expressed in absolute terms (this rule is exact for uncorrelated variables).

  Using this interpretation, a simple equation can be derived for the uncertainty of the sum, that when expressed in percentage terms becomes:

EQUATION 6.3

$$U_{\text{total}} = \frac{\sqrt{(U_1 \bullet x_1)^2 + (U_2 \bullet x_2)^2 + \ldots + (U_n \bullet x_n)^2}}{x_1 + x_2 + \ldots + x_n}$$

Where:

U_{total} is the percentage uncertainty in the sum of the quantities (half the 95% confidence interval divided by the total (i.e. mean) and expressed as a percentage);

x_i and U_i are the uncertain quantities and the percentage uncertainties associated with them, respectively.

- *Rule B*: Where uncertain quantities are to be combined by multiplication, the same rule applies except that the standard deviations must all be expressed as fractions of the appropriate mean values (this rule is approximate for all random variables).

  A simple equation can also be derived for the uncertainty of the product, expressed in percentage terms:

EQUATION 6.4

$$U_{\text{total}} = \sqrt{U_1^2 + U_2^2 + \ldots + U_n^2}$$

Where:

U_{total} is the percentage uncertainty in the product of the quantities (half the 95% confidence interval divided by the total and expressed as a percentage);

U_i are the percentage uncertainties associated with each of the quantities.

The greenhouse gas inventory is principally the sum of products of emission factors and activity data. Therefore, Rules A and B can be used repeatedly to estimate the uncertainty of the total inventory. In practice, uncertainties found in inventory source categories vary from a few percent to orders of magnitude, and may be correlated. This is not consistent with the assumptions of Rules A and B that the variables are uncorrelated with a standard deviation of less than about 30% of the mean, but under these circumstances, Rules A and B may still be used to obtain an approximate result. Alternatively, a stochastic simulation (the Monte Carlo method) can be used, that can combine uncertainties with any probability distribution, range, and correlation structure, provided they have been suitably quantified. Thus, two tiers for uncertainty analysis are described below:

- *Tier 1*: Estimation of uncertainties by source category using the error propagation equation via Rules A and B, and simple combination of uncertainties by source category to estimate overall uncertainty for one year and the uncertainty in the trend.
- *Tier 2*: Estimation of uncertainties by source category using Monte Carlo analysis, followed by the use of Monte Carlo techniques to estimate overall uncertainty for one year and the uncertainty in the trend.

Monte Carlo analysis can also be used in a restricted way within Tier 1 to combine activity data and emission factor uncertainties that have very wide or non-normal probability distributions or both. This approach can also help deal with source categories within Tier 1 that are estimated by process models, rather than by the classical ‘emission factor times activity data’ calculation. The choice between methods is discussed in Section 6.3.1 below.

6.3.1 Comparison between tiers and choice of method

Use of either Tier 1 or Tier 2 will provide far greater insight than previously available into how individual source categories and greenhouse gases contribute to uncertainty in total emissions in any year, and to the trend in total emissions between years.

Application of Tier 2 to the UK inventory (Eggleston *et al*., 1998) suggests that the 95% confidence interval is asymmetric and lies between about 7% below and 20% above the mean. Application of Tier 1 (see Appendix 6A.2, Tier 1 Uncertainty Calculation Example) suggests an uncertainty of about ±20%. Since the approximations inherent in Tier 1 mean that it cannot deal with asymmetry, this comparison is encouraging. Physically, the reason for the asymmetry identified under Tier 2 is that the uncertainty range of some very uncertain source categories is constrained by the knowledge that the emissions cannot be less than zero. The Tier 2 method can make use of this extra knowledge, but the Tier 1 method cannot. On trends between years, the Tier 2 study by Eggleston *et al*. suggests that the 95% confidence interval is roughly symmetrical and lies between 5% above and 5% below the mean.[3] The corresponding Tier 1 result gives a range of about ±2%. The lower Tier 1 value is partly because the trend estimated here is for the period 1990 to 1997, whereas the Tier 2 estimate was for 1990 to 2010, but this is unlikely to account for all the differences. Nevertheless, both methods still give similar magnitudes in the trend uncertainty that is less than the uncertainty in total emissions in any year.

Further national comparisons between methods would be very useful in developing understanding. The Tier 1 method, being spreadsheet based, is very easy to apply and would represent hardly any additional effort for an inventory agency also undertaking Tier 2. Therefore, for the present, it is *good practice* for all countries undertaking uncertainty analysis to report Tier 1 results, and for all inventory agencies with sufficient resources and expertise to undertake Tier 2.

6.3.2 Tier 1 – Estimating uncertainties by source category with simplifying assumptions

The Tier 1 analysis estimates uncertainties by using the error propagation equation in two steps. First, the Rule B approximation is used to combine emission factor and activity data ranges by source category and greenhouse gas. Second, the Rule A approximation is used to arrive at the overall uncertainty in national emissions and the trend in national emissions between the base year and the current year.

The Tier 1 approach should be implemented using Table 6.1, Tier 1 Uncertainty Calculation and Reporting that can be set up on commercial spreadsheet software. The table is completed at the source category level using uncertainty ranges for activity data and emission factors consistent with the sectoral *good practice guidance* in Chapters 2 to 5. Different gases should be entered separately as CO_2 equivalents (i.e. the emissions should be multiplied by 100-year GWP values). Trend uncertainties are estimated using two sensitivities:

- *Type A sensitivity*: the change in the difference in overall emissions between the base year and the current year, expressed as a percentage, resulting from a 1% increase in emissions of a given source category and gas in both the base year and the current year.
- *Type B sensitivity*: the change in the difference in overall emissions between the base year and the current year, expressed as a percentage, resulting from a 1% increase in emissions of a given source category and gas in the current year only.

Conceptually, Type A sensitivity arises from uncertainties that affect emissions in the base year and the current year equally, and Type B sensitivity arises from uncertainties that affect emissions in the current year only. Uncertainties that are fully correlated between years will be associated with Type A sensitivities, and

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[3] Specifically a fall in emissions of 6 ±5%.

uncertainties that are not correlated between years will be associated with Type B sensitivities. The discussion in Sections 6.2.1 to 6.2.4 above suggests that emission factor uncertainties will tend to have Type A sensitivities, and activity data uncertainties will tend to have Type B. However, this association will not always hold and it is possible to apply Type A sensitivities to activity data, and Type B sensitivities to emission factors to reflect particular national circumstances. Type A and Type B sensitivities are simplifications introduced for the analysis of correlation.

Once the uncertainties introduced into national emissions by Type A and Type B sensitivities have been calculated, they can be summed using the error propagation equation (Rule A) to give the overall uncertainty in the trend.

The columns of Table 6.1, Tier 1 Uncertainty Calculation and Reporting, are labelled A to Q and contain the following information:

- A and B show the IPCC source category and greenhouse gas.
- C and D are the inventory estimates in the base year and the current year[4] respectively, for the source category and gas specified in columns A and B, expressed in CO_2 equivalents.
- E and F contain the uncertainties for the activity data and emission factors respectively, derived from a mixture of empirical data and expert judgement as previously described in this chapter, entered as half the 95% confidence interval divided by the mean and expressed as a percentage. The reason for halving the 95% confidence interval is that the value entered in columns E and F then corresponds to the familiar plus or minus value when uncertainties are loosely quoted as ‘plus or minus x%’, so expert judgements of this type can be directly entered in the spreadsheet. If uncertainty is known to be highly asymmetrical, enter the larger percentage difference between the mean and the confidence limit.
- G is the combined uncertainty by source category derived from the data in columns E and F using the error propagation equation (Rule B). The entry in column G is therefore the square root of the sum of the squares of the entries in columns E and F.
- H shows the uncertainty in column G as a percentage of total national emissions in the current year. This is a measure of the degree of uncertainty introduced into the national emissions total by the source category in question. The entry in each row of column H is the entry in column G multiplied by the entry in column D, divided by the total at the foot of column D. The total at the foot of column H is an estimate of the percentage uncertainty in total national emissions in the current year, calculated from the entries above using Rule A. This total is obtained by summing the squares of all the entries in column H and taking the square root.
- I shows how the percentage difference in emissions between the base year and the current year changes in response to a one percent increase in source category emissions in both the base year and the current year. This shows the sensitivity of the trend in emissions to a systematic uncertainty in the emissions estimate (i.e. one that is correlated between the base year and the current year). This is the Type A sensitivity as defined above. Appendix 6A.1 provides the derivation for the formula for the entries in column I.
- J shows how the percentage difference in emissions between the base year and the current year changes in response to a one percent increase in source category emissions in the current year only. This shows the sensitivity of the trend in emissions to random error in the emissions estimate (i.e. one, that is not correlated, between the base year and the current year). This is the Type B sensitivity as described above. The formula for the entries in column J is derived in Appendix 6A.
- K uses the information in columns I and F to show the uncertainty introduced into the trend in emissions by emission factor uncertainty, under the assumption that uncertainty in emission factors is correlated between years. If the user decides that the emission factor uncertainties are not correlated between years then the entry in column J should be used in place of that in column I and the result multiplied by $\sqrt{2}$. The formula for the entries in column K is derived in Appendix 6A.
- L uses the information in columns J and E to show the uncertainty introduced into the trend in emissions by activity data uncertainty, under the assumption that uncertainty in activity data is not correlated between years. If the user decides that the activity data uncertainties are correlated between years then the entry in column I should be used in place of that in column J and the $\sqrt{2}$ factor does not then apply. The formula for the entries in column L is derived in Appendix 6A.

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[4] The current year is the most recent year for which inventory data are available.

- M is an estimate of the uncertainty introduced into the trend in national emissions by the source category in question. Under Tier 1, this is derived from the data in columns K and L using Rule B. The entry in column M is therefore the square root of the sum of the squares of the entries in columns K and L. The total at the foot of this column is an estimate of the total uncertainty in the trend, calculated from the entries above using the error propagation equation. This total is obtained by summing the squares of all the entries in column M and taking the square root. The formula for the entries in column M and the total at the foot of column M is shown in Appendix 6A.1.
- Columns N to Q are used for indicators and cross referencing to footnotes.
- N contains D, M or R, depending on whether the emission factor uncertainty range is based on default (D) information in source category guidance, measurements (M) made for the purpose or national referenced (R) information.
- O contains D, M or R, depending on whether the activity data uncertainty range is based on default information in sector guidance, measurements made for the purpose or national referenced information.
- P contains the reference numbers of any expert judgements used to estimate uncertainties in this source category.
- Q contains the number of an explanatory footnote to go at bottom of table to identify documentary reference of uncertainty data (including measured data) or other comments relevant to the line.

An example of the spreadsheet with all the numerical data completed is provided in Appendix 6A.2, Tier 1 uncertainty calculation example.

TABLE 6.1

TIER 1 UNCERTAINTY CALCULATION AND REPORTING

A	B	C	D	E	F	G	H	I	J	K	L	M
IPCC Source category	Gas	Base year emissions	Year t emissions	Activity data uncertainty	Emission factor uncertainty	Combined uncertainty	Combined uncertainty as % of total national emissions in year t	Type A sensitivity	Type B sensitivity	Uncertainty in trend in national emissions introduced by emission factor uncertainty	Uncertainty in trend in national emissions introduced by activity data uncertainty	Uncertainty introduced into the trend in total national emissions
		Input data	Input data	Input data	Input data	$\sqrt{E^2+F^2}$	$\frac{G \bullet D}{\sum D}$	Note B	$\frac{D}{\sum C}$	$I \bullet F$ Note C	$J \bullet E \bullet \sqrt{2}$ Note D	$\sqrt{K^2+L^2}$
		Gg CO_2 equivalent	Gg CO_2 equivalent	%	%	%	%	%	%	%	%	%
E.g. 1.A.1. Energy Industries Fuel 1	CO_2											
E.g. 1.A.1. Energy Industries Fuel 2	CO_2											
Etc...	…											
		$\sum C$	$\sum D$				$\sqrt{\sum H^2}$					$\sqrt{\sum M^2}$
Total												

TABLE 6.1 (CONTINUED)

TIER 1 UNCERTAINTY CALCULATION AND REPORTING

A (continued)	B (continued)	N	O	P	Q
IPCC Source category	Gas	Emission factor quality indicator	Activity data quality indicator	Expert judgement reference numbers	Footnote reference number
		Note E	Note E		
E.g. 1.A.1. Energy Industries Fuel 1	CO_2				
E.g. 1.A.1. Energy Industries Fuel 2	CO_2				
Etc...	…				
Total					

Note A If only total uncertainty is known for a source category (not for emission factor and activity data separately), then:

- If uncertainty is correlated across years, enter the uncertainty into column F, and enter 0 in column E;
- If uncertainty is not correlated across years, enter the uncertainty into column E and enter 0 in column F.

Note B

$$\frac{0.01 \bullet D_x + \sum D_i - (0.01 \bullet C_x + \sum C_i)}{(0.01 \bullet C_x + \sum C_i)} \bullet 100 - \frac{\sum D_i - \sum C_i}{\sum C_i} \bullet 100$$

Note C

In the case where no correlation between emission factors is assumed, sensitivity B should be used and the result multiplied by √2:

$$K_x = J_x \bullet F_x \bullet \sqrt{2}$$

Note D

In the case where correlation between activity data is assumed, sensitivity A should be used and the √2 is not required:

$$L_x = I_x \bullet E_x$$

Note E

Please use the following abbreviations:
D – IPCC source category default
M – measurement based
R – national referenced data

6.3.3 Tier 1 aggregation and reporting

Table 6.1, Tier 1 Uncertainty Calculation and Reporting, has one line for each source category, fuel (where appropriate), and greenhouse gas and should be used for reporting.

Although the Tier 1 method allows for correlation over time, as described above, it does not account for correlation and dependency between source categories that may occur because the same activity data or emission factors may be used for multiple estimates. Often one gas dominates the source category and this reduces the effect of any correlation. However, correlation and dependency may be significant for fossil fuels because a given fuel is used with the same emission factor across several sub-categories, and if (as is sometimes the case) total consumption of a fuel is better known than consumption disaggregated by source category, hidden dependencies will exist within the statistics because of the constraint provided by overall consumption. Dependency and correlation can be addressed by aggregating the source categories to the level of overall consumption of individual fuels before the uncertainties are combined. This entails some loss of detail in reporting on uncertainties but will deal with the dependencies where they are thought to be significant (e.g. where the uncertainties in fossil fuel emissions when aggregated from the source category level are greater than expected). The example Tier 1 calculation using UK data provided in Appendix 6A.2 has fossil fuel categories aggregated in this way. This has the advantage of allowing compatibility with the categories suggested in Chapter 7 for the *key source category* analysis.

6.4 TIER 2 – ESTIMATING UNCERTAINTIES BY SOURCE CATEGORY USING MONTE CARLO ANALYSIS

Under Tier 2, the simplifying assumptions required for Tier 1 can be relaxed. Tier 2 uses Monte Carlo analysis to combine source category uncertainties.

The principle of Monte Carlo analysis is to select random values of emission factor and activity data from within their individual probability density functions, and to calculate the corresponding emission values. This procedure is repeated many times, using a computer, and the results of each calculation run build up the overall emission probability density function. Monte Carlo analysis can be performed at the source category level, for aggregations of source categories or for the inventory as a whole.

Monte Carlo analysis can deal with probability density functions of any physically possible shape and width, can handle varying degrees of correlation (both in time and between source categories) and can deal with more complex models (e.g. the 1st order decay for CH_4 from landfills) as well as simple 'emission factor times activity data' calculations.

Eggleston *et al*. (1998) provide an example of Monte Carlo analysis, applied to a national greenhouse gas inventory and used to estimate uncertainties both in overall emissions and emissions trends. Another example of the use of Monte Carlo analysis is given in McCann *et al*. (1994). A general description of the Monte Carlo method can be found in Fishman (1996).

Like all methods, Monte Carlo analysis only provides satisfactory results if it is properly implemented. This requires the analyst to have scientific and technical understanding of the inventory. Of course, the results will only be valid to the extent that the input data, including any expert judgements, are sound.

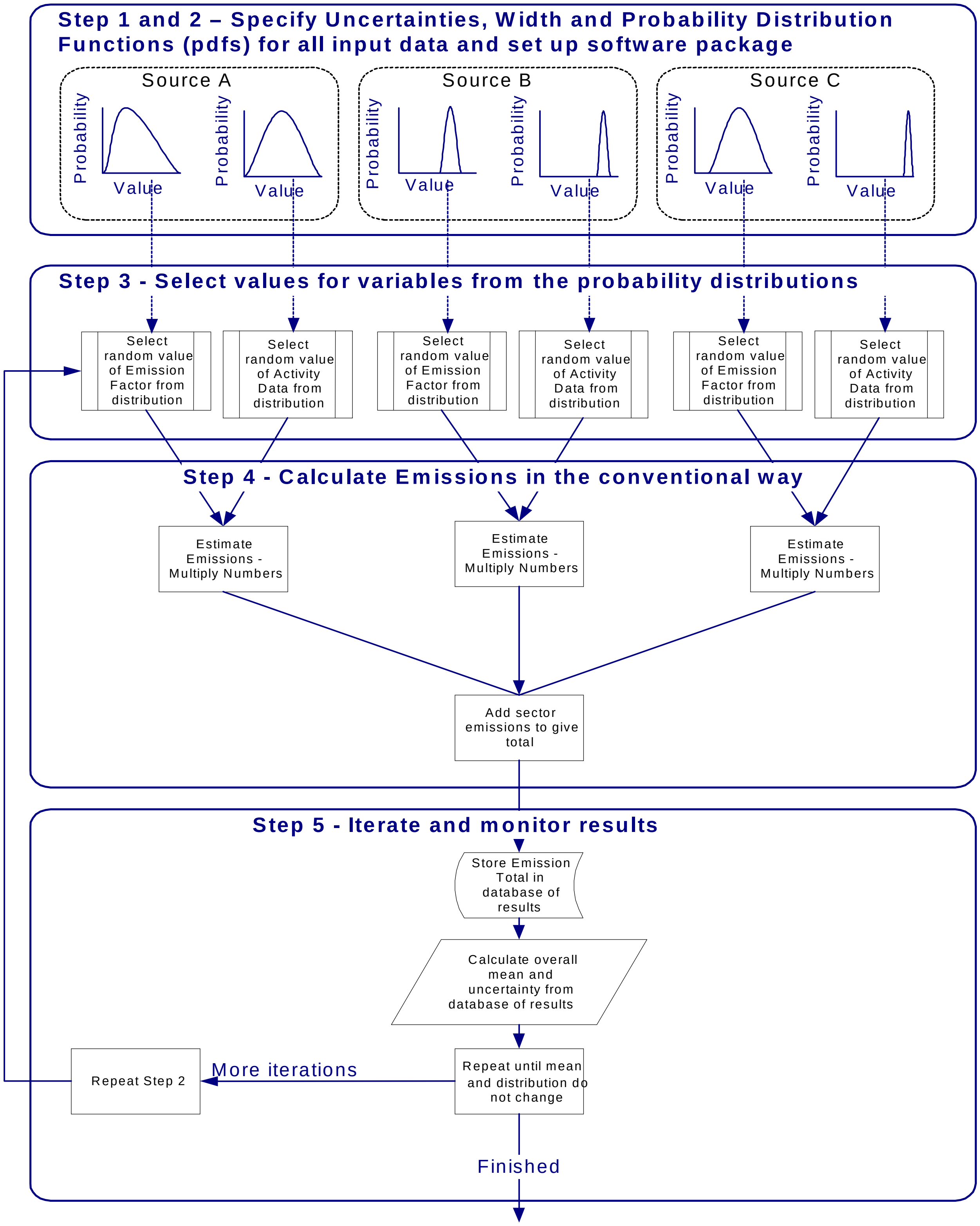
The Monte Carlo approach consists of five clearly defined steps shown in Figure 6.1. Only the first two of these require effort from the user, the remainder being handled by the software package. Section 6.5.3 contains a short discussion of various software packages.

- **Step 1 – Specify source category uncertainties.** Specify the uncertainties in the basic data. This includes emission factors and activity data, their associated means and probability distribution functions, and any cross correlation between source categories. Take account of the information in Sections 6.2.1 to 6.2.5.
- **Step 2 – Set up software package.** The emission inventory calculation, the probability density functions and the correlation values should be set up in the Monte Carlo package.

The software automatically performs the subsequent steps.

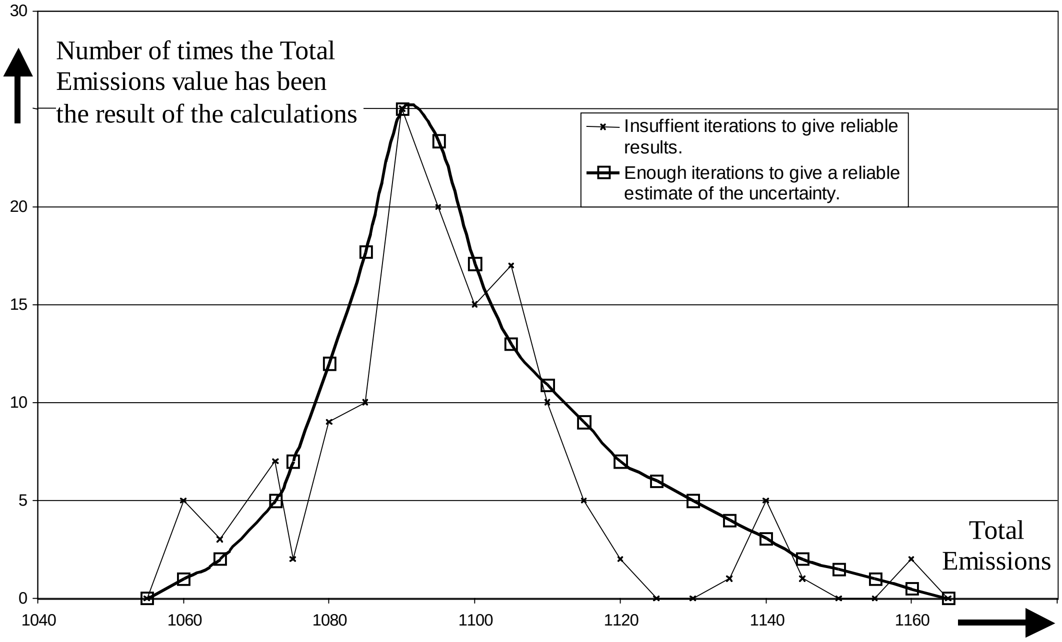
- **Step 3 – Select random variables.** This is the start of the iterations. For each input data item, emission factor or activity data, a number is randomly selected from the probability density function of that variable.
- **Step 4 – Estimate emissions.** The variables selected in Step 3 are used to estimate total emissions. The example given in Figure 6.1 assumes three source categories, each estimated as activity multiplied by an emission factor, and then summed to give total emissions. The calculations can be more complex. Emissions by gas can be multiplied by GWP values, in order to obtain total national emissions in CO_2 equivalent. Correlations of 100% are easy to incorporate, and good Monte Carlo packages allow other correlations to be included. Since the emission calculations should be the same as those used to estimate the national inventory, the Monte Carlo process could be fully integrated into the annual emission estimates.
- **Step 5 – Iterate and monitor results.** The calculated total from step 4 is stored, and the process then repeats from step 3. The mean of the totals stored gives an estimate of the total emission. Their distribution gives an estimate of the probability density function of the result. As the process repeats, the mean approaches the final answer. When the mean no longer changes by more than a predefined amount, the calculation can be terminated. When the estimate for the 95% confidence range is determined to within ± 1%, then an adequately stable result has been found. Convergence can be checked by plotting a frequency plot of the estimates of the emission. This plot should be reasonably smooth (Figure 6.2, Example frequency plots of the results of a Monte Carlo simulation). These actions should be handled by the software, with the user specifying either a number of iterations or convergence criteria.

Figure 6.1 Illustration of Monte Carlo Method



This example assumes three emission source categories each where the emission is calculated as Activity Data • Emission Factor.

Figure 6.2 Example Frequency Plots of the Results of a Monte Carlo Simulation



6.4.1 Tier 2 uncertainties in trends

The Tier 2 Monte Carlo method can be used to estimate uncertainties in the trend as well as in the absolute emission value in a given year. The procedure is a simple extension of that described in the previous section.

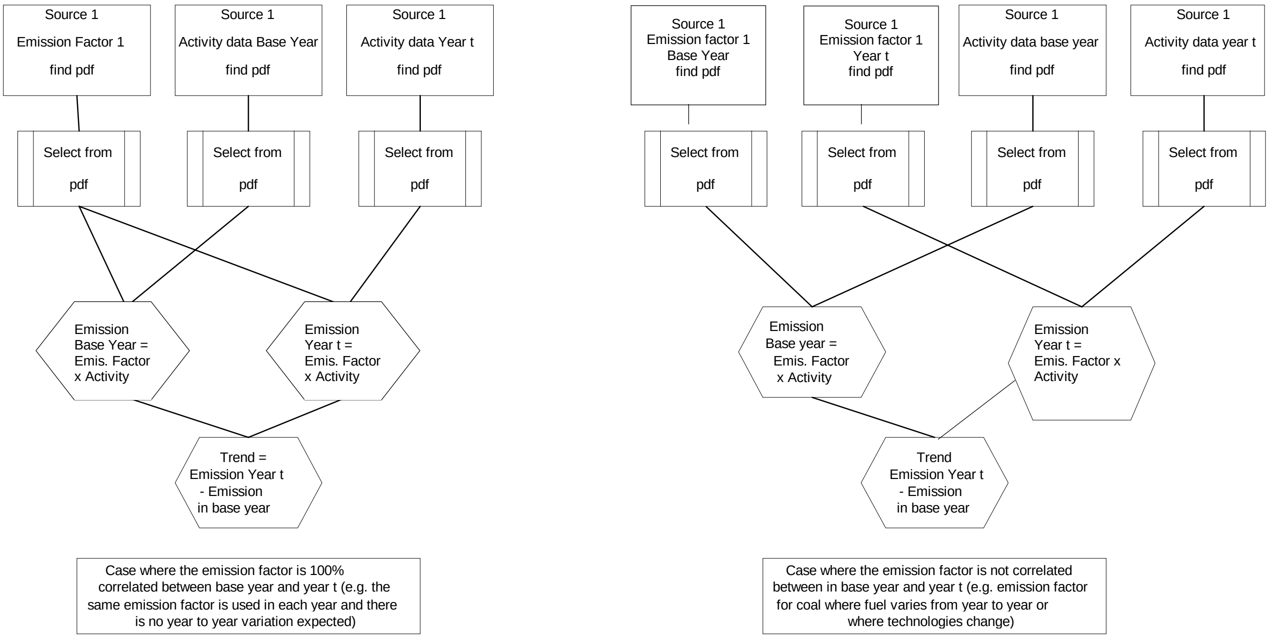
The trend is defined here as the difference between the base year and the year of interest (year t). Therefore, the Monte Carlo analysis needs to be set up to estimate both years simultaneously. The procedure is:

- **Step 1 – Specify source category uncertainties.** Determine the probability density functions for each emission factor and activity. This is the same process as described above except that it needs to be done for both the base year and the current year, and relationships between the data need to be considered. For many source categories, the same emission factor will be used for each year (i.e. the emission factors for both years are 100% correlated). In these cases, one distribution is described and the value selected from it is used for each year in step 3. Changes in the technologies or practices will alter the emission factor over time. In this case, two emission factors should be used, that have a lower or zero correlation. If the emission factors contain a random element or vary unpredictably from year to year, then separate emission factors should also be used (e.g. with fossil fuel carbon content that can change according to the market supply of the fuel and also contains its own uncertainty). Generally, activity rates are assumed to be uncorrelated between years, and so two distributions should be input, even if their parameters are the same, so that two different random selections from these distributions will be generated in step 3. The computer package used may well enable other correlations to be set up and these capabilities could be used if sufficient information is available. However, this will probably be necessary in only a few cases.
- **Step 2 – Set up software package.** The software package should be set up as previously described, except that the probability distribution functions will need to capture the relationship between emissions in two years, and for trend calculations there need to be two separate but simultaneous calculations of the emissions in the base year and year t. In cases where the input data is assumed to be 100% correlated (mainly some emission factors) care needs to be taken that the same random number selected from the probability distribution function is used in estimating both years. A final calculation is then needed to find the difference between the two years.

Subsequent steps are, in most cases, performed automatically by the software package.

- **Step 3 – Select random variables**. The computer program will proceed as previously described, taking account of any correlation between probability density functions (PDF). Figure 6.3, below, shows the calculation scheme for trend analysis
- **Step 4 – Estimate Emissions.** As in the previous description, the variables selected in Step 3 will be used to estimate the total emissions.
- **Step 5 – Results.** The emissions total calculated in step 4 is stored in a data file. The process then repeats from step 3 until there is adequate convergence of the results. Considerations for this are the same as described above. A range of results is estimated at the same time including total and sectoral emissions for the base year, total and sectoral emissions for year *t*, and the differences (trends) between these for the total and any sectors of interest.

Figure 6.3 Calculation Scheme for Monte Carlo Analysis of the Absolute Emissions and the Trend of a Single Source Category, Estimated as Emission Factor Times an Activity Rate



6.4.2 Reporting Tier 2 uncertainty analysis

The following data format is suitable for reporting the results of the Monte Carlo simulation for emissions by source category, by fuel (where appropriate) and by greenhouse gas expressed as CO_2 equivalent. In Table 6.2, the overall uncertainty in the national emissions trend appears at the foot of columns I and J. Inventory agencies performing a Tier 2 analysis should also report the results of a Tier 1 analysis using Table 6.1, as set out in Section 6.3.1, Comparison between tiers and choice of method.

TABLE 6.2

TIER 2 UNCERTAINTY REPORTING

A	B	C	D	E	F	G	H	I	J
IPCC Source category	Gas	Base year emissions	Year t emissions	Uncertainty in year t emissions as % of emissions in the category		Uncertainty introduced on national total in year t	% change in emissions between year t and base year	Range of likely % change between year t and base year	
		(Gg CO_2 equivalent)	(Gg CO_2 equivalent)	% below (2.5 percentile)	% above (97.5 percentile)	(%)	(%)	Lower % (2.5 percentile)	Upper % (97.5 percentile)
e.g. 1.A.1 Energy Industries Fuel 1	CO_2								
e.g. 1.A.2 Energy Industries Fuel 2	CO_2								
Etc…	…								
Total						▨			

6.5 PRACTICAL CONSIDERATIONS IN USING MONTE CARLO SIMULATION

Monte Carlo simulation requires that the analyst specify probability distributions for each model input for which the uncertainty is to be quantified. The assumption is that the simulation is a reasonable representation of the real world. The probability distributions may be obtained by a variety of methods, including statistical analysis of data, or the elicitation of expert judgement. A key consideration is to develop the distributions for the inputs so that they are all based upon the same underlying assumptions regarding averaging time, location, and other conditioning factors relevant to the particular assessment (e.g. climatological conditions influencing agricultural greenhouse gas emissions). For this reason, one should not assume that an uncertainty distribution from another country is directly applicable as an input to an inventory.

6.5.1 Specifying probability distributions for inventory inputs

Monte Carlo simulation requires identification of the model inputs for which probability distributions are to be assigned, and development of the corresponding probability distributions. Methods for developing distributions based upon elicitation of expert judgement have already been reviewed in this chapter. Methods for developing distributions based upon statistical analysis of data are described and illustrated by Cullen and Frey (1999). Other useful references include Hahn and Shapiro (1967), Ang and Tang (1975), D'Agostino and Stephens (1986), Morgan and Henrion (1990), and USEPA (1996, 1997, 1999). Some examples of probabilistic analyses applied to emission inventories are given by Frey *et al.* (1998) and Frey *et al.* (1999).

In order to use data as a basis for developing distributions, the first critical step is to determine if the data are a random, representative sample, in the case of a sample from a population. Some key questions to ask regarding the data include:

- Are the data representative of the variety of conditions pertaining to the emission or activity factors specific to national circumstances?
- Are the data a random sample?
- What is the averaging time associated with the data set, and is it the same as for the assessment (which will be for annual emissions in a given year)?

If the data are a random, representative sample, then the distribution can be established directly using classical statistical techniques, even if the sample size is small. It may be necessary to convert data using an appropriate averaging time. General advice on choosing probability density functions is provided in Annex 1, Conceptual Basis for Uncertainty Analysis, Section 2.5, Good Practice Guidance for Selecting a Probability Density Function.

In the ideal case, available data will represent an annual average for an emission factor or an annual total for activity data. In this case, the data would represent a single sample from a population distribution of annual average values. The estimated standard deviation of the population would be an appropriate measure of uncertainty in annual emissions. In other cases, the data may represent an exhaustive census of the sum of all activity (e.g. total energy use for a particular fuel). In this case, information regarding errors in the measurements or survey instruments would form a basis for assessing uncertainty. The range of uncertainty of activity data might be bounded using independent methods or consistency checks. For example, fuel consumption data can be compared with estimates of production, including estimates of production via different methods.

In the case of a population sample, the most critical aspect to evaluate is whether the data are random and representative of the population. If these conditions are met, classical statistical methods can be used to define the distribution. If not, then some combination of data analysis and expert elicitation of distributions will be required. In the former case, Cullen and Frey (1999) suggest exploration of the data set using summary statistics and graphics to evaluate essential features (e.g. central tendency, range of variation, skewness). The insights obtained by examining the data, combined with knowledge of the processes that generated the data, should be considered when selecting a mathematical or numerical representation of the distribution for input into the Monte Carlo simulation.

Once a particular distribution is selected as a candidate for fitting to the data set, techniques such as 'maximum likelihood estimation[5]' or the 'method of matching moments[6]' can be used to estimate the parameters of the distribution. The goodness-of-fit of the distribution can be evaluated in numerous ways, including comparison of the fitted cumulative distribution function (CDF) with the original data set, probability plots, and goodness-of-fit tests (e.g. Cullen and Frey, 1999). It is important that the selection of a parametric distribution to represent a data set should be based not solely upon goodness-of-fit tests, but upon similarities in processes that generated the data versus the theoretical basis for a distribution (e.g. Hahn and Shapiro, 1967).

If the data are averaged over less than one year, it may be necessary to extrapolate the uncertainty over the year. Consider an example in which the data set represents variability in daily average emissions measurements for a particular source category. One approach, described in detail by Frey and Rhodes (1996), is to fit a parametric distribution to the data set for daily variability, use a numerical technique known as bootstrap simulation to estimate uncertainty in the parameters of the distribution, and use Monte Carlo simulation to simulate randomised annual averages of the emission factor. Using bootstrap simulation, the uncertainty in the sampling distribution for the parameters for the fitted distribution can be simulated (e.g. Efron and Tibshirani, 1993; Frey and Rhodes, 1996; Frey and Burmaster, 1999).

A simple form of bootstrap simulation works as follows: from the fitted distribution, a random synthetic data set of the same sample size as the original dataset is simulated using Monte Carlo simulation. The synthetic data set is referred to as a *bootstrap sample*. For the bootstrap sample, any statistic or parameter can be calculated, such as a mean or parameters of a new distribution fitted to the synthetic data set. A statistic or parameter estimated from a bootstrap sample is referred to as a *bootstrap replicate* of that statistic or parameter. This process is then repeated many times (typically 500 to 1,000), generating a corresponding number of bootstrap samples and duplicated statistics. The statistics will take on different values each time because the bootstrap samples are randomised versions patterned after the original data set. Thus, this method is a numerical technique for estimating sampling distributions for any statistic for any type of distribution for which the statistic exists. In essence, bootstrap simulation is a numerical technique for simulating random sampling error. The 500 to 1,000 bootstrap samples imply a corresponding number of alternative plausible distributions from which the original data set could have been a random sample. For these alternative distributions, each of which reflects daily variability in the example, one can simulate a year's worth of emissions estimates (i.e. 365 random samples of daily emissions summed to give an annual total or averaged to give an annual average emission factor), thereby yielding 500 to 1,000 estimates of annual mean or annual total emissions. The distribution of these estimates will describe uncertainty in the annual case based upon random sampling error. A key assumption in this example is that there is no autocorrelation among the daily values, and that the daily values are representative of annual conditions – that there are for example no seasonal effects that the sample fails to capture.

6.5.2 How much effort is needed to characterise uncertainty in an inventory input?

Ideally, the amount of effort devoted to characterising uncertainty in an inventory input should be proportional to its importance to the overall uncertainty assessment. It would not be a good use of limited resources to spend large amounts of time exhaustively collecting data and expert judgements for a source category that has little effect on overall uncertainty. Similarly, it would be a shortcoming of an assessment not to devote reasonable resources to quantifying uncertainty in inputs to which the overall uncertainty in the inventory is highly sensitive. Thus, many analysts who perform probabilistic simulation suggest an iterative approach to performing the simulation. In the first iteration of an uncertainty analysis, preliminary assessments of uncertainty of inputs may be made and propagated through the inventory solely for the purpose of making a preliminary identification of what the main sources of uncertainty are. Methods for assessing the importance of each input are described in references such as Morgan and Henrion (1990), Frey and Cullen (1999), and others. An example of one relatively simple technique is to calculate the correlation coefficient between the simulated numerical values of the inventory output distribution and the numerical values simulated for each input distribution. This correlation reflects the strength of the linear relationship between the two. The larger the magnitude of the correlation

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[5] The method of maximum likelihood selects as estimates the values of the parameters that maximise the likelihood (the joint probability function or joint density function) of the observed sample.

[6] The method of moments finds estimators of unknown parameters by equating corresponding sample and population moments. The method is easy to employ and provides consistent estimators. In many cases the method of moments estimators are biased (Wackerly, Mendenhall III and Scheaffer, 1996; pp. 395-397).

coefficient, the stronger is the relationship between uncertainty in the input and uncertainty in the output, indicating that the input should be considered as a 'sensitive' one. Many software packages will perform the sensitivity calculation automatically for the user and present them graphically.

After identifying the sensitive inputs, efforts can then be directed as appropriate to improve the estimate of uncertainty for only those inputs. Then, the final uncertainty analysis can be performed with greater confidence on the basis that important inputs have received proportionally greater attention than insensitive inputs.

Another point regarding iteration pertains to the longer-term aspects of performing uncertainty analyses. It can be daunting to set up a Monte Carlo simulation for the first time. However, as the inventory agency gains experience with these analyses, the agency will likely find it easier to improve the analysis in the future. Monte Carlo analysis is typically a learning process for all involved, because it motivates critical and important questions regarding the basis for and quality of an emission inventory. Thus, over time, Monte Carlo simulation will help in deciding where to focus data collection activities that will result in improved confidence regarding the inventory.

6.5.3 Choosing a simulation technique and a simulation sample size

There are several commercially available software tools that can be used to perform Monte Carlo simulation. Examples of these include Crystal Ball, @Risk, Analytica, and Mathematica. The first two are add-ins for commonly used spreadsheet programs. Many software tools offer an option of different sampling methods, including random Monte Carlo simulation and variations of Latin Hypercube Sampling (LHS). LHS can produce 'smoother' looking model output distributions for sample sizes of only a few hundred samples. The disadvantage of using LHS is that one must decide ahead of time how many iterations to use. This is because two or more LHS simulations cannot be combined since they will use overlapping strata, leading to difficulties in interpreting results. In some cases, LHS can yield underestimates of the higher moments of probability distributions, since the stratification method also can preclude clustering of very high or low values as can occur in random data sets. The overall suggestion is to use random Monte Carlo simulation as the default method, because it will give flexibility to continue a random simulation to larger and larger simulation sample sizes if necessary until the model output distribution converges. Cullen and Frey (1999) provide more information on the comparison of LHS and Monte Carlo simulation (pp. 207-213).

6.5.4 Dependence and correlation among inventory inputs

A key issue often considered by analysts when setting up a probabilistic analysis is whether there are dependencies or correlations among model inputs. Ideally, it is preferable to define the model so that the inputs are as statistically independent of each other as possible. Rather than to try to estimate activity data for many sub-categories for which data are derived at least in part by differences, it may be better to assign uncertainties to better known aggregate measures of activity. For example, residential fuel use might be estimated as the difference between total consumption and usage in the transportation, industrial, and commercial sectors. In this case, the estimate of uncertainty in residential fuel use is negatively correlated with the uncertainties in fuel use in the other sub-categories, and may even be very large compared to the uncertainty in total consumption. Thus, rather than try to estimate uncertainties separately for each sub-category, it would be more practical to estimate uncertainty for total consumption, for which good estimates and cross-checks may be available.

6.5.5 Does correlation matter?

An important point to remember is that dependencies, even if they exist, may not be important to the assessment of uncertainties. Dependencies among inputs will matter only if the dependencies exist between two inputs to which the uncertainty in the inventory is sensitive and if the dependencies are sufficiently strong. In contrast, weak dependencies among inputs, or strong dependencies among inputs to which the uncertainty in the inventory is insensitive, will be of relatively little consequence to the analysis.

6.5.6 Some methods for dealing with dependencies or correlation

When dependencies among inputs are judged to be of importance, then a variety of techniques can be considered for incorporating them into the analysis. Examples include: (i) modelling the dependence explicitly; (ii) stratifying or aggregating the source categories to minimise the effect of the dependencies; (iii) simulating correlation using restricted pairing methods (that are included in many software packages); (iv) use of resampling techniques in cases where multivariate datasets are available; (v) considering bounding or sensitivity cases (e.g. one case assuming independence and another case assuming complete positive correlation). More discussion and examples of these types of methods are given in Cullen and Frey (1999), Morgan and Henrion (1990), and USEPA (1996). These documents also contain reference lists with citations to relevant literature.

6.5.7 Specifying correlation in inventory inputs

Many software packages allow specification of a correlation between model inputs (e.g. Iman and Conover, 1982). In some cases, these packages may offer this feature only with LHS, while in others it may be available also in conjunction with random Monte Carlo simulation. There is a detail regarding these methods that advanced users will want to note, which is that these software tools can induce a rank correlation between any two or more distributions, but not a sample correlation. However, there are methods that one can use to specify sample correlation in some types of distributions, such as for multivariate normal distributions (see Morgan and Henrion, 1990 or Cullen and Frey, 1999 for examples).

6.5.8 Analysing inventory outputs

Many software packages allow the user to display probability density functions (PDF), cumulative distribution functions (CDF) and provide output of summary statistics for a given model input. Typically, the CDF will appear to be a smoother curve than the PDF for any given case. Furthermore, the CDF allows for quantitative interpretations of the median, 95 percent confidence interval, or any other percentile of the distribution. Thus, for practical purposes, the CDF is often the most useful representation of the model output. The PDF is useful for obtaining qualitative insights regarding the output, such as whether it is positively skewed.

6.5.9 Encouragement of use of appropriate techniques

The guidance offered here is not meant to preclude the use of improved methods as they become available. Furthermore, this document does not cover all situations that may be faced by an analyst. Therefore, the inventory agency is encouraged to refer to the references cited below for additional suggestions on how to perform uncertainty analyses.

6.6 CONCLUSION

The methods described in this chapter should enable inventory agencies to estimate and report the uncertainty in total emissions in any year, and the uncertainty in the trend between years, together with the contribution that each source category makes to these overall uncertainties. This information should help prioritise efforts to improve the precision of inventories in future, and can show how the overall and trend uncertainties respond as the uncertainties in individual source categories are reduced.

APPENDIX 6A.1

DERIVATION OF THE FORMULAE IN TABLE 6.1 (TIER 1)

EXPLANATION OF THE VARIABLES

C_x = Value of an entry in column C and row x

n = number of emission categories (rows)

$\sum C_i$ = Sum over all emissions categories (rows) of the inventory from i=1 to i=n

COLUMN A-F

Input data

COLUMN G

Combined uncertainty using error propagation equation

$$G_x = \sqrt{{E_x}^2 + {F_x}^2}$$

COLUMN H

Combined uncertainty as a percentage of the total emissions in year t.

$$H_x = \frac{G_x \bullet D_x}{\sum D_i}$$

The total in column H (total emission uncertainty) is obtained using the error propagation equation:

$$\text{Total of column H} = \frac{\sqrt{\sum_x \left[\left(\sum_x D_x \right)^2 \bullet (H_x)^2 \right]}}{\sum_x D_x} = \sqrt{\sum_x {H_x}^2}$$

COLUMN I

Entries in column I show how the difference in emissions between the base year and the year t changes in response to a 1% increase in emissions of source category *x* emissions in the base year and year t. This shows the sensitivity of the trend in emissions to a systematic uncertainty in the emission estimate – i.e. one that is correlated between the base year and year t. This sensitivity is described as type A sensitivity.

I_x = percentage trend if source category x is increased by 1% in both years – percentage trend without increase

$$= \frac{0.01 \bullet D_x + \sum D_i - (0.01 \bullet C_x + \sum C_i)}{(0.01 \bullet C_x + \sum C_i)} \bullet 100 - \frac{\sum D_i - \sum C_i}{\sum C_i} \bullet 100$$

COLUMN J

Entries in column J show how the difference in emissions between the base year and year t changes in response to a 1% increase in the emissions of source category *x* in year t only. This shows the sensitivity of the trend in emissions to random uncertainty error in the emissions estimate – i.e. one that is not correlated between the base year and year Y. This sensitivity is described as type B sensitivity.

J_x = percentage trend if source category x is increased by 1% in year t – percentage trend without increase

$$= \frac{0.01 \bullet D_x + \sum D_i - \sum C_i}{\sum C_i} \bullet 100 - \frac{\sum D_i - \sum C_i}{\sum C_i} \bullet 100$$

$$= \frac{D_x}{\sum C_i}$$

COLUMN K

Under the assumption that the same emission factor is used in both years and the actual emission factors are fully correlated, the % error introduced by it is equal in both years. Therefore the formula for the uncertainty introduced on the trend by the emission factor is:

$$K_x = \text{sensitivity A} \bullet \text{uncertainty of emission factor}$$
$$= I_x \bullet F_x$$

In case no correlation between emission factors is assumed, sensitivity B should be used and the result needs to be increased by √2 for the reason given below in the main derivation for column L:

$$K_x = \text{sensitivity B} \bullet \text{uncertainty of emission factor} \bullet \sqrt{2}$$
$$= J_x \bullet F_x \bullet \sqrt{2}$$

COLUMN L

The trend is the difference between the emissions in the base year and in the year t. Therefore the uncertainty of the activity data of the base year and t has to be taken into account. The two uncertainties combined using the error propagation equation and the assumption that the uncertainty is the same in the base year and year t is:

$$= \sqrt{(\text{uncertainty (activity data, base year)})^2 + (\text{uncertainty (activity data, year t)})^2}$$
$$\approx \sqrt{(\text{uncertainty (activity data, year t)})^2 \bullet 2}$$
$$= E_x \bullet \sqrt{2}$$

Since activity data in both years are assumed to be independent, column L equals:

L_x = sensitivity B • combined uncertainty of activity data of both years

$$= J_x \bullet E_x \bullet \sqrt{2}$$

In case correlation between activity data is assumed, sensitivity A should be used and the √2 factor does not apply.

$$L_x = I_x \bullet E_x$$

COLUMN M

In column M figures the combined uncertainty introduced on the trend by the uncertainty in the activity data and the emissions factor.

$$M_x = \sqrt{K_x{}^2 + L_x{}^2}$$

The entries M_i in column M are combined to obtain the total uncertainty of the trend using the error propagation equation as follows:

$$\text{Total of column M} = \frac{\sqrt{\sum_x \left[\left(\sum_x (D_x - C_x) \right)^2 \bullet (M_x)^2 \right]}}{\sum_x (D_x - C_x)} = \sqrt{M_1{}^2 + M_2{}^2 + ... + M_n{}^2}$$

APPENDIX 6A.2
TIER 1 UNCERTAINTY CALCULATION EXAMPLE

The following spreadsheet shows an example calculation for the national greenhouse gas inventory of the United Kingdom.

TABLE 6.3

TIER 1 UNCERTAINTY CALCULATION AND REPORTING EXAMPLE

	A	B	C	D	E	F	G	H	I	J	K	L	M
	IPCC Source Category	Gas	Base year emissions 1990	Year t emissions 1997	Activity data uncertainty	Emission factor uncertainty	Combined uncertainty	Combined uncertainty as % of total national emissions in year t	Type A sensitivity	Type B sensitivity	Uncertainty in trend in national emissions introduced by emission factor uncertainty	Uncertainty in trend in national emissions introduced by activity data uncertainty	Uncertainty introduced into the trend in total national emissions
			Gg CO2 equivalent	Gg CO2 equivalent	%	%	%	%	%	%	%	%	%
1A	Coal	CO2	238 218	142 266	1.2	6	6.1	1.2	-0.0966	0.1840	-0.58	0.31	0.66
1A	Oil	CO2	208 684	196 161	1	2	2.2	0.6	0.0076	0.2538	0.02	0.36	0.36
1A	Natural Gas	CO2	111 052	181 691	2	1	2.2	0.6	0.1039	0.2351	0.10	0.66	0.67
1A	Other (waste)	CO2	138	741	7	20	21.2	0.0	0.0008	0.0010	0.02	0.01	0.02
1B	Solid Fuel Transformation	CO2	2 573	1 566	1.2	6	6.1	0.0	-0.0010	0.0020	-0.01	0.00	0.01
1B	Oil & Natural Gas	CO2	8 908	6 265		14	14.0	0.1	-0.0024	0.0081	-0.03	0.00	0.03
2A1	Cement Production	CO2	6 693	6 157	1	2	2.2	0.0	0.0001	0.0080	0.00	0.01	0.01
2A2	Lime Production	CO2	1 192	1 703	1	5	5.1	0.0	0.0008	0.0022	0.00	0.00	0.01
2A3	Limestone & Dolomite use	CO2	1 369	1 551	1	5	5.1	0.0	0.0004	0.0020	0.00	0.00	0.00
2A4	Soda Ash Use	CO2	116	120	15	2	15.1	0.0	0.0000	0.0002	0.00	0.00	0.00
2B	Ammonia Production	CO2	1 358	814		5	5.0	0.0	-0.0005	0.0011	0.00	0.00	0.00
2C1	Iron&Steel Production	CO2	3 210	1 495	1.2	6	6.1	0.0	-0.0019	0.0019	-0.01	0.00	0.01
5D	Land Use Change & Forestry	CO2	31 965	27 075	5	54	54.2	2.1	-0.0027	0.0350	-0.14	0.25	0.29
6C	MSW Incineration	CO2	660	29	7	20	21.2	0.0	-0.0007	0.0000	-0.01	0.00	0.01
		CO2 Total	616 137	567 634									
1A	All Fuel	CH4	2 507	1 975	1.2	50	50.0	0.1	-0.0004	0.0026	-0.02	0.00	0.02
1B1	Coal Mining	CH4	17 188	6 687	1	13	13.0	0.1	-0.0116	0.0087	-0.15	0.01	0.15
	Solid Fuel Transformation	CH4	215	173	6	50	50.4	0.0	0.0000	0.0002	0.00	0.00	0.00
1B2	Natural Gas Transmission	CH4	8 103	7 301	2	15	15.1	0.2	-0.0001	0.0094	0.00	0.03	0.03
	Offshore Oil& Gas	CH4	2 402	1 957	10	26	27.9	0.1	-0.0003	0.0025	-0.01	0.04	0.04
2C	Iron & Steel Production	CH4	16	13	1.2	50	50.0	0.0	0.0000	0.0000	0.00	0.00	0.00
4A	Enteric Fermentation	CH4	19 177	18 752	1	20	20.0	0.5	0.0016	0.0243	0.03	0.03	0.05
4B	Manure Management	CH4	2 338	2 325	1	30	30.0	0.1	0.0003	0.0030	0.01	0.00	0.01
4F	Field Burning	CH4	266	0	25	50	55.9	0.0	-0.0003	0.0000	-0.02	0.00	0.02
6A	Solid Waste Disposal	CH4	23 457	17 346	15	46	48.4	1.2	-0.0052	0.0224	-0.24	0.48	0.53
6B	Wastewater Handling	CH4	701	726	15	48	50.3	0.1	0.0001	0.0009	0.01	0.02	0.02
6C	Waste Incineration	CH4	1	1	7	50	50.5	0.0	0.0000	0.0000	0.00	0.00	0.00
		CH4 total	76 371	57 257									

TABLE 6.3

TIER 1 UNCERTAINTY CALCULATION AND REPORTING EXAMPLE

	A	B	C	D	E	F	G	H	I	J	K	L	M
	IPCC Source Category	Gas	Base year emissions 1990	Year t emissions 1997	Activity data uncertainty	Emission factor uncertainty	Combined uncertainty	Combined uncertainty as % of total national emissions in year t	Type A sensitivity	Type B sensitivity	Uncertainty in trend in national emissions introduced by emission factor uncertainty	Uncertainty in trend in national emissions introduced by activity data uncertainty	Uncertainty introduced into the trend in total national emissions
			Gg CO2 equivalent	Gg CO2 equivalent	%	%	%	%	%	%	%	%	%
1A2& 1A4& 1A5	Other Combustion	N2O	3 865	3 562	1.2	195	195.0	1.0	0.0001	0.0046	0.01	0.01	0.01
1A3	Transport	N2O	1 300	3 645	1.4	170	170.0	0.9	0.0032	0.0047	0.54	0.01	0.54
1B2	Oil & Natural Gas	N2O	3	2	10	110	110.5	0.0	0.0000	0.0000	0.00	0.00	0.00
2B	Adipic Acid Production	N2O	25 136	17 766	0.5	15	15.0	0.4	-0.0067	0.0230	-0.10	0.02	0.10
2B	Nitric Acid Production	N2O	4 383	3 723	10	230	230.2	1.2	-0.0004	0.0048	-0.08	0.07	0.11
4B	Manure Management	N2O	1 583	1 559	1	509[a]	509.0	1.1	0.0002	0.0020	0.08	0.00	0.08
4D	Agricultural Soils	N2O	29 472	29 098	1	509	509.0	21.0	0.0029	0.0376	1.47	0.05	1.47
4F	Field Burning	N2O	78	0	10	230	230.2	0.0	-0.0001	0.0000	-0.02	0.00	0.02
6B	Wastewater Handling	N2O	153	157	1	100	100.0	0.0	0.0000	0.0002	0.00	0.00	0.00
6C	Waste Incineration	N2O	115	11	7	230	230.1	0.0	-0.0001	0.0000	-0.03	0.00	0.03
		N2O Total	66 089	59 525									
2	Industrial Processes	HFC	11 374	18 447	2	25	25.1	0.7	0.0104	0.0239	0.26	0.07	0.27
3	Industrial Processes	PFC	2 281	661	5	19	19.6	0.0	-0.0018	0.0009	-0.03	0.01	0.04
4	Industrial Processes	SF6	724	1 170	10	8	12.8	0.0	0.0007	0.0015	0.01	0.02	0.02
		Halocarbon & SF6 Total											
	Total Emissions	GWP weighted total	772 976	704 693									
	Total Uncertainties				Overall uncertainty in the year (%)			21.3			Trend uncertainty (%)		2.0

[a] Uncertainty estimated from lognormal distribution used in Monte Carlo simulation. I.e. (97.5 percentile-mean)/mean *100.

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7

METHODOLOGICAL CHOICE AND RECALCULATION

CO-CHAIRS, EDITORS AND EXPERTS

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AUTHORS OF BACKGROUND PAPERS

Kristin Rypdal (Norway), Ketil Flugsrud (Norway), and William Irving (USA)

CONTRIBUTORS

Roberto Acosta (UNFCCC Secretariat), William Ageymang-Bonsu (Ghana), Simon Bentley (Australia), Marcelo Fernandez (Chile), Pavel Fott (Czech Republic), Jorge Gasca (Mexico), Anke Herold (Germany), Taka Hiraishi (Japan), Robert Hoppaus (IPCC-NGGIP/TSU), William Irving (USA), Natalja Kohv (Estonia), Nils Lindth (Sweden), Thomas Martinsen (IPCC/OECD), Pauline McNamara (Switzerland), Alexander Nakhutin (Russian Federation), Buruhani Nyenzi (Tanzania), Riitta Pipatti (Finland), Kristin Rypdal (Norway), and Geoff Salway (UK)

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7.1 INTRODUCTION

This chapter addresses two cross-cutting issues in inventory preparation: (i) how to identify *key source categories* in the national inventory, and (ii) how to systematically manage methodological change over time and ensure that trends in national emissions are consistently estimated.

Methodological choice for individual source categories is important in managing overall inventory uncertainty. Generally, inventory uncertainty is lower when emissions are estimated using the most rigorous methods, but due to finite resources, this may not be feasible for every source category. It is *good practice* to identify those source categories that have the greatest contribution to overall inventory uncertainty in order to make the most efficient use of available resources. By identifying these *key source categories* in the national inventory, inventory agencies can prioritise their efforts and improve their overall estimates. Such a process will lead to improved inventory quality, as well as greater confidence in the emissions estimates that are developed. It is *good practice* for each inventory agency to identify its national *key source categories* in a systematic and objective manner.

A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both.

Any inventory agency that has prepared an emissions inventory will be able to identify *key source categories* in terms of their contribution to the absolute level of national emissions. For those inventory agencies that have prepared a time series, the quantitative determination of *key source categories* should include evaluation of both the absolute level and the trend in emissions. Evaluating only the influence of a source category on the overall level of emissions provides limited information about why the source category is key. Some *key source categories* may not be identified if the influence of their trend is not taken into account.

The quantitative approaches to determine *key source categories* are described in Section 7.2.1, Quantitative Approaches to Identify Key Source Categories. Both a basic Tier 1 approach and a Tier 2 approach, which accounts for uncertainty, are described. In addition to making a quantitative determination of *key source categories*, it is *good practice* to consider qualitative criteria. These qualitative criteria include high uncertainty, mitigation, significant anticipated changes in future emission levels, and significant differences between the estimate and what would be expected using an IPCC default method or factor. The application of these criteria is described in more detail in Section 7.2.2, Qualitative Approaches to Identify Key Source Categories. The ways in which *key source categories* are to be managed within the inventory are also described along with references to other relevant sections of this report.

Inventory agencies will, from time to time, have good reason to change or refine the methods used to estimate emissions from particular source categories. Such changes may be made, for example, in order to improve the estimates of *key source categories*. These changes must be accompanied by a recalculation of previously prepared estimates in order to ensure that the reported emission trend is reliable. As far as possible, the time series should be recalculated using the same method in all years. In some cases, however, the same data sources for all years will not be available. Guidance on how to recalculate emissions to ensure consistency in the trend in situations where the same method cannot be used in every year is described in Section 7.3, Recalculations.

7.2 DETERMINING NATIONAL KEY SOURCE CATEGORIES

In each country's national inventory, certain source categories are particularly significant in terms of their contribution to the overall uncertainty of the inventory. It is important to identify these *key source categories* so that the resources available for inventory preparation may be prioritised and the best possible estimates prepared for the most significant source categories.

The results of the *key source category* determination will be most useful if the analysis is done at the appropriate level of detail.

Table 7.1, Suggested IPCC Source Categories, lists the source categories that should be analysed, and identifies special considerations related to the analysis, where relevant. For example, the combustion of fossil fuels is a large emission source category that can be broken down into sub-source categories, and even to the level of individual plants or boilers. The following guidance describes *good practice* in determining the appropriate level of analysis to identify *key source categories*:

- The analysis should be performed at the level of IPCC source categories (i.e. at the level at which the IPCC methods are described). The analysis should be performed using CO_2-equivalent emissions calculated using the global warming potentials (GWPs) specified in the *Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, Part I: UNFCCC reporting guidelines on annual inventories* (*UNFCCC Guidelines*).
- Each greenhouse gas emitted from a single source category should be considered separately, unless there are specific methodological reasons for treating gases collectively. For example, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are emitted from mobile sources. The *key source category* evaluation should be performed for each of these gases separately because the methods, emission factors and related uncertainties differ for each gas. In contrast, a collective evaluation of hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) may be appropriate for some source categories, such as emissions from substitutes for Ozone Depleting Substances (ODS substitutes).
- Source categories that use the same emission factors based on common assumptions should be aggregated before analysis. This approach can also help deal with cross-correlations between source categories in the uncertainty analysis, as explained in Chapter 6, Quantifying Uncertainties in Practice, Section 6.3.3, Tier1 Aggregation and Reporting. The same pattern of aggregation should be used both to quantify uncertainties and to identify *key source categories* unless the associated activity data uncertainties are very different.

Finally, for each *key source category*, the inventory agency should determine if certain sub-source categories are particularly significant (i.e. represent a significant share of the emissions). In the case of CH_4 emissions from enteric fermentation in domestic livestock, for example, emissions from particular species (e.g. cattle, buffalo or sheep) are likely to represent the major share of emissions. This also applies to industrial sources where a few larger plants account for most of the emissions of that source category. It may be appropriate to focus efforts towards methodological improvements on these most significant sub-source categories.

7.2.1 Quantitative approaches to identify key source categories

It is *good practice* for each inventory agency to identify its national *key source categories* in a systematic and objective manner, by performing a quantitative analysis of the relationships between the level and the trend of each source category's emissions and total national emissions.

The decision tree in Figure 7.1, Decision Tree to Identify Key Source Categories, illustrates how inventory agencies can determine which approach to use for the identification of *key source categories*. Any inventory agency that has developed an emissions inventory will be able to perform the Tier 1 Level Assessment and identify the source categories whose level has a significant effect on total national emissions. Those inventory agencies that have developed emissions inventories for more than one year will also be able to perform the Tier 1 Trend Assessment and identify sources that are key because of their contribution to the total trend of national emissions. Both assessments are described in Section 7.2.1.1, Tier 1 Method to Identify Key Source Categories.

TABLE 7.1
SUGGESTED IPCC SOURCE CATEGORIES [a,b]

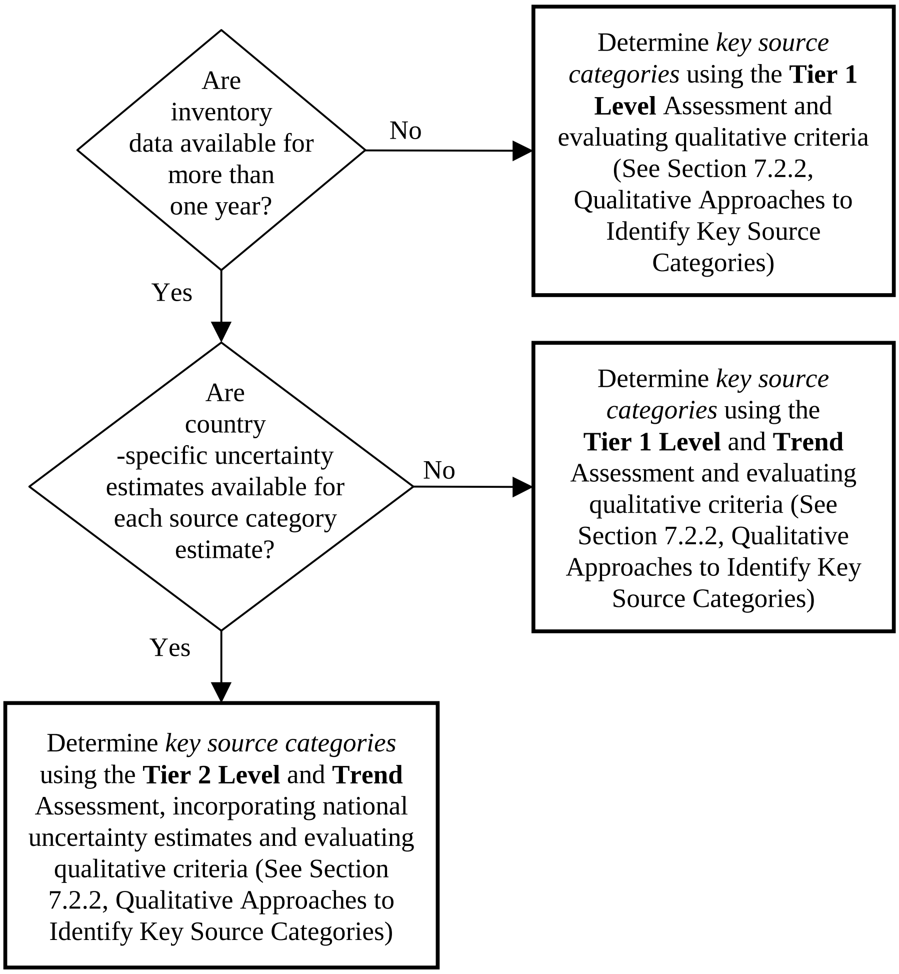
Source Categories to be Assessed in Key Source Category Analysis	Special Considerations
ENERGY	
CO_2 Emissions from Stationary Combustion	Disaggregate to the level where emission factors are distinguished. In most inventories, this will be the main fuel types. If emission factors are determined independently for some sub-source categories, these should be distinguished in the analysis.
Non-CO_2 Emissions from Stationary Combustion	Assess CH_4 and N_2O separately.
Mobile Combustion: Road Vehicles	Assess CO_2, CH_4 and N_2O separately.
Mobile Combustion: Water-borne Navigation	Assess CO_2, CH_4 and N_2O separately.
Mobile Combustion: Aircraft	Assess CO_2, CH_4 and N_2O separately.
Fugitive Emissions from Coal Mining and Handling	If this source is key, it is likely that underground mining will be the most significant sub-source category.
Fugitive Emissions from Oil and Gas Operations	This source category comprises several sub-source categories which may be significant. Inventory agencies should assess this source category, if it is key, to determine which sub-source categories are most important.
INDUSTRIAL PROCESSES	
CO_2 Emissions from Cement Production	
CO_2 Emissions from Lime Production	
CO_2 Emissions from the Iron and Steel Industry	
N_2O Emissions from Adipic Acid and Nitric Acid Production	Assess adipic acid and nitric acid separately.
PFC Emissions from Aluminium Production	
Sulfur hexafluoride (SF_6) from Magnesium Production	
SF_6 Emissions from Electrical Equipment	
SF_6 Emissions from Other Sources of SF_6	
SF_6 Emissions from Production of SF_6	
PFC, HFC, SF_6 Emissions from Semiconductor Manufacturing	Assess emissions from all compounds jointly on a GWP-weighted basis, since they are all used in similar fashions in the process.
Emissions from Substitutes for Ozone Depleting Substances (ODS Substitutes)	Assess emissions from all HFCs and PFCs used as substitutes for ODS jointly on a GWP-weighted basis, given the importance of having a consistent method for all ODS sources.
HFC-23 Emissions from HCFC-22 Manufacture	
AGRICULTURE	
CH_4 Emissions from Enteric Fermentation in Domestic Livestock	If this source category is key, it is likely that cattle, buffalo and sheep will be the most significant sub-source categories.
CH_4 Emissions from Manure Management	If this source category is key, it is likely that cattle and swine will be the most significant sub-source categories.
N_2O Emissions from Manure Management	
CH_4 and N_2O Emissions from Savanna Burning	Assess CH_4 and N_2O separately.
CH_4 and N_2O Emissions from Agricultural Residue Burning	Assess CH_4 and N_2O separately.
Direct N_2O Emissions from Agricultural Soils	
Indirect N_2O Emissions from Nitrogen Used in Agriculture	
CH_4 Emissions from Rice Production	
WASTE	
CH_4 Emissions from Solid Waste Disposal Sites	
Emissions from Wastewater Handling	Assess CH_4 and N_2O separately.
Emissions from Waste Incineration	Assess CO_2 and N_2O separately.
OTHER	Other sources of direct greenhouse gas emissions not listed above should also be included, if possible.

[a] The LUCF Sector is not included in this table. In principle, the methods described in this chapter to identify *key source categories* could be applied to LUCF, but further work on this topic is necessary.
[b] In some cases, inventory agencies may make some modification to this list of IPCC source categories to reflect particular national circumstances.

When using the Tier 1 approach, *key source categories* are identified using a pre-determined cumulative emissions threshold. The pre-determined threshold has been determined based on an evaluation of several inventories, and is aimed at establishing a general level where 90% of inventory uncertainty will be covered by *key source categories*. This evaluation is described in more detail in Section 7.2.1.1, Tier 1 Method to Identify Key Source Categories.

If nationally derived source-level uncertainties are available, inventory agencies can use Tier 2 to identify *key source categories*. The Tier 2 approach is a more detailed analysis that builds on the Tier 1 approach, and it is likely to reduce the number of *key source categories* that need to be considered. Under Tier 2, the results of the Tier 1 analysis are multiplied by the relative uncertainty of each source category. *Key source categories* are those that represent 90% of the uncertainty contribution, instead of applying the pre-determined cumulative emissions threshold. This approach is described in more detail in Section 7.2.1.2, Tier 2 Method to Identify Key Source Categories, Considering Uncertainties. If both the Tier 1 and the Tier 2 assessment have been performed, it is *good practice* to use the results of the Tier 2 analysis.

Figure 7.1 Decision Tree to Identify Key Source Categories



7.2.1.1 TIER 1 METHOD TO IDENTIFY KEY SOURCE CATEGORIES

The Tier 1 method to identify *key source categories* assesses the impacts of various source categories on the level and, if possible, the trend, of the national emissions inventory. When the national inventory estimates are available for several years, it is *good practice* to assess the contribution of each source category to both the level and trend of the national inventory. If only a single year's inventory is available, only a Level Assessment can be performed.

The Tier 1 method to identify *key source categories* can be readily completed using a spreadsheet analysis. Tables 7.2 and 7.3 illustrate the format of the analysis. Separate spreadsheets are suggested for the Level and

Trend Assessments because it is necessary to sort the results of the analysis according to two different columns, and the output of the sorting process is more difficult to track if the analyses are combined in the same table. Both tables use a format similar to that described in Chapter 6, Quantifying Uncertainties in Practice. In both tables, columns A through D are inputs of the national inventory data. Appendix 7A.1 illustrates the application of the Tier 1 approach to the US inventory.

LEVEL ASSESSMENT (TABLE 7.2)

The contribution of each source category to the total national inventory level is calculated according to Equation 7.1:

EQUATION 7.1

Source Category Level Assessment = Source Category Estimate / Total Estimate

$$L_{x,t} = E_{x,t} / E_t$$

Where:

$L_{x,t}$ is the Level Assessment for source x in year t

Source Category Estimate ($E_{x,t}$) is the emission estimate of source category x in year t

Total Estimate (E_t) is the total inventory estimate in year t

Table 7.2 presents a spreadsheet that can be used for the Level Assessment.

TABLE 7.2
SPREADSHEET FOR THE TIER 1 ANALYSIS – LEVEL ASSESSMENT

A IPCC Source Categories	**B** Direct Greenhouse Gas	**C** Base Year Estimate	**D** Current Year Estimate	**E** Level Assessment	**F** Cumulative Total of Column E
Total					

Where:

Column A: List of IPCC source categories (see Table 7.1, Suggested IPCC Source Categories)

Column B: Direct greenhouse gas

Column C: Base year emissions estimates from the national inventory data, in CO_2-equivalent units

Column D: Current year emissions estimates from the most recent national inventory, in CO_2-equivalent units

Column E: Level Assessment from Equation 7.1

Column F: Cumulative total of Column E

In the table, the calculations necessary for the Level Assessment are computed in Column E, following Equation 7.1. Thus, the value of the source category Level Assessment should be entered in Column E for each source category, and the sum of all the entries in this column entered in the total line of the table. All entries in Column E should be positive as the analysis deals with emission source categories only. *Key source categories* are those that, when summed together in descending order of magnitude, add up to over 95% of the total of Column E.[1] In order to make this determination, the source categories (i.e. the rows of the table) should be sorted in descending order of magnitude of the Level Assessment. The cumulative total of Column E should then be computed in Column F.

---

[1] This threshold was determined to be the level at which 90% of the uncertainty in a ‘typical’ inventory would be covered by *key source categories* (Flugsrud *et al.*, 1999, and Norwegian Pollution Control Authority, 1999). Note that if the LUCF Sector is considered in the analysis, the pre-determined threshold may need to be re-evaluated, because it was established based on an evaluation of source categories only.

The Level Assessment should be performed for all years for which inventory estimates are available. If previous inventory estimates have not changed, there is no need to recalculate the previous years' analysis. If any estimates have been changed or recalculated, however, the analysis for that year should be updated. Any source category that meets the 95% threshold in any year should be identified as a *key source category*.

TREND ASSESSMENT (TABLE 7.3)

The contribution of each source category's trend to the trend in the total inventory can be assessed if more than one year of inventory data are available, according to Equation 7.2:

EQUATION 7.2[2]

Source Category Trend Assessment = (Source Category Level Assessment) • | (Source Category Trend – Total Trend) |

$$T_{x,t} = L_{x,t} \bullet | \{[(E_{x,t} - E_{x,0}) / E_{x,t}] - [(E_t - E_0) / E_t]\} |$$

Where:

$T_{x,t}$ is the contribution of the source category trend to the overall inventory trend, called the Trend Assessment. The Trend Assessment is always recorded as an absolute value, i.e. a negative value is always recorded as the equivalent positive value.

$L_{x,t}$ is the Level Assessment for source x in year t (derived in Equation 7.1)

$E_{x,t}$ and $E_{x,0}$ are the emissions estimates of source category x in years t and 0, respectively

E_t and E_0 are the total inventory estimates in years t and 0, respectively

The Source Category Trend is the change in the source category emissions over time, computed by subtracting the base year (year 0) estimate for source category x from the current year (year t) estimate and dividing by the current year estimate.[3]

The Total Trend is the change in the total inventory emissions over time, computed by subtracting the base year (year 0) estimate for the total inventory from the current year (year t) estimate and dividing by the current year estimate.

The Trend Assessment will identify source categories that have a different trend to the trend of the overall inventory.[4] As differences in trend are more significant to the overall inventory level for larger source categories, the result of the trend difference (i.e. the source category trend minus total trend) is multiplied by the result of the level assessment ($L_{x,t}$ from Equation 7.1) to provide appropriate weighting. Thus, *key source categories* will be those where the source category trend diverges significantly from the total trend, weighted by the emission level of the source category.

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[2] From Flugsrud *et al*. (1999) and Norwegian Pollution Control Authority (1999).

[3] Although it is common to look at growth rates in the form of $(E_t - E_0) / E_0$, where the growth rate is measured from an initial value in year 0, the functional form of Equation 7.2 has been designed to minimise occurrences of division by zero and to enable analysis of the importance of source categories with very low emissions in the base year (e.g. substitutes for ozone depleting substances). In rare circumstances, inventory agencies may find that the denominator term for a particular source category (i.e. the current year estimate) is zero, or close to zero. In this case, the results of the Level Assessment and application of the qualitative criteria should be used to determine if the source category is key.

[4] See Flugsrud *et al*. (1999) for more discussion of this approach to trend analysis.

Table 7.3 presents a spreadsheet that can be used for the Trend Assessment.

TABLE 7.3
SPREADSHEET FOR THE TIER 1 ANALYSIS – TREND ASSESSMENT

A IPCC Source Categories	**B** Direct Greenhouse Gas	**C** Base Year Estimate	**D** Current Year Estimate	**E** Trend Assessment	**F** % Contribution to Trend	**G** Cumulative Total of Column F
Total						

Where:

Column A: List of IPCC source categories (see Table 7.1, Suggested IPCC Source Categories)

Column B: Direct greenhouse gas

Column C: Base year emissions estimates from the national inventory data, in CO2-equivalent units

Column D: Current year emissions estimates from the most recent national inventory, in CO2-equivalent units

Column E: Trend Assessment from Equation 7.2 recorded as an absolute number

Column F: Percentage contribution to the total trend of the national inventory

Column G: Cumulative total of Column F, calculated by summing Column F from the first row to the current row

The entries in columns A through D should be identical to those used in Table 7.2, Spreadsheet for the Tier 1 Analysis – Level Assessment. The calculations necessary for the Trend Assessment are computed in column E, following Equation 7.2. The absolute value of $T_{x,t}$ should be entered in Column E for each source category, and the sum of all the entries entered in the total line of the table.[5] Each source category's percentage contribution to the total of Column E should be computed and entered in Column F, and this column should be used to identify those source categories that contribute 95% to the trend of the inventory in absolute terms. Once the entries for Column F are computed, the source categories (i.e. the rows of the table) should be sorted in descending order of magnitude, based on Column F. The cumulative total of Column F should then be computed in Column G. *Key source categories* are those that, when summed together in descending order of magnitude, add up to more than 95% of Column G.

DETERMINING THE THRESHOLD

The proposed threshold of 95% for both the Level Assessment ($L_{x,t}$) and the Trend Assessment ($T_{x,t}$) was developed from a review of emissions estimates and uncertainty for several inventories. As described in Flugsrud *et al.* (1999), two analyses were performed. In the first, the relationship between the percentage of emissions and the percentage of total inventory uncertainty was compared for national GHG inventories of 35 Parties included in Annex I to the United Nations Framework Convention on Climate Change (UNFCCC). The results for three inventories are shown in Figure 7.2, Cumulative Fraction of Uncertainty by Cumulative Fraction of Total Emissions, which indicates that a threshold of 90% of emissions would account for 55-85% of uncertainty, a threshold of 95% of emissions would account for 75-92% of uncertainty, and a threshold of 97% of emissions would account for 85-95% of uncertainty. Figure 7.2 also shows the number of source categories associated with the various thresholds in inventories. As it indicates, 90% of the uncertainty is generally covered by 10-15 *key source categories*.

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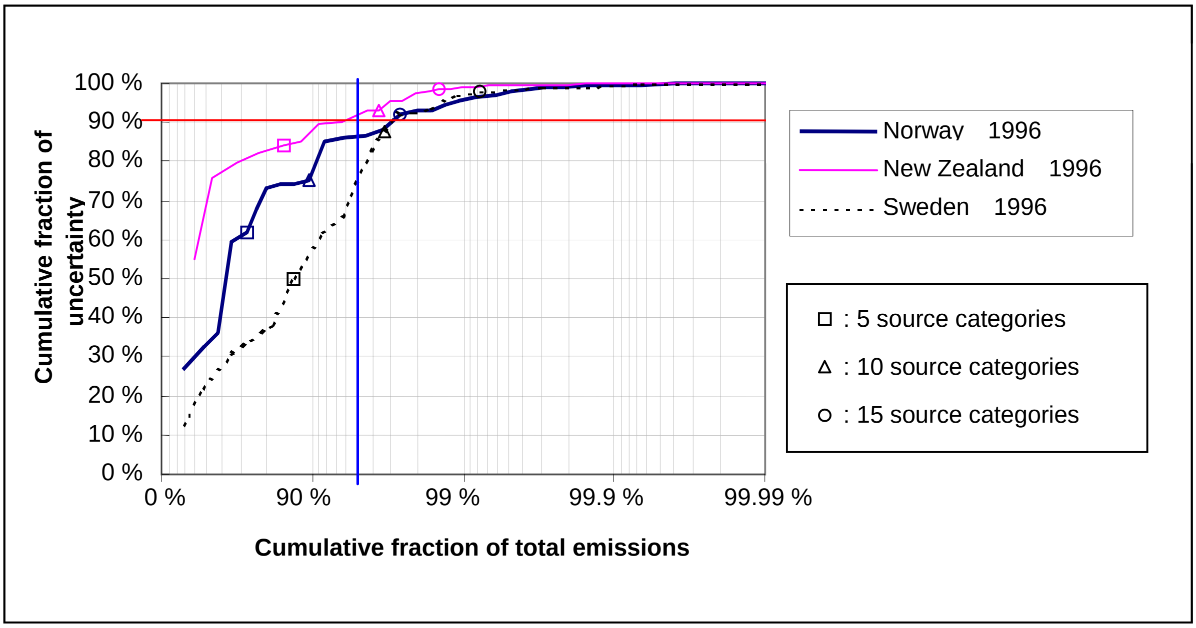
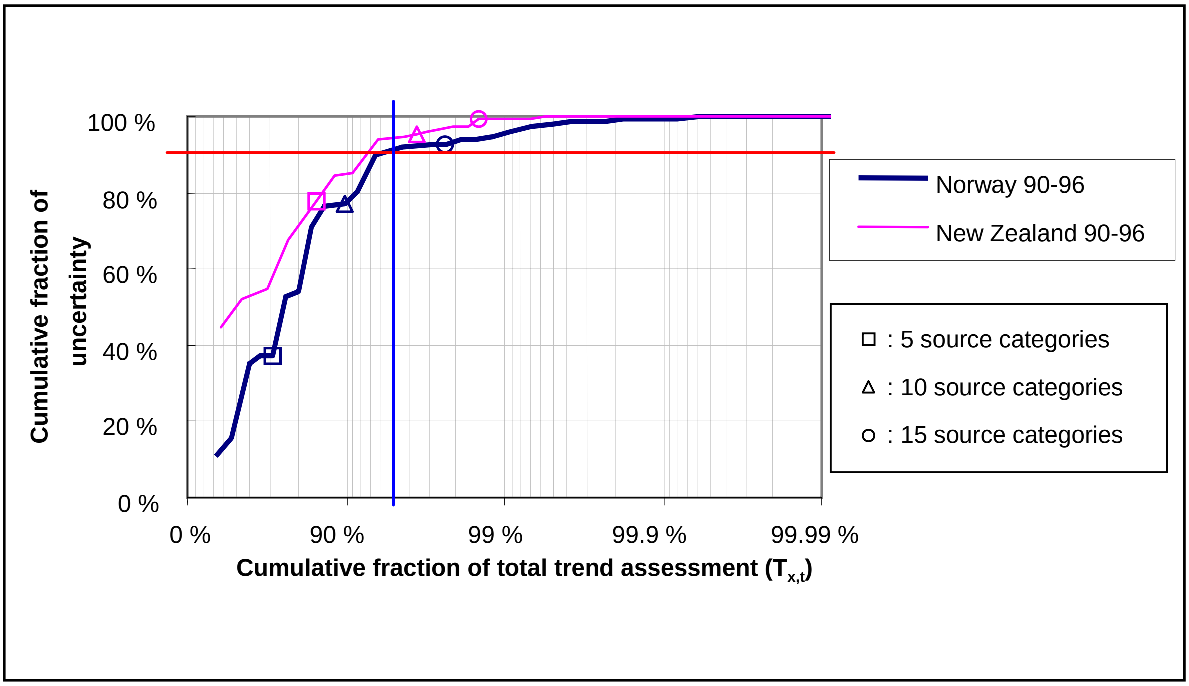
[5] Unlike the Level Assessment, where all entries will be positive if only source categories are considered, in the Trend Assessment negative values will occur if emissions of the source category decline by more in percentage terms than emissions of the overall inventory, or grow by a smaller amount. In this analysis the negative and positive values are considered equivalent, and the absolute values of these are recorded in the table.

Figure 7.2 Cumulative Fraction of Uncertainty by Cumulative Fraction of Total Emissions



The second aspect of the analysis compared the results of the trend assessment with the cumulative uncertainty in the inventory. As Figure 7.3 shows, in this case a threshold of 90% of the total trend assessment ($T_{x,t}$) would account for 75-85% of uncertainty, a threshold of 95% of the total trend assessment would account for 90-95% of uncertainty, and a threshold of 97% would account for 92-98% of the uncertainty. As in Figure 7.2, using the 95% threshold will generally cover 10-15 source categories in the inventory.

Figure 7.3 Cumulative Fraction of Trend Uncertainty by Cumulative Fraction of Total Trend Assessment



Based on a review of these analyses, a general threshold of 95% for both the Level Assessment ($L_{x,t}$) and the Trend Assessment ($T_{x,t}$) is suggested as a reasonable approximation of 90% of the uncertainty for the Tier 1 method, where a pre-determined threshold is needed. Obviously, other thresholds could be established if it were determined that a different level of uncertainty should be covered by *key source categories*. Inventory agencies can also determine the specific national thresholds for *key source categories* needed to cover 90% of their uncertainty, based on their national uncertainty analyses. The approach for doing this is described in Section 7.2.1.2 below.

7.2.1.2 TIER 2 METHOD TO IDENTIFY KEY SOURCE CATEGORIES, CONSIDERING UNCERTAINTIES

A more sophisticated Tier 2 approach can be used to identify *key source categories* using the results of the uncertainty analysis described in Chapter 6, Quantifying Uncertainties in Practice. The Tier 2 approach is consistent with, but not necessarily required for, *good practice*. Inventory agencies are encouraged to use Tier 2 if possible, because it can provide additional insight into the reasons that particular source categories are key and can assist in prioritising activities to improve inventory quality and reduce overall uncertainty. It should be recognised that, because of the different approaches, there may be a few differences in the *key source categories* that are identified. In such situations, the results of the Tier 2 approach should be utilised. In addition, the Tier 2 approach is likely to reduce the number of *key source categories* that need to be considered. If source category uncertainties are not available, inventory agencies need not develop them solely for the purpose of conducting the Tier 2 analysis of *key source categories*. Instead, they can use the Tier 1 approach, as described in Section 7.2.1.1, Tier 1 Method to Identify Key Source Categories.

Methods for incorporating the two types of uncertainty analyses described in Chapter 6, Quantifying Uncertainties in Practice, into the determination of *key source categories* are presented below.

INCORPORATING CHAPTER 6 TIER 1 SOURCE CATEGORY UNCERTAINTIES

The *key source category* analysis may be enhanced by incorporating national source category uncertainty estimates developed under a Tier 1 uncertainty analysis (described in Chapter 6, Quantifying Uncertainties in Practice, Section 6.3.2, Tier 1 – Estimating Uncertainties by Source Category with Simplifying Assumptions). These uncertainty estimates are developed using the error propagation equation to combine emission factor and activity data uncertainties by source category and gas. The simplified approach is implemented at the source category level, using uncertainty ranges for emission factors and activity data consistent with the guidance in Chapters 2-5. The source category uncertainties are incorporated by weighting the Tier 1 Level and Trend Assessment results by the source category's relative uncertainty. Thus, the equations used for the quantitative analysis are modified as shown below.

LEVEL ASSESSMENT

Equation 7.3 describes the Tier 2 Level Assessment including uncertainty. The result of this assessment ($LU_{x,t}$) is identical to the result of quantifying uncertainties in practice, as shown in column H of Table 6.1, Tier 1 Uncertainty Calculation and Reporting, in Chapter 6, Quantifying Uncertainties in Practice. So, if Table 6.1 has been completed, it is not necessary to recalculate Equation 7.3.

EQUATION 7.3

Level Assessment, with Uncertainty = Tier 1 Level Assessment • Relative Source Uncertainty

$$LU_{x.t} = L_{x,t} \bullet U_{x,t}$$

TREND ASSESSMENT

Equation 7.4 shows how the Tier 2 Trend Assessment can be expanded to include uncertainty.

EQUATION 7.4

Trend Assessment, with Uncertainty = Tier 1 Trend Assessment • Relative Source Uncertainty

$$TU_{x,t} = T_{x,t} \bullet U_{x,t}$$

Where:

$L_{x,t}$ and $T_{x,t}$ are calculated using Equations 7.1 and 7.2

$U_{x,t}$ is the relative source category uncertainty in year t (if relevant) as calculated for the Tier 1 uncertainty analysis described in Chapter 6, Quantifying Uncertainties in Practice. Specifically, the source category uncertainties should be the same as those reported in Table 6.1, Column G.

INCORPORATING MONTE CARLO ANALYSIS

In Chapter 6, Quantifying Uncertainties in Practice, Monte Carlo analysis is presented as the Tier 2 approach for quantitative uncertainty assessment. Whereas the Tier 1 analysis requires simplified assumptions to develop source category uncertainty, Monte Carlo analysis can handle large uncertainties, complexities in the probability density functions, correlation and both simple and complex emission estimate equations, among other things. Monte Carlo analysis is also useful for performing sensitivity analyses on the inventory to identify the principal factors driving inventory uncertainty. These types of insights can be valuable in the identification of *key source categories* and prioritising resources for inventory improvement. If available, the relative source category uncertainties generated by Monte Carlo analysis can be used in Equations 7.3 and 7.4 using the larger difference between the mean and the confidence limit where the confidence limits are asymmetrical.

ESTABLISHING A NATIONAL THRESHOLD

Use of national inventory uncertainty also makes it possible to adjust the *key source category* threshold, if necessary, to explicitly reflect 90% of the uncertainty in the national inventory. Thus, rather than apply the pre-determined threshold of 95% of the Level and Trend Assessments used in Section 7.2.1.1, Tier 1 Method to Identify Key Source Categories, inventory agencies can use their own uncertainty analyses to develop the threshold.

7.2.2 Qualitative approaches to identify key source categories

There are other criteria to consider when determining *key source categories* that are not as easily assessed through a quantitative analysis. These criteria include:

- *Mitigation techniques and technologies*: If emissions from a source category are being reduced significantly through the use of mitigation techniques or technologies, it is *good practice* to identify these source categories as key. This will ensure that they are prioritised within the inventory and that high quality emissions estimates are prepared. It will also ensure that the methods used are transparent with respect to mitigation which is important for assessing inventory quality.

- *High expected emission growth*: If inventory agencies expect emissions from a source category to grow significantly in the future, they are encouraged to identify that source category as key. Some of these categories will have been identified by the current Trend Assessment (i.e. use of Equations 7.2 or 7.4), and others will be identified by Trend Assessment in the future. Designating a source category as key in anticipation of future emission growth is desirable, because it can result in earlier use of high tier *good practice* methods and earlier collection of more detailed data. This can, in turn, reduce the likelihood of future methodological changes and simplify the recalculation of the emissions estimates over the time series if methodological changes are made.

- *High uncertainty*: If inventory agencies are not taking uncertainty explicitly into account by using the Tier 2 method to identify *key source categories*, they may want to identify the most uncertain source categories as key. This is because the most can be gained in reducing overall inventory uncertainty by improving these estimates of highly uncertain source categories. Designating such source categories as key can therefore lead to improvements in inventory quality.

- *Unexpectedly low or high emissions*: Order of magnitude checks, as described in Chapter 8, Quality Assurance and Quality Control, Section 8.7.1.4, Emission Comparisons, can help identify calculation errors and discrepancies. Inventory agencies may want to identify those source categories that show unexpectedly low or high emissions estimates as key. It is *good practice* to focus attention on those source categories where unexpected results are observed, to ensure that the results are reliable. The source category QA/QC procedures as described in Chapter 8, Quality Assurance and Quality Control, Section 8.7, Source Category-specific QC Procedures (Tier 2), may be implemented if unexpectedly low or high source categories are designated as key.

In most cases, the application of these qualitative criteria will identify source categories already defined as key through the quantitative analysis. Some additional source categories may be identified and these may be added to the list of *key source categories*.

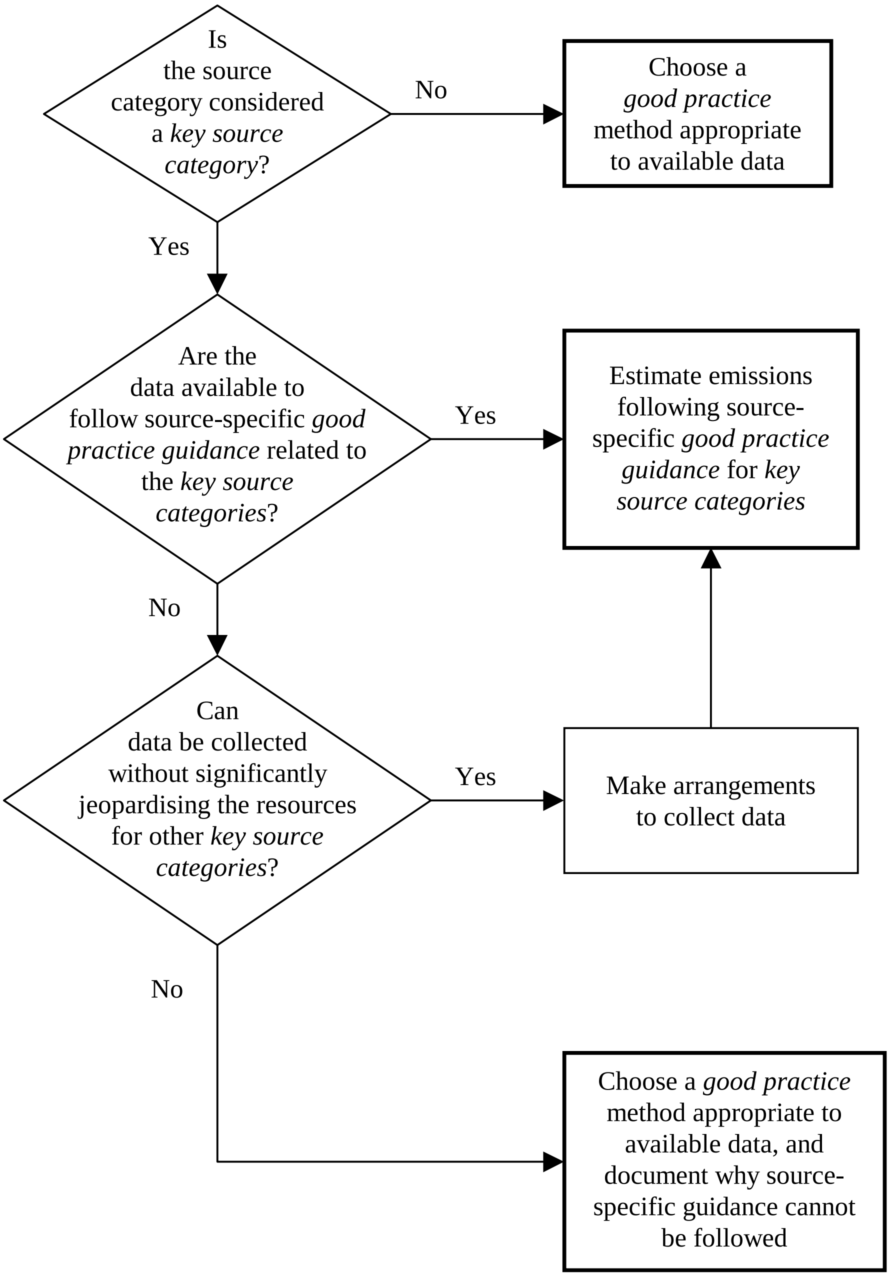
7.2.3 Application of results

Identification of national *key source categories* is important because the resources available for preparing inventories are finite and their use should be prioritised. It is essential that estimates be prepared for all source categories, in order to ensure completeness. As far as possible, *key source categories* should receive special consideration in terms of two important inventory aspects.

First, additional attention ought to be focused on *key source categories* with respect to methodological choice. As shown in the decision tree in Figure 7.4, Decision Tree to Choose a Good Practice Method, inventory agencies are encouraged to use source category-specific *good practice* methods for their *key source categories*, unless resources are unavailable. For many source categories, higher tier (i.e. Tier 2) methods are suggested for *key source categories*, although this is not always the case. For guidance on the specific application of this principle to particular *key source categories*, inventory agencies should follow the guidance and decision trees in Chapters 2-5.

Second, it is *good practice* that *key source categories* receive additional attention with respect to quality assurance and quality control (QA/QC). In Chapter 8, Quality Assurance and Quality Control, detailed guidance is provided on QA/QC for source categories in the inventory. As described in that chapter, it is *good practice* to carry out detailed source-level quality control and quality assurance on *key source categories*.

Figure 7.4 Decision Tree to Choose a Good Practice Method



7.2.4 Reporting and documentation

It is *good practice* to clearly identify the *key source categories* in the inventory. This information is essential for documenting and explaining the choice of method for each source category. In addition, inventory agencies should list the criteria by which each *key source category* was identified (e.g. level, trend, or qualitative), and the method used to conduct the quantitative analysis (e.g. Tier 1 or Tier 2).

Table 7.4 should be used to record the results of the *key source category* analysis. This table provides columns for reporting the results of the analysis and the criteria by which each source category was identified.

TABLE 7.4
SOURCE CATEGORY ANALYSIS SUMMARY

Quantitative Method Used : ☐ Tier 1 ☐ Tier 2

A **IPCC Source Categories**	B **Direct Greenhouse Gas**	C **Key Source Category Flag (Yes or No)**	D **If C is Yes, Criteria for Identification**	E **Comments**

Where:

Column A: List of IPCC source categories – entry should be the same as column A in Tables 7.2 and 7.3

Column B: Direct greenhouse gas – entry should be the same as column B in Tables 7.2 and 7.3

Column C: Key source category flag – enter ‘Yes’ if the source category is key

Column D: Criteria by which key source category was identified – for each key source category identified in Column C, enter one or more of the following: ‘Level’ for Level Assessment, ‘Trend’ for Trend Assessment, or ‘Qualitative’ for qualitative criteria

Column E: Comments – enter any explanatory material

7.3 RECALCULATIONS

As inventory capacity and data availability improve, the methods used to prepare emissions estimates will be updated and refined. Such changes or refinements are desirable when they result in more accurate and complete estimates. In order to assess emission trends it is important that the entire time series of emissions, not just the most recent years, be calculated using the changed or refined methods. It is *good practice* to recalculate historic emissions when methods are changed or refined, when new source categories are included in the national inventory, or when errors in the estimates are identified and corrected.

A *methodological change* occurs when an inventory agency uses a different tier to estimate emissions from a source category or when it moves from a tier described in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (*IPCC Guidelines*) to a national method. Methodological changes are often driven by the development of new and different data sets. An example of a methodological change is if an inventory agency begins to use a higher tier method instead of a Tier 1 default method for an industrial source category because it has obtained site-specific emissions measurement data that can be used directly or for development of national emission factors.

A *methodological refinement* occurs when an inventory agency uses the same tier to estimate emissions but applies it using a different data source or a different level of aggregation. An example of a refinement would be if new data permit further disaggregation of a livestock enteric fermentation model, so that resulting animal categories are more homogenous. In this case, the estimate is still being developed using a Tier 2 method, but it is applied at a more detailed level of aggregation. Another possibility is that data of a similar level of aggregation but higher quality could be introduced, due to improved data collection methods.

This section discusses how to determine when methods should be changed or refined, and it describes *good practice* for recalculating emissions. Recalculations of the whole time series should be documented as described below, and consistent with source-specific *good practice guidance*. As far as possible, use of refined emissions data or changed methods should be peer reviewed or validated in another way before being implemented, especially if data in the base year will change as a result.

7.3.1 Reasons for recalculations

7.3.1.1 CHANGES OR REFINEMENTS IN METHODS

It is *good practice* to change or refine methods when:

- *Available data have changed*: The availability of data is a critical determinant of the appropriate method, and thus changes in available data may lead to changes or refinements in methods. As inventory agencies gain experience and devote additional resources to preparing greenhouse gas emissions inventories, it is expected that data availability will improve.[6]
- *The previously used method is not consistent with good practice guidance for that source category*: Inventory agencies should review the guidance for each source category in Chapters 2-5.
- *A source category has become key*: A source category might not be considered key in the base year, depending on the criteria used, but could become key in a future year. For example, many countries are only beginning to substitute HFCs and PFCs for ozone depleting substances being phased out under the Montreal Protocol. Although current emissions from this source category are low, they could become key in the future based on trend or level. Inventory agencies anticipating significant growth in a source category may want to consider this possibility before it becomes key.
- *The previously used method is insufficient to reflect mitigation activities in a transparent manner*: As techniques and technologies for reducing emissions are introduced, inventory agencies should use methods that can account for the resulting decrease in emissions in a transparent manner. Where the previously used methods are insufficiently transparent, it is *good practice* to change or refine them.
- *The capacity for inventory preparation has increased*: Over time, the human or financial capacity or both to prepare inventories may increase. If inventory agencies increase inventory capacity, it is *good practice* to

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[6] In some circumstances data collections may be reduced which can also lead to a change or refinement in method.

change or refine methods so as to produce more accurate, complete or transparent estimates, particularly for *key source categories*.

- *New methods become available*: In the future, new methods may be developed that take advantage of new technologies or improved scientific understanding. For example, remote-sensing technology may make it possible to estimate emissions from natural gas pipelines more accurately than by using simple production-based emission factors, or improvements in emission monitoring technology may make it possible to directly monitor more emissions. Inventory agencies should ensure that their methods are consistent with the *IPCC Guidelines* and with this report on *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (*Good Practice Report*).

7.3.1.2 INCLUSION OF NEW SOURCES

In some circumstances, inventory agencies may identify new source categories or new gases that should be included in their emissions inventories. In this case, an inventory agency will need to develop or implement a new methodology. This situation is not formally considered a methodological change or refinement, but is mentioned here because guidance provided in Section 7.3.2, Approaches to Recalculations, regarding how to develop a consistent time series is relevant when considering new source categories.

7.3.1.3 CORRECTION OF ERRORS

It is possible that the implementation of the QA/QC procedures described in Chapter 8, Quality Assurance and Quality Control, will lead to the identification of errors or mistakes in the emissions inventory. As noted in that chapter, it is *good practice* to correct errors in previously submitted estimates. In a strict sense, the correction of errors should not be considered a methodological change or refinement. This situation is noted here, however, because the guidance described in Section 7.3.2 below should be taken into consideration when making necessary corrections.

7.3.2 Approaches to recalculations

All emissions estimates in a time series should be estimated consistently, which means that previously submitted estimates should be evaluated for consistency and recalculated if necessary whenever methods are changed or refined. As described below, previous estimates should be recalculated using the new methods for all years in the time series. For many source categories, it should be possible to do this. In some cases, however, it may not be possible to use the same method for all inventory years. This situation may arise more frequently in the future, as the base year of the inventory becomes more distant in time. If it is not possible to use the same method in all years, the alternative approaches described in Section 7.3.2.2, Alternative Recalculation Techniques, should be evaluated.

It is important to note that some changes or refinements to methods will be applicable across the entire time series, while others may only be applicable in particular years. For example, if mitigation technologies have been introduced, it may be necessary to consider the appropriate approach to phase in gradual changes in emission factors or technology deployment. Thus, the specific characteristics of the source category and the methodological change or refinement should be carefully evaluated when undertaking a recalculation.

7.3.2.1 RECALCULATIONS USING A NEW METHOD FOR ALL YEARS

It is *good practice* to recalculate previous estimates using the same method and a consistent set of data in every inventory year. This approach is the most reliable means of ensuring an accurate and consistent trend over the time period.

In some cases, it may not be possible to recalculate previous estimates using the same method and a consistent data set over the entire time series. The most probable difficulty with using a new method for recalculation is the lack of a complete data set for past years. Before concluding that necessary data are not available, particularly in the case of *key source categories*, it is *good practice* to consider a variety of means of obtaining them. For example, it may be possible to initiate new data collection activities, or to obtain additional data from statistical offices, sector experts, or industry contacts, making arrangements for the protection of confidential business information if necessary.

7.3.2.2 ALTERNATIVE RECALCULATION TECHNIQUES

Several alternative recalculation techniques are available if full recalculation using the same method is not possible. Each technique is appropriate in certain situations, as determined by considerations such as data availability and the nature of the methodological modification. Selecting an alternative technique requires evaluating the specific circumstances, and determining the best option for the particular case.

The principal approaches for inventory recalculations are summarised in Table 7.5 below and described in more detail below. These approaches can be applied at the level of the method (in the case of a methodological change) or at the level of the underlying data (in the case of a methodological refinement).

TABLE 7.5
SUMMARY OF APPROACHES TO RECALCULATIONS

Approach	Applicability	Comments
Overlap	Data necessary to apply both the previously used and the new method must be available for at least one year.	• Most reliable when the overlap between two or more sets of annual emissions estimates can be assessed. • If the relationship observed using the two methods is inconsistent, the recalculation should be based on two or more annual emissions estimates. • If the emission trends observed using the previously used and new methods are inconsistent and random, this approach is not *good practice*.
Surrogate Method	Emission factors or activity data used in the new method are strongly correlated with other well-known and more readily available indicative data.	• Multiple indicative data sets (singly or in combination) should be tested in order to determine the most strongly correlated. • Should not be done for long periods.
Interpolation	Data needed for recalculation using the new method are available for intermittent years during the time series.	• Emissions estimates can be linearly interpolated for the periods when the new method cannot be applied.
Trend Extrapolation	Data for the new method are not collected annually and are not available at the beginning or the end of the time series.	• Most reliable if the trend over time is constant. • Should not be used if the trend is changing (in this case, the surrogate method may be more appropriate). • Should not be done for long periods.

OVERLAP

When a method is changed or modified, the estimates prepared using both the previously used and the new method should be compared in terms of the level and the trend. If the new method cannot be used for all years, it may be possible to develop a time series based on the relationship (or overlap) observed between the two methods during the years when both can be used. Essentially, the time series is constructed by assuming that there is a consistent relationship between the results of the previously used and new method. The emissions estimates for those years when the new method cannot be used directly are developed by proportionally adjusting the previously developed emissions estimates, based on the relationship observed during the period of overlap.

The overlap method is most commonly used when there is a proportional relationship between the two methods. In this case, the emissions associated with the new method are estimated according to Equation 7.5:

EQUATION 7.5

$$y_0 = x_0 \bullet \left(\sum_{i=m}^{n} y_i \bigg/ \sum_{i=m}^{n} x_i \right)$$

Where:

y_0 is the recalculated emission estimate computed using the overlap method

x_0 is the estimate developed using the previously used method

sum of y_i and x_i are the estimates prepared using the new and previously used methods during the period of overlap, as denoted by years m through n

A relationship between the previously used and new methods can be evaluated by comparing the overlap between only one set of annual emissions estimates, but it is preferable to compare multiple years. This is because comparing only one year may lead to bias and it is not possible to evaluate trends. Other relationships between the old and new estimates may also be observed through an assessment of overlap. For example, a constant difference may be observed. In this case, the emissions associated with the new method are estimated by adjusting the previous estimate by the constant amount. For more information on the overlap method of recalculating (which can also be called 'splicing methodologies'), refer to Annex 1, Conceptual Basis for Uncertainty Analysis.

SURROGATE METHOD

The surrogate method relates emissions estimates to underlying activity or other indicative data. Changes in these data are used to simulate the trend in emissions. The estimate should be related to the statistical data source that best explains the time variations of the emission source category. For example, mobile source emissions may be related to trends in vehicle distances travelled, emissions from domestic wastewater may be related to population, and industrial emissions may be related to production levels in the relevant industry.

In its simplest form, the emissions estimate will be related to a single type of data as shown in Equation 7.6:

EQUATION 7.6

$$y_0 = y_t \bullet (s_0 / s_t)$$

Where:

y is the emission estimate in years 0 and t

s is the surrogate statistical parameter in years 0 and t

In some cases, more accurate relationships may be developed by relating emissions to more than one statistical parameter. Regression analysis may be useful in selecting the appropriate surrogate data parameters.

Using surrogate methods to estimate otherwise unavailable data can improve the accuracy of estimates developed by the interpolation and trend extrapolation approaches discussed below.

INTERPOLATION

In some cases it may be possible to apply a method intermittently throughout the time series. For example, necessary detailed statistics may only be collected every few years, or it may be impractical to conduct detailed surveys on an annual basis. In this case, estimates for the intermediate years in the time series can be developed by interpolating between the detailed estimates. If information on the general trends or underlying parameters is available, then the surrogate method is preferable.

TREND EXTRAPOLATION

When detailed estimates have not been prepared for the base year or the most recent year in the inventory, it may be necessary to extrapolate from the closest detailed estimate. Extrapolation can be conducted either forward (to estimate more recent emissions) or backward (to estimate a base year). Trend extrapolation simply assumes that the observed trend in emissions during the period when detailed estimates are available remains constant over the period of extrapolation. Given this assumption, it is clear that trend extrapolation should not be used if the emission growth trend is not constant over time. Extrapolation should also not be used over long periods of time without detailed checks at intervals to confirm the continued validity of the trend.

SPECIFIC SITUATIONS

In some cases, it may be necessary to develop a customised approach in order to best estimate the emissions over time. For example, the standard alternatives may not be valid when technical conditions are changing throughout the time series (e.g. due to the introduction of mitigation technology). In this case, revised emission factors may be needed and it will also be necessary to carefully consider the trend in the factors over the period. Where customised approaches are used, it is *good practice* to document them thoroughly, and in particular to give special consideration to how the resultant emissions estimates compare to those that would be developed using the more standard alternatives.

7.3.3 Documentation

Clear documentation of recalculations is essential for transparent emissions estimates, and to demonstrate that the recalculation is an improvement in accuracy and completeness. In general, the following information should be provided whenever recalculations are undertaken:

- The effect of the recalculations on the level and trend of the estimate (by providing the estimates prepared using both the previously used and new methods);
- The reason for the recalculation (see Section 7.3.1, Reason for Recalculations);
- A description of the changed or refined method;
- Justification for the methodological change or refinement in terms of an improvement in accuracy, transparency, or completeness;
- The approach used to recalculate previously submitted estimates;
- The rationale for selecting the approach which should include a comparison of the results obtained using the selected approach and other possible alternatives, ideally including a simple graphical plot of emissions vs. time or relevant activity data or both.

APPENDIX 7A.1
EXAMPLE OF TIER 1 KEY SOURCE CATEGORY IDENTIFICATION

The application of the Tier 1 quantitative analysis to the US emissions inventory for 1990-1997 is shown in Tables 7.A1 to 7.A3. Both the Level and the Trend Assessment were conducted using emissions estimates from USEPA (1999). A qualitative assessment was not conducted in this example, but it was not anticipated that additional source categories would have been identified. The Tier 2 approach was not used because source category uncertainty estimates following the guidance provided in Chapter 6, Quantifying Uncertainties in Practice, were not available at the time of publication of *Good Practice Report.*

The results of the Level Assessment are shown in Table 7.A1, with *key source categories* shaded. The entries for columns A-D were taken directly from USEPA (1999). Entries in Column E were calculated using Equation 7.1. The source categories (i.e. rows of the table) were sorted on column E in descending order of magnitude, and then the cumulative total was included in Column F. *Key source categories* are those which added up to 95% of the entries in Column E after this sorting process.

The results of the Trend Assessment are shown in Table 7.A2, with *key source categories* shaded. As in Table 7.A1, the entries for columns A-D were taken directly from USEPA (1999). Entries in Column E were calculated using Equation 7.2 and entering the absolute value of the result. Column F was calculated as the percentage of the source category entry in Column E over the total for all source categories in Column E. *Key source categories* according to the Trend Assessment were identified by sorting the source category entries in Column F from largest to smallest. Column G was used to determine the cumulative total of Column F, and *key source categories* are those which added up to 95% of the entries in Column F after the sorting process.

Table 7.A3 summarises the results of the analysis, following the reporting and documentation suggestions in Section 7.2.4, Reporting and Documentation. As the table indicates, 17 *key source categories* are identified for the US inventory based on the results of this analysis. All major fuels (i.e. coal, oil and gas) used in the source category ‘CO_2 Emissions from Stationary Combustion’ were identified as key, for both level and trend. Eight other source categories are key in terms of both the Level and the Trend Assessments. Two source categories – CH_4 Emissions from Manure Management and Indirect N_2O Emissions from Nitrogen Used in Agriculture – are key only in terms of the Level Assessment. The remaining six source categories, all but one of which are Industrial Processes Sector emissions, are key only in terms of the Trend Assessment. For most of the *key source categories* identified due to trend, emissions are falling significantly. A few source categories, such as Emissions from Substitutes for Ozone Depleting Substances source category, are key because of rapid emissions growth.

TABLE 7.A1
TIER 1 ANALYSIS – LEVEL ASSESSMENT (US INVENTORY)

A IPCC Source Categories[a]	B Direct Greenhouse Gas	C Base Year Estimate (Mt Carbon Equivalent [b])	D Current Year Estimate (Mt Carbon Equivalent [b])	E Level Assessment	F Cumulative Total of Column E
CO_2 Emissions from Stationary Combustion – Coal	CO_2	481.6	533.3	0.29	0.29
Mobile Combustion – Road & Other	CO_2	338.1	381.0	0.21	0.50
CO_2 Emissions from Stationary Combustion – Gas	CO_2	266.0	313.1	0.17	0.68
CO_2 Emissions from Stationary Combustion – Oil	CO_2	176.8	177.5	0.10	0.77
CH_4 Emissions from Solid Waste Disposal Sites	CH_4	56.2	66.7	0.04	0.81
Direct N_2O Emissions from Agricultural Soils	N_2O	46.6	53.7	0.03	0.84
Mobile Combustion: Aircraft	CO_2	50.5	50.1	0.03	0.87
Fugitive Emissions from Oil and Gas Operations	CH_4	34.5	35.1	0.02	0.89
CH_4 Emissions from Enteric Fermentation in Domestic Livestock	CH_4	32.7	34.1	0.02	0.91
Indirect N_2O Emissions from Nitrogen Used in Agriculture	N_2O	18.8	20.4	0.01	0.92
Fugitive Emissions from Coal Mining and Handling	CH_4	24.0	18.8	0.01	0.93
CH_4 Emissions from Manure Management	CH_4	14.9	17.0	0.01	0.94
Mobile Combustion: Road and Other	N_2O	13.0	16.9	0.01	0.95
Mobile Combustion: Marine	CO_2	16.4	15.4	0.01	0.96
Emissions from Substitutes for Ozone Depleting Substances	Several	0.3	14.7	0.01	0.96
CO_2 Emissions from Cement Production	CO_2	8.9	10.2	0.01	0.97
HFC-23 Emissions from HCFC-22 Manufacture	HFC	9.5	8.2	0.01	0.97
SF_6 Emissions from Electrical Equipment	SF_6	5.6	7.0	<0.01	0.98
Non-CO_2 Emissions from Stationary Combustion	N_2O	3.8	4.1	<0.01	0.98
N_2O Emissions from Adipic Acid Production	N_2O	4.7	3.9	<0.01	0.98
CO_2 Emissions from Lime Production	CO_2	3.3	3.9	<0.01	0.98
N_2O Emissions from Nitric Acid Production	N_2O	3.3	3.8	<0.01	0.99
CO_2 Emissions from Other Industrial Processes	CO_2	2.7	3.6	<0.01	0.99
SF_6 from Magnesium Production	SF_6	1.7	3.0	<0.01	0.99
N_2O Emissions from Manure Management	N_2O	2.6	3.0	<0.01	0.99
PFC Emissions from Aluminium Production	PFC	4.9	2.9	<0.01	0.99
CH_4 Emissions from Rice Production	CH_4	2.5	2.7	<0.01	0.99
Emissions from Wastewater Handling	N_2O	2.1	2.3	<0.01	1.00
Non-CO_2 Emissions from Stationary Combustion	CH_4	2.3	2.2	<0.01	1.00
Mobile Combustion: Road & Other	CH_4	1.4	1.4	<0.01	1.00
PFC, HFC and SF_6 Emissions from Semiconductor Manufacturing	Several	0.2	1.3	<0.01	1.00
Emissions from Wastewater Handling	CH_4	0.9	0.9	<0.01	1.00
Mobile Combustion: Aviation	N_2O	0.5	0.5	<0.01	1.00
CH_4 Emissions from Other Industrial Sources	CH_4	0.3	0.4	<0.01	1.00
CH_4 Emissions from Agricultural Residue Burning	CH_4	0.2	0.2	<0.01	1.00
Mobile Combustion: Marine	N_2O	0.1	0.1	<0.01	1.00
Emissions from Waste Incineration	N_2O	0.1	0.1	<0.01	1.00
N_2O Emissions from Agricultural Residue Burning	N_2O	0.1	0.1	<0.01	1.00
TOTAL		1632.1	1813.6	1.00	

[a] LUCF is not included in this analysis.

[b] Estimates should be presented in CO_2-equivalent units as indicated in the notes to Tables 7.2 and 7.3.

Source: USEPA (1999).

TABLE 7.A2
TIER 1 ANALYSIS – TREND ASSESSMENT (US INVENTORY)

A	**B**	**C**	**D**	**E**	**F**	**G**
IPCC Source Categories[a]	**Direct Greenhouse Gas**	**Base Year Estimate (Mt Carbon Equivalent**[b]**)**	**Current Year Estimate (Mt Carbon Equivalent**[b]**)**	**Trend Assessment**	**% Contribution to Trend**	**Cumulative total of Column F**
CO_2 Emissions from Stationary Combustion – Oil	CO_2	176.8	177.5	0.01	19	0.19
CO_2 Emissions from Stationary Combustion – Gas	CO_2	266.0	313.1	0.01	17	0.36
Emissions from Substitutes for Ozone Depleting Substances	Several	0.3	14.7	0.01	14	0.50
Fugitive Emissions from Coal Mining and Handling	CH_4	24.0	18.8	<0.01	8	0.58
Mobile Combustion: Aviation	CO_2	50.5	50.1	<0.01	6	0.64
Mobile Combustion: Road & Other	CO_2	338.1	381.0	<0.01	5	0.69
CH_4 Emissions from Solid Waste Disposal Sites	CH_4	56.2	66.7	<0.01	4	0.73
Fugitive Emissions from Oil & Gas Operations	CH_4	34.5	35.1	<0.01	3	0.76
Mobile Combustion: Marine	CO_2	16.4	15.4	<0.01	3	0.79
PFC Emissions from Aluminium Production	PFC	4.9	2.9	<0.01	3	0.82
Mobile Combustion: Road & Other	N_2O	13.0	16.9	<0.01	2	0.84
HFC-23 Emissions from HCFC-22 Manufacture	HFC	9.5	8.2	<0.01	2	0.87
CH_4 Emissions from Enteric Fermentation in Domestic Livestock	CH_4	32.7	34.1	<0.01	2	0.89
Direct N_2O Emissions from Agricultural Soils	N_2O	46.6	53.7	<0.01	2	0.91
CO_2 Emissions from Stationary Combustion – Coal	CO_2	481.6	533.3	<0.01	2	0.92
N_2O Emissions from Adipic Acid Production	N_2O	4.7	3.9	<0.01	1	0.94
SF_6 from Magnesium Production	SF_6	1.7	3.0	<0.01	1	0.95
PFC, HFC and SF_6 Emissions from Semiconductor Manufacturing	Several	0.2	1.3	<0.01	1	0.96
SF_6 Emissions from Electrical Equipment	SF_6	5.6	7.0	<0.01	1	0.97
CO_2 Emissions from Other Industrial Processes	CO_2	2.7	3.6	<0.01	1	0.97
Indirect N_2O Emissions from Nitrogen Used in Agriculture	N_2O	18.8	20.4	<0.01	<1	0.98
CH_4 Emissions from Manure Management	CH_4	14.9	17.0	<0.01	<1	0.98
Non-CO_2 Emissions from Stationary Combustion	CH_4	2.3	2.2	<0.01	<1	0.99
CO_2 Emissions from Cement Production	CO_2	8.9	10.2	<0.01	<1	0.99
CO_2 Emissions from Lime Production	CO_2	3.3	3.9	<0.01	<1	0.99
Mobile Combustion: Road & Other	CH_4	1.4	1.4	<0.01	<1	0.99
N_2O Emissions from Nitric Acid Production	N_2O	3.3	3.8	<0.01	<1	0.99
Non-CO_2 Emissions from Stationary Combustion	N_2O	3.8	4.1	<0.01	<1	1.0
N_2O Emissions from Manure Management	N_2O	2.6	3.0	<0.01	<1	1.0
Emissions from Wastewater Handling	CH_4	0.9	0.9	<0.01	<1	1.0
CH_4 Emissions from Rice Production	CH_4	2.5	2.7	<0.01	<1	1.0
CH_4 Emissions from Other Industrial Processes	CH_4	0.3	0.4	<0.01	<1	1.0
Mobile Combustion: Aviation	N_2O	0.5	0.5	<0.01	<1	1.0
Emissions from Wastewater Handling	N_2O	2.1	2.3	<0.01	<1	1.0
CH_4 Emissions from Agricultural Residue Burning	CH_4	0.2	0.2	<0.01	<1	1.0
Mobile Combustion: Marine	N_2O	0.1	0.1	<0.01	<1	1.0
Emissions from Waste Incineration	N_2O	0.1	0.1	<0.01	<1	1.0
N_2O Emissions from Agricultural Residue Burning	N_2O	0.1	0.1	<0.01	<1	1.0
Total		1632.1	1813.6	0.05	1.00	

[a] LUCF is not included in this analysis.

[b] Estimates should be presented in CO_2-equivalent units as indicated in the notes to Tables 7.2 and 7.3.

Source: USEPA (1999).

TABLE 7.A3
SOURCE CATEGORY ANALYSIS SUMMARY (US INVENTORY)

Quantitative Method Used : ☑ Tier 1 ☐ Tier 2

A **IPCC Source Categories**	**B** **Direct Greenhouse Gas**	**C** **Key Source Category Flag**	**D** **If Column C is Yes, Criteria for Identification**	**E** **Comments**
ENERGY SECTOR				
CO_2 Emissions from Stationary Combustion – Coal	CO_2	Yes	Level, Trend	
CO_2 Emissions from Stationary Combustion – Oil	CO_2	Yes	Level, Trend	
CO_2 Emissions from Stationary Combustion – Gas	CO_2	Yes	Level, Trend	
Non-CO_2 Emissions from Stationary Combustion	CH_4	No		
Non-CO_2 Emissions from Stationary Combustion	N_2O	No		
Mobile Combustion: Road & Other	CO_2	Yes	Level, Trend	
Mobile Combustion: Road and Other	CH_4	No		
Mobile Combustion: Road and Other	N_2O	Yes	Level, Trend	
Mobile Combustion: Aviation	CO_2	Yes	Level, Trend	
Mobile Combustion: Aviation	N_2O	No		
Mobile Combustion: Marine	CO_2	Yes	Trend	
Mobile Combustion: Marine	N_2O	No		
Fugitive Emissions from Coal Mining and Handling	CH_4	Yes	Level, Trend	
Fugitive Emissions from Oil & Gas Operations	CH_4	Yes	Level, Trend	
INDUSTRIAL SECTOR				
CO_2 Emissions from Cement Production	CO_2	No		
CO_2 Emissions from Lime Production	CO_2	No		
CO_2 Emissions from Other Industrial Processes	CO_2	No		
CH_4 Emissions from Other Industrial Processes	CH_4	No		
N_2O Emissions from Adipic Acid Production	N_2O	Yes	Trend	
N_2O Emissions from Nitric Acid Production	N_2O	No		
PFC Emissions from Aluminium Production	PFC	Yes	Trend	
SF_6 from Magnesium Production	SF_6	Yes	Trend	
SF_6 Emissions from Electrical Equipment	SF_6	No		
PFC, HFC and SF_6 Emissions from Semiconductor Manufacturing	SF_6	No		
Emissions from Substitutes for Ozone Depleting Substances	Several	Yes	Trend	
HFC-23 Emissions from HCFC-22 Manufacture	HFC	Yes	Trend	
AGRICULTURE SECTOR				
CH_4 Emissions from Enteric Fermentation in Domestic Livestock	CH_4	Yes	Level, Trend	
CH_4 Emissions from Manure Management	CH_4	Yes	Level	
N_2O Emissions from Manure Management	N_2O	No		
Direct N_2O Emissions from Agricultural Soils	N_2O	Yes	Level, Trend	
Indirect N_2O Emissions from Nitrogen Used in Agriculture	N_2O	Yes	Level	
CH_4 Emissions from Rice Production	CH_4	No		
CH_4 Emissions from Agricultural Residue Burning	CH_4	No		
N_2O Emissions from Agricultural Residue Burning	N_2O	No		
WASTE SECTOR				
CH_4 Emissions from Solid Waste Disposal Sites	CH_4	Yes	Level, Trend	
Emissions from Wastewater Handling	CH_4	No		
Emissions from Wastewater Handling	N_2O	No		
Emissions from Waste Incineration	N_2O	No		

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8

QUALITY ASSURANCE AND QUALITY CONTROL

CO-CHAIRS, EDITORS AND EXPERTS

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Taka Hiraishi (Japan) and Buruhani Nyenzi (Tanzania)

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Carlos M Lòpez Cabrera (Cuba) and Leo A Meyer (Netherlands)

Expert Group: Quality Assurance and Quality Control (QA/QC)

CO-CHAIRS

Kay Abel (Australia) and Michael Gillenwater (USA)

AUTHOR OF BACKGROUND PAPER

Joe Mangino (USA)

CONTRIBUTORS

Sal Emmanuel (IPCC-NGGIP/TSU), Jean-Pierre Fontelle (France), Michael Gytarsky (Russia), Art Jaques (Canada), Magezi-Akiiki (Uganda), and Joe Mangino (USA)

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8 QUALITY ASSURANCE AND QUALITY CONTROL

8.1 INTRODUCTION

An important goal of IPCC *good practice guidance* is to support the development of national greenhouse gas inventories that can be readily assessed in terms of quality and completeness. It is *good practice* to implement quality assurance and quality control (QA/QC) procedures in the development of national greenhouse gas inventories to accomplish this goal.

This guidance establishes *good practice* consistent with the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (*IPCC Guidelines*). The QA/QC *good practice guidance* outlined here reflects practicality, acceptability, cost-effectiveness, existing experience, and the potential for application on a world-wide basis. A QA/QC programme contributes to the objectives of *good practice guidance*, namely to improve transparency, consistency, comparability, completeness, and confidence in national inventories of emissions estimates.

The outcomes of the QA/QC process may result in a reassessment of inventory or source category uncertainty estimates. For example, if data quality is found to be lower than previously thought and this situation cannot be rectified in the timeframe of the current inventory, the uncertainty estimates ought to be re-evaluated.

The terms ‘quality control’ and ‘quality assurance’ are often used incorrectly. The definitions of QC and QA in Box 8.1 will be used for the purposes of *good practice guidance*.

BOX 8.1

DEFINITION OF QA/QC

Quality Control (QC) is a system of routine technical activities, to measure and control the quality of the inventory as it is being developed. The QC system is designed to:

(i) Provide routine and consistent checks to ensure data integrity, correctness, and completeness;

(ii) Identify and address errors and omissions;

(iii) Document and archive inventory material and record all QC activities.

QC activities include general methods such as accuracy checks on data acquisition and calculations and the use of approved standardised procedures for emission calculations, measurements, estimating uncertainties, archiving information and reporting. Higher tier QC activities include technical reviews of source categories, activity and emission factor data, and methods.

Quality Assurance (QA) activities include a planned system of review procedures conducted by personnel not directly involved in the inventory compilation/development process. Reviews, preferably by independent third parties, should be performed upon a finalised inventory following the implementation of QC procedures. Reviews verify that data quality objectives were met, ensure that the inventory represents the best possible estimates of emissions and sinks given the current state of scientific knowledge and data available, and support the effectiveness of the QC programme.

Before implementing QA/QC activities, it is necessary to determine which techniques should be used, and where and when they will be applied. There are technical and practical considerations in making these decisions. The technical considerations related to the various QA/QC techniques are discussed in general in this chapter, and specific applications to source categories are described in the source category-specific *good practice guidance* in Chapters 2 to 5. The practical considerations involve assessing national circumstances such as available resources and expertise and the particular characteristics of the inventory. The level of QA/QC activities should be compatible with the methods or tiers used to estimate emissions for particular source categories. In addition, resources should be focused on priority areas, such as the *key source categories* (as described in Chapter 7, Methodological Choice and Recalculation, 7.2, Determining National Key Source Categories) and source categories where changes have occurred in methods or data acquisition since the last inventory compilation.

8.2 PRACTICAL CONSIDERATIONS IN DEVELOPING QA/QC SYSTEMS

Implementing QA/QC procedures requires resources, expertise and time. In developing any QA/QC system, it is expected that judgements will need to be made on the following:

- Resources allocated to QC for different source categories and the compilation process;
- Time allocated to conduct the checks and reviews of emissions estimates;
- Availability and access to information on activity data and emission factors, including data quality;
- Procedures to ensure confidentiality of inventory and source category information, when required;
- Requirements for archiving information;
- Frequency of QA/QC checks on different parts of the inventory;
- The level of QC appropriate for each source category;
- Whether increased effort on QC will result in improved emissions estimates and reduced uncertainties;
- Whether sufficient expertise is available to conduct the checks and reviews.

In practice, the QA/QC system is only part of the inventory development process and inventory agencies do not have unlimited resources. Quality control requirements, improved accuracy and reduced uncertainty need to be balanced against requirements for timeliness and cost effectiveness. A *good practice* system seeks to achieve that balance and to enable continuous improvement of inventory estimates.

Within the QA/QC system, *good practice* provides for greater effort for *key source categories* and for those source categories where data and methodological changes have recently occurred, than for other source categories. It is unlikely that inventory agencies will have sufficient resources to conduct all the QA/QC procedures outlined in this chapter on all source categories. In addition, it is not necessary to conduct all of these procedures every year. For example, data collection processes conducted by national statistical agencies are not likely to change significantly from one year to the next. Once the inventory agency has identified what quality controls are in place, assessed the uncertainty of that data, and documented the details for future inventory reference, it is unnecessary to revisit this aspect of the QC procedure every year. However, it is *good practice* to check the validity of this information periodically as changes in sample size, methods of collection, or frequency of data collection may occur. The optimal frequency of such checks will depend on national circumstances.

While focusing QA/QC activities on *key source categories* will lead to the most significant improvements in the overall inventory estimates, it is *good practice* to plan to conduct at least the general procedures outlined in Section 8.6, General QC Procedures (Tier 1), on all parts of the inventory over a period of time. Some source categories may require more frequent QA/QC than others because of their significance to the total inventory estimates, contribution to trends in emissions over time or changes in data or characteristics of the source category, including the level of uncertainty. For example, if technological advancements occur in an industrial source category, it is *good practice* to conduct a thorough QC check of the data sources and the compilation process to ensure that the inventory methods remain appropriate.

It is recognised that resource requirements will be higher in the initial stages of implementing any QA/QC system than in later years. As capacity to conduct QA/QC procedures develops in the inventory agency and in other associated organisations, improvements in efficiency should be expected.

General QC procedures outlined in Table 8.1, Tier 1 General Inventory Level QC Procedures, and a peer review of the inventory estimates are considered minimal QA/QC activities for all inventory compilations. The general procedures require no additional expertise in addition to that needed to develop the estimates and compile the inventory and should be performed on estimates developed using Tier 1 or higher tier methods for source categories. A review of the final inventory report by a person not involved in the compilation is also *good practice*, even if the inventory were compiled using only Tier 1 methods. More extensive QC and more rigorous review processes are encouraged if higher tier methods have been used. Availability of appropriate expertise may limit the degree of independence of expert reviews in some cases. The QA/QC process is intended to ensure transparency and quality.

There may be some inventory items that involve confidential information, as discussed in Chapters 2 to 5. The inventory agency should have procedures in place during a review process to ensure that reviewers respect that confidentiality.

8.3 ELEMENTS OF A QA/QC SYSTEM

The following are the major elements to be considered in the development of a QA/QC system to be implemented in tracking inventory compilation:

- An inventory agency responsible for coordinating QA/QC activities;
- A QA/QC plan;
- General QC procedures (Tier 1);
- Source category-specific QC procedures (Tier 2);
- QA review procedures;
- Reporting, documentation, and archiving procedures.

For purposes of the QA/QC system, the Tier 2 QC approach includes all procedures in Tier 1 plus additional source category-specific activities.

8.4 INVENTORY AGENCY

The inventory agency is responsible for coordinating QA/QC activities for the national inventory. The inventory agency may designate responsibilities for implementing and documenting these QA/QC procedures to other agencies or organisations. The inventory agency should ensure that other organisations involved in the preparation of the inventory are following applicable QA/QC procedures.

The inventory agency is also responsible for ensuring that the QA/QC plan is developed and implemented. It is *good practice* for the inventory agency to designate a QA/QC coordinator, who would be responsible for ensuring that the objectives of the QA/QC programme are implemented.

8.5 QA/QC PLAN

A QA/QC plan is a fundamental element of a QA/QC system, and it is *good practice* to develop one. The plan should, in general, outline QA/QC activities that will be implemented, and include a scheduled time frame that follows inventory preparation from its initial development through to final reporting in any year. It should contain an outline of the processes and schedule to review all source categories.

The QA/QC plan is an internal document to organise, plan, and implement QA/QC activities. Once developed, it can be referenced and used in subsequent inventory preparation, or modified as appropriate (i.e. when changes in processes occur or on advice of independent reviewers). This plan should be available for external review.

In developing and implementing the QA/QC plan, it may be useful to refer to the standards and guidelines published by the International Organization for Standardization (ISO), including the ISO 9000 series (see Box 8.2). Although ISO 9000 standards are not specifically designed for emissions inventories, they have been applied by some countries to help organise QA/QC activities.

BOX 8.2

ISO AS A DATA QUALITY MANAGEMENT SYSTEM

The International Organization for Standardization (ISO) series programme provides standards for data documentation and audits as part of a quality management system. Though the ISO series is not designed explicitly for emissions data development, many of the principles may be applied to ensure the production of a quality inventory. Inventory agencies may find these documents useful source material for developing QA/QC plans for greenhouse gas inventories. Some countries (e.g. the United Kingdom and the Netherlands) have already applied some elements of the ISO standards for their inventory development process and data management.

The following standards and guidelines published under the ISO series may supplement source category-specific QA/QC procedures for inventory development and provide practical guidance for ensuring data quality and a transparent reporting system.

ISO 9004-1:	General quality guidelines to implement a quality system.
ISO 9004-4:	Guidelines for implementing continuous quality improvement within the organisation, using tools and techniques based on data collection and analysis.
ISO 10005:	Guidance on how to prepare quality plans for the control of specific projects.
ISO 10011-1:	Guidelines for auditing a quality system.
ISO 10011-2:	Guidance on the qualification criteria for quality systems auditors.
ISO 10011-3:	Guidelines for managing quality system audit programmes.
ISO 10012:	Guidelines on calibration systems and statistical controls to ensure that measurements are made with the intended accuracy.
ISO 10013:	Guidelines for developing quality manuals to meet specific needs.

Source: http://www.iso.ch/

8.6 GENERAL QC PROCEDURES (TIER 1)

The focus of general QC techniques is on the processing, handling, documenting, archiving and reporting procedures that are common to all the inventory source categories. Table 8.1, Tier 1 General Inventory Level QC Procedures, lists the general QC checks that the inventory agency should use routinely throughout the preparation of the annual inventory. Most of the checks shown in Table 8.1 could be performed by cross-checks, recalculation, or through visual inspections. The results of these QC activities and procedures should be documented as set out in Section 8.10.1, Internal Documentation and Archiving, below. If checks are performed electronically, these systems should be periodically reviewed to ensure the integrity of the checking function.

It will not be possible to check all aspects of inventory input data, parameters and calculations every year. Checks may be performed on selected sets of data and processes, such that identified *key source categories* are considered every year. Checks on other source categories may be conducted less frequently. However, a sample of data and calculations from every sector should be included in the QC process each year to ensure that all sectors are addressed on an ongoing basis. In establishing criteria and processes for selecting the sample data sets and processes, it is *good practice* for the inventory agency to plan to undertake QC checks on all parts of the inventory over an appropriate period of time.

TABLE 8.1

TIER 1 GENERAL INVENTORY LEVEL QC PROCEDURES

QC Activity	Procedures
Check that assumptions and criteria for the selection of activity data and emission factors are documented.	• Cross-check descriptions of activity data and emission factors with information on source categories and ensure that these are properly recorded and archived.
Check for transcription errors in data input and reference	• Confirm that bibliographical data references are properly cited in the internal documentation. • Cross-check a sample of input data from each source category (either measurements or parameters used in calculations) for transcription errors.
Check that emissions are calculated correctly.	• Reproduce a representative sample of emissions calculations. • Selectively mimic complex model calculations with abbreviated calculations to judge relative accuracy.
Check that parameter and emission units are correctly recorded and that appropriate conversion factors are used.	• Check that units are properly labelled in calculation sheets. • Check that units are correctly carried through from beginning to end of calculations. • Check that conversion factors are correct. • Check that temporal and spatial adjustment factors are used correctly.
Check the integrity of database files.	• Confirm that the appropriate data processing steps are correctly represented in the database. • Confirm that data relationships are correctly represented in the database. • Ensure that data fields are properly labelled and have the correct design specifications. • Ensure that adequate documentation of database and model structure and operation are archived.
Check for consistency in data between source categories.	• Identify parameters (e.g. activity data, constants) that are common to multiple source categories and confirm that there is consistency in the values used for these parameters in the emissions calculations.
Check that the movement of inventory data among processing steps is correct.	• Check that emissions data are correctly aggregated from lower reporting levels to higher reporting levels when preparing summaries. • Check that emissions data are correctly transcribed between different intermediate products.

TABLE 8.1 (CONTINUED)

TIER 1 GENERAL INVENTORY LEVEL QC PROCEDURES

QC Activity	Procedures
Check that uncertainties in emissions and removals are estimated or calculated correctly.	• Check that qualifications of individuals providing expert judgement for uncertainty estimates are appropriate. • Check that qualifications, assumptions and expert judgements are recorded. Check that calculated uncertainties are complete and calculated correctly. • If necessary, duplicate error calculations or a small sample of the probability distributions used by Monte Carlo analyses.
Undertake review of internal documentation.	• Check that there is detailed internal documentation to support the estimates and enable duplication of the emission and uncertainty estimates. • Check that inventory data, supporting data, and inventory records are archived and stored to facilitate detailed review. • Check integrity of any data archiving arrangements of outside organisations involved in inventory preparation.
Check methodological and data changes resulting in re-calculations.	• Check for temporal consistency in time series input data for each source category. • Check for consistency in the algorithm/method used for calculations throughout the time series.
Undertake completeness checks.	• Confirm that estimates are reported for all source categories and for all years from the appropriate base year to the period of the current inventory. • Check that known data gaps that result in incomplete source category emissions estimates are documented.
Compare estimates to previous estimates.	• For each source category, current inventory estimates should be compared to previous estimates. If there are significant changes or departures from expected trends, re-check estimates and explain any difference.

The checks in Table 8.1, should be applied irrespective of the type of data used to develop the inventory estimates and are equally applicable to source categories where default values or national data are used as the basis for the estimates.

In some cases, emissions estimates are prepared for the inventory agency by outside consultants or agencies. The inventory agency should ensure that the QC checks listed in Table 8.1, Tier 1 General Inventory Level QC Procedure, are communicated to the consultants/agencies. This will assist in making sure that QC procedures are performed and recorded by the consultant or outside agency. The inventory agency should review these QA/QC activities. In cases where official national statistics are relied upon – primarily for activity data – QC procedures may already have been implemented on these national data. However, it is *good practice* for the inventory agency to confirm that national statistical agencies have implemented adequate QC procedures equivalent to those in Table 8.1.

Due to the quantity of data that needs to be checked for some source categories, automated checks are encouraged where possible. For example, one of the most common QC activities involves checking that data keyed into a computer database are correct. A QC procedure could be set up to use an automated range check (based on the range of expected values of the input data from the original reference) for the input values as recorded in the database. A combination of manual and automated checks may constitute the most effective procedures in checking large quantities of input data.

8.7 SOURCE CATERGORY-SPECIFIC QC PROCEDURES (TIER 2)

In contrast to general inventory QC techniques, source category-specific QC procedures are directed at specific types of data used in the methods for individual source categories and require knowledge of the emission source category, the types of data available and the parameters associated with emissions.

It is important to note that Tier 2 source category-specific QC activities are in addition to the general QC conducted as part of Tier 1 (i.e. include QC checks listed in Table 8.1). The source category-specific measures are applied on a case-by-case basis focusing on *key source categories* (see Chapter 7, Methodological Choice and Recalculation) and on source categories where significant methodological and data revisions have taken place. It is *good practice* that inventory agencies applying higher tier methods in compiling national inventories utilise Tier 2 QC procedures. Specific applications of source category-specific Tier 2 QC procedures are provided in the energy, agriculture, industrial processes and waste chapters of this report (Chapters 2 to 5).

Source category-specific QC activities include the following:

- Emission data QC;
- Activity data QC;
- QC of uncertainty estimates.

The first two activities relate to the types of data used to prepare the emissions estimates for a given source category. QC of uncertainty estimates covers activities associated with determining uncertainties in emissions estimates (for more information on the determination of these uncertainties, see Chapter 6, Quantifying Uncertainties in Practice).

The actual QC procedures that need to be implemented by the inventory agency will depend on the method used to estimate the emissions for a given source category. If estimates are developed by outside agencies, the inventory agency may, upon review, reference the QC activities of the outside agency as part of the QA/QC plan. There is no need to duplicate QC activities if the inventory agency is satisfied that the QC activities performed by the outside agency meet the minimum requirements of the QA/QC plan.

8.7.1 Emissions data QC

The following sections describe QC checks on IPCC default factors, country-specific emission factors, and direct emission measurements from individual sites (used either as the basis for a site-specific emission factor or directly for an emissions estimate). Emission comparison procedures are described in Section 8.7.1.4, Emission Comparisons. Inventory agencies should take into account the practical considerations discussed in Section 8.2, Practical Considerations in Developing QA/QC Systems, when determining what level of QC activities to undertake.

8.7.1.1 IPCC DEFAULT EMISSION FACTORS

Where IPCC default emission factors are used, it is *good practice* for the inventory agency to assess the applicability of these factors to national circumstances. This assessment may include an evaluation of national conditions compared to the context of the studies upon which the IPCC default factors were based. If there is insufficient information on the context of the IPCC default factors, the inventory agency should take account of this in assessing the uncertainty of the national emissions estimates based on the IPCC default emission factors. For *key source categories*, inventory agencies should consider options for obtaining emission factors that are known to be representative of national circumstances. The results of this assessment should be documented.

If possible, IPCC default emission factor checks could be supplemented by comparisons with national site or plant-level factors to determine their representativeness relative to actual sources in the country. This supplementary check is *good practice* even if data are only available for a small percentage of sites or plants.

8.7.1.2 COUNTRY-SPECIFIC EMISSION FACTORS

Country-specific emission factors may be developed at a national or other aggregated level within the country based on prevailing technology, science, local characteristics and other criteria. These factors are not necessarily site-specific, but are used to represent a source category or sub-source category. Two steps are necessary to ensure *good practice* emission factor QC for country-specific factors.

The first is to perform QC checks on the data used to develop the emission factors. The adequacy of the emission factors and the QA/QC performed during their development should be assessed. If emission factors were developed based on site-specific or source-level testing, then the inventory agency should check if the measurement programme included appropriate QC procedures.

Frequently, country-specific emission factors will be based on secondary data sources, such as published studies or other literature.[1] In these cases, the inventory agency could attempt to determine whether the QC activities conducted during the original preparation of the data are consistent with the applicable QC procedures outlined in Table 8.1 and whether any limitations of the secondary data have been identified and documented. The inventory agency could also attempt to establish whether the secondary data have undergone peer review and record the scope of such a review.

If it is determined that the QA/QC associated with the secondary data is adequate, then the inventory agency can simply reference the data source for QC documentation and document the applicability of the data for use in emissions estimates.

If it is determined that the QA/QC associated with the secondary data is inadequate, then the inventory agency should attempt to have QA/QC checks on the secondary data established. It should also reassess the uncertainty of any emissions estimates derived from the secondary data. The inventory agency may also reconsider how the data are used and whether any alternative data, (including IPCC default values) may provide a better estimate of emissions from this source category.

Second, country-specific factors and circumstances should be compared with relevant IPCC default factors and the characteristics of the studies on which the default factors are based. The intent of this comparison is to determine whether country-specific factors are reasonable, given similarities or differences between the national source category and the ‘average’ source category represented by the defaults. Large differences between country-specific factors and default factors should be explained and documented.

A supplementary step is to compare the country-specific factors with site-specific or plant-level factors if these are available. For example, if there are emission factors available for a few plants (but not enough to support a bottom-up approach) these plant-specific factors could be compared with the aggregated factor used in the inventory. This type of comparison provides an indication of both the reasonableness of the country-specific factor and its representativeness.

8.7.1.3 DIRECT EMISSION MEASUREMENTS

Emissions from a source category may be estimated using direct measurements in the following ways:

- Sample emissions measurements from a facility may be used to develop a representative emission factor for that individual site, or for the entire category (i.e. for development of a national level emission factor);
- Continuous emissions monitoring (CEM) data may be used to compile an annual estimate of emissions for a particular process. In theory, CEM can provide a complete set of quantified emissions data across the inventory period for an individual facility process, and does not have to be correlated back to a process parameter or input variable like an emission factor.

Regardless of how direct measurement data are being used, the inventory agency should review the processes and check the measurements as part of the QC activities.

Use of standard measurement methods improves the consistency of resulting data and knowledge of the statistical properties of the data. If standard reference methods for measuring specific greenhouse gas emissions (and removals) are available, inventory agencies should encourage plants to use these. If specific standard methods are not available, the inventory agency should confirm whether nationally or internationally recognised standard methods such as ISO 10012 are used for measurements and whether the measurement equipment is calibrated and maintained properly.

For example, ISO has published standards that specify procedures to quantify some of the performance characteristics of all air quality measurement methods such as bias, calibration, instability, lower detection limits, sensitivity, and upper limits of measurement (ISO, 1994). While these standards are not associated with a

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[1] Secondary data sources refer to reference sources for inventory data that are not designed for the express purpose of inventory development. Secondary data sources typically include national statistical databases, scientific literature, and other studies produced by agencies or organisations not associated with the inventory development.

reference method for a specific greenhouse gas source category, they have direct application to QC activities associated with estimations based on measured emission values.

Where direct measurement data from individual sites are in question, discussions with site managers can be useful to encourage improvement of the QA/QC practices at the sites. Also, supplementary QC activities are encouraged for bottom-up methods based on site-specific emission factors where significant uncertainty remains in the estimates. Site-specific factors can be compared between sites and also to IPCC or national level defaults. Significant differences between sites or between a particular site and the IPCC defaults should elicit further review and checks on calculations. Large differences should be explained and documented.

8.7.1.4 EMISSION COMPARISONS

It is standard QC practice to compare emissions from each source category with emissions previously provided from the same source category or against historical trends and reference calculations as described below. The objective of these comparisons (often referred to as ‘reality checks’) is to ensure that the emission values are not wildly improbable or that they fall within a range that is considered reasonable. If the estimates seem unreasonable, emission checks can lead to a re-evaluation of emission factors and activity data before the inventory process has advanced to its final stages.

The first step of an emissions comparison is a consistency and completeness check using available historical inventory data for multiple years. The emission levels of most source categories do not abruptly change from year to year, as changes in both activity data and emission factors are generally gradual. In most circumstances, the change in emissions will be less than 10% per year. Thus, significant changes in emissions from previous years may indicate possible input or calculation errors. After calculating differences, the larger percentage differences (in any direction) should be flagged, by visual inspection of the list, by visual inspection of the graphical presentation of differences (e.g. in a spreadsheet) or by using a dedicated software programme that puts flags and rankings in the list of differences.

It is *good practice* to also check the annual increase or decrease of changes in emissions levels in significant sub-source categories of some source categories. Sub-source categories may show greater percentage changes than the aggregated source categories. For example, total emissions from petrol cars are not likely to change substantially on an annual basis, but emissions from sub-source categories, such as catalyst-equipped petrol cars, may show substantial changes if the market share is not in equilibrium or if the technology is changing and rapidly being adopted in the marketplace.

It is *good practice* to check the emissions estimates for all source categories or sub-source categories that show greater than 10% change in a year compared to the previous year’s inventory. Source categories and sub-source categories should be ranked according to the percentage difference in emissions from the previous year.

Supplementary emission comparisons can also be performed, if appropriate, including order-of-magnitude checks and reference calculations.

ORDER-OF-MAGNITUDE CHECKS

Order of magnitude checks look for major calculation errors and exclusion of major source categories or sub-source categories. Method-based comparisons may be made depending on whether the emissions for the source category were determined using a top-down or bottom-up approach. For example, if N_2O estimates for nitric acid production were determined using a bottom-up approach (i.e. emissions estimates were determined for each individual production plant based on plant-specific data), the emissions check would consist of comparing the sum of the individual plant-level emissions to a top-down emission estimate based on national nitric acid production figures and IPCC default Tier 1 factors. If significant differences are found in the comparison, further investigation using the source category-specific QC techniques described in Section 8.7, Source Category-Specific QC Procedures (Tier 2), would be necessary to answer the following questions:

- Are there inaccuracies associated with any of the individual plant estimates (e.g. an extreme outlier may be accounting for an unreasonable quantity of emissions)?
- Are the plant-specific emission factors significantly different from each other?
- Are the plant-specific production rates consistent with published national level production rates?
- Is there any other explanation for a significant difference, such as the effect of controls, the manner in which production is reported or possibly undocumented assumptions?

This is an example of how the result of a relatively simple emission check can lead to a more intensive investigation of the representativeness of the emissions data. Knowledge of the source category is required to isolate the parameter that is causing the difference in emissions estimates and to understand the reasons for the difference.

REFERENCE CALCULATIONS

Another emission comparison may be used for source categories that rely on empirical formulas for the calculation of emissions. Where such formulas are used, final calculated emission levels should follow stochiometric ratios and conserve energy and mass. In a number of cases where emissions are calculated as the sum of sectoral activities based on the consumption of a specific commodity (e.g. fuels or products like HFCs, PFCs or SF_6), the emissions could alternatively be estimated using apparent consumption figures: national total production + import – export ± stock changes. For CO_2 from fossil fuel combustion, a reference calculation based on apparent fuel consumption per fuel type is mandatory according to the *IPCC Guidelines*. Another example is estimating emissions from manure management. The total quantity of methane produced should not exceed the quantity that could be expected based on the carbon content of the volatile solids in the manure.

Discrepancies between inventory data and reference calculations do not necessarily imply that the inventory data are in error. It is important to consider that there may be large uncertainties associated with the reference calculations themselves when analysing discrepancies.

8.7.2 Activity data QC

The estimation methods for many source categories rely on the use of activity data and associated input variables that are not directly prepared by the inventory agency. Activity data is normally collated at a national level using secondary data sources or from site-specific data prepared by site or plant personnel from their own measurements. Inventory agencies should take into account the practical considerations discussed above when determining the level of QC activities to undertake.

8.7.2.1 NATIONAL LEVEL ACTIVITY DATA

Where national activity data from secondary data sources are used in the inventory, it is *good practice* for the inventory agency or its designees to evaluate and document the associated QA/QC activities. This is particularly important with regard to activity data, since most activity data are originally prepared for purposes other than as input to estimates of greenhouse gas emissions. Though not always readily available, many statistical organisations, for example, have their own procedures for assessing the quality of the data independently of what the end use of the data may be. If it is determined that these procedures satisfy minimum activities listed in the QA/QC plan, the inventory agency can simply reference the QA/QC activities conducted by the statistical organisation.

It is *good practice* for the inventory agency to determine if the level of QC associated with secondary activity data includes those QC procedures listed in Table 8.1. In addition, the inventory agency may establish whether the secondary data have been peer reviewed and record the scope of this review. If it is determined that the QA/QC associated with the secondary data is adequate, then the inventory agency can simply reference the data source and document the applicability of the data for use in its emissions estimates.

If it is determined that the QC associated with the secondary data is inadequate, then the inventory agency should attempt to have QA/QC checks on the secondary data established. It should also reassess the uncertainty of emissions estimates in light of the findings from its assessment of the QA/QC associated with secondary data. The inventory agency should also reconsider how the data are used and whether any alternative data, including IPCC default values and international data sets, may provide for a better estimate of emissions. If no alternative data sources are available, the inventory agency should document the inadequacies associated with the secondary data QC as part of its summary report on QA/QC (see Section 8.10.2, Reporting, for reporting guidance).

For example, in the transportation category, countries typically use either fuel usage or kilometer (km) statistics to develop emissions estimates. The national statistics on fuel usage and kms travelled by vehicles are usually prepared by a different agency from the inventory agency. However, it is the responsibility of the inventory agency to determine what QA/QC activities were implemented by the agency that prepared the original fuel usage and km statistics for vehicles. Questions that may be asked in this context are:

- Does the statistical agency have a QA/QC plan that covers the preparation of the data?
- What sampling protocol was used to estimate fuel usage or kms travelled?
- How recently was the sampling protocol reviewed?
- Has any potential bias in the data been identified by the statistical agency?

- Has the statistical agency identified and documented uncertainties in the data?
- Has the statistical agency identified and documented errors in the data?

National level activity data should be compared with previous year's data for the source category being evaluated. *Activity data* for most source categories tend to exhibit relatively consistent changes from year to year without sharp increases or decreases. If the national activity data for any year diverge greatly from the historical trend, the activity data should be checked for errors. If the general mathematical checks do not reveal errors, the characteristics of the source category could be investigated and any change identified and documented.

Where possible, a comparison check of activity data from multiple reference sources should be undertaken. This is important for source categories that have a high level of uncertainty associated with their estimates. For example, many of the agricultural source-categories rely on government statistics for activity data such as livestock populations, areas under cultivation, and the extent of prescribed burning. Similar statistics may be prepared by industry, universities, or other organisations and can be used to compare with standard reference sources. As part of the QC check, the inventory agency should ascertain whether independent data have been used to derive alternative activity data sets. In some cases, the same data are treated differently by different agencies to meet varying needs. Comparisons may need to be made at a regional level or with a subset of the national data since many alternative references for such activity data have limited scope and do not cover the entire nation.

8.7.2.2 SITE-SPECIFIC ACTIVITY DATA

Some methods rely on the use of site-specific activity data used in conjunction with IPCC default or country-specific emission factors. Site or plant personnel typically prepare these estimates of activity, often for purposes other than as inputs to emissions inventories. QC checks should focus on inconsistencies between sites to establish whether these reflect errors, different measurement techniques, or real differences in emissions, operating conditions or technology.

A variety of QC checks can be used to identify errors in site-level activity data. The inventory agency should establish whether recognised national or international standards were used in measuring activity data at the individual sites. If measurements were made according to recognised national or international standards and a QA/QC process is in place, the inventory agency should satisfy itself that the QA/QC process at the site is acceptable under the inventory QA/QC plan and at least includes Tier 1 activities. Acceptable QC procedures in use at the site may be directly referenced. If the measurements were not made using standard methods and QA/QC is not of an acceptable standard, then the use of these activity data should be carefully evaluated, uncertainty estimates reconsidered, and qualifications documented.

Comparisons of activity data from different reference sources may also be used to expand the activity data QC. For example, in estimating PFC emissions from primary aluminium smelting, many inventory agencies use smelter-specific activity data to prepare the inventory estimates. A QC check of the aggregated activity data from all aluminium smelters can be made against national production statistics for the industry. Also, production data can be compared across different sites, possibly with adjustments made for plant capacities, to evaluate the reasonableness of the production data. Similar comparisons of activity data can be made for other manufacturing-based source categories where there are published data on national production. If outliers are identified, they should be investigated to determine if the difference can be explained by the unique characteristics of the site or there is an error in the reported activity.

Site-specific activity data checks may also be applied to methods based on product usage. For example, one method for estimating SF_6 emissions from use in electrical equipment relies on an account balance of gas purchases, gas sales for recycling, the amount of gas stored on site (outside of equipment), handling losses, refills for maintenance, and the total holding capacity of the equipment system. This account balance system should be used at each facility where the equipment is in place. A QC check of overall national activity could be made by performing the same kind of account balancing procedure on a national basis. This national account balancing would consider national sales of SF_6 for use in electrical equipment, the nation-wide increase in the total handling capacity of the equipment (that may be obtained from equipment manufacturers), and the quantity of SF_6 destroyed in the country. The results of the bottom-up and top-down account balancing analyses should agree or large differences should be explained. Similar accounting techniques can be used as QC checks on other categories based on gas usage (e.g. substitutes for ozone-depleting substances) to check consumption and emissions.

8.7.3 QC of uncertainty estimates

QC should also be undertaken on calculations or estimates of uncertainty associated with emissions estimates. *Good practice* for estimating inventory uncertainties is described in Chapter 6, Quantifying Uncertainties in Practice, and relies on calculations of uncertainty at the source category level that are then combined to summary levels for the entire inventory. Some of the methods rely on the use of measured data associated with the emission factors or activity data to develop probability density functions from which uncertainty estimates can be made. In the absence of measured data, many uncertainty estimates will rely on expert judgement.

It is *good practice* for QC procedures to be applied to the uncertainty estimations to confirm that calculations are correct and that there is sufficient documentation to duplicate them. The assumptions on which uncertainty estimations have been based should be documented for each source category. Calculations of source category-specific and aggregated uncertainty estimates should be checked and any errors addressed. For uncertainty estimates involving expert judgement, the qualifications of experts should also be checked and documented, as should the process of eliciting expert judgement, including information on the data considered, literature references, assumptions made and scenarios considered. Chapter 6 contains advice on how to document expert judgements on uncertainties.

8.8 QA PROCEDURES

Good practice for QA procedures requires an objective review to assess the quality of the inventory, and also to identify areas where improvements could be made. The inventory may be reviewed as a whole or in parts. QA procedures are utilised in addition to the Tier 1 and Tier 2 QC. The objective in QA implementation is to involve reviewers that can conduct an unbiased review of the inventory. It is *good practice* to use QA reviewers that have not been involved in preparing the inventory. Preferably these reviewers would be independent experts from other agencies or a national or international expert or group not closely connected with national inventory compilation. Where third party reviewers outside the inventory agency are not available, staff from another part of the inventory agency not involved in the portion of the inventory being reviewed can also fulfil QA roles.

It is *good practice* for inventory agencies to conduct a basic expert peer review (Tier 1 QA) prior to inventory submission in order to identify potential problems and make corrections where possible. It is also *good practice* to apply this review to all source categories in the inventory. However, this will not always be practical due to timing and resource constraints. *Key source categories* should be given priority as well as source categories where significant changes in methods or data have been made. Inventory agencies may also choose to perform more extensive peer reviews or audits or both as additional (Tier 2) QA procedures within the available resources.

More specific information on QA procedures related to individual source categories is provided in the source category-specific QA/QC sections in Chapters 2 to 5.

EXPERT PEER REVIEW

Expert peer review consists of a review of calculations or assumptions by experts in relevant technical fields. This procedure is generally accomplished by reviewing the documentation associated with the methods and results, but usually does not include rigorous certification of data or references such as might be undertaken in an audit. The objective of the expert peer review is to ensure that the inventory's results, assumptions, and methods are reasonable as judged by those knowledgeable in the specific field. Expert review processes may involve technical experts and, where a country has formal stakeholder and public review mechanisms in place, these reviews can supplement but not replace expert peer review.

There are no standard tools or mechanisms for expert peer review, and its use should be considered on a case-by-case basis. If there is a high level of uncertainty associated with an emission estimate for a source category, expert peer review may provide information to improve the estimate, or at least to better quantify the uncertainty. Expert reviews may be conducted on all parts of a source category. For example, if the activity data estimates from oil and natural gas production are to be reviewed but not the emission factors, experts in the oil and gas industry could be involved in the review to provide industry expertise even if they do not have direct experience in greenhouse gas emissions estimation. Effective peer reviews often involve identifying and contacting key industrial trade organisations associated with specific source categories. It is preferable for this expert input to be sought early in the inventory development process so that the experts can participate from the start. It is *good practice* to involve relevant experts in development and review of methods and data acquisition.

The results of expert peer review, and the response of the inventory agency to those findings, may be important to widespread acceptance of the final inventory. All expert peer reviews should be well documented, preferably in a report or checklist format that shows the findings and recommendations for improvement.

AUDITS

For the purpose of *good practice* in inventory preparation, audits may be used to evaluate how effectively the inventory agency complies with the minimum QC specifications outlined in the QC plan. It is important that the auditor be independent of the inventory agency as much as possible so as to be able to provide an objective assessment of the processes and data evaluated. Audits may be conducted during the preparation of an inventory, following inventory preparation, or on a previous inventory. Audits are especially useful when new emission estimation methods are adopted, or when there are substantial changes to existing methods. It is desirable for the inventory agency to develop a schedule of audits at strategic points in the inventory development. For example, audits related to initial data collection, measurement work, transcription, calculation and documentation may be conducted. Audits can be used to verify that the QC steps identified in Table 8.1 have been implemented and that source category-specific QC procedures have been implemented according to the QC plan.

8.9 VERIFICATION OF EMISSIONS DATA

Options for inventory verification processes are described in Annex 2, Verification. Verification techniques can be applied during inventory development as well as after the inventory is compiled.

Comparisons with other independently compiled, national emissions data (if available) are a quick option to evaluate completeness, approximate emission levels and correct source category allocations. These comparisons can be made for different greenhouse gases at national, sectoral, source category, and sub-source category levels, as far as the differences in definitions enable them.

Although the inventory agency is ultimately responsible for the compilation and submission of the national greenhouse gas inventory, other independent publications on this subject may be available (e.g. from scientific literature or other institutes or agencies). These documents may provide the means for comparisons with other national estimates.

The verification process can help evaluate the uncertainty in emissions estimates, taking into account the quality and context of both the original inventory data and data used for verification purposes. Where verification techniques are used, they should be reflected in the QA/QC plan. Improvements resulting from verification should be documented, as should detailed results of the verification process.

8.10 DOCUMENTATION, ARCHIVING AND REPORTING

8.10.1 Internal documentation and archiving

As part of general QC procedures, it is *good practice* to document and archive all information required to produce the national emissions inventory estimates. This includes:

- Assumptions and criteria for selection of activity data and emission factors;
- Emission factors used, including references to the IPCC document for default factors or to published references or other documentation for emission factors used in higher tier methods;
- Activity data or sufficient information to enable activity data to be traced to the referenced source;
- Information on the uncertainty associated with activity data and emission factors;
- Rationale for choice of methods;
- Methods used, including those used to estimate uncertainty;
- Changes in data inputs or methods from previous years;
- Identification of individuals providing expert judgement for uncertainty estimates and their qualifications to do so;

- Details of electronic databases or software used in production of the inventory, including versions, operating manuals, hardware requirements and any other information required to enable their later use;
- Worksheets and interim calculations for source category estimates and aggregated estimates and any re-calculations of previous estimates;
- Final inventory report and any analysis of trends from previous years;
- QA/QC plans and outcomes of QA/QC procedures.

It is *good practice* for inventory agencies to maintain this documentation for every annual inventory produced and to provide it for review. It is *good practice* to maintain and archive this documentation in such a way that every inventory estimate can be fully documented and reproduced if necessary. Inventory agencies should ensure that records are unambiguous; for example, a reference to ‘IPCC default factor’ is not sufficient. A full reference to the particular document (e.g. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*) is necessary in order to identify the source of the emission factor because there may have been several updates of default factors as new information has become available.

Records of QA/QC procedures are important information to enable continuous improvement to inventory estimates. It is *good practice* for records of QA/QC activities to include the checks/audits/reviews that were performed, when they were performed, who performed them, and corrections and modifications to the inventory resulting from the QA/QC activity.

8.10.2 Reporting

It is *good practice* to report a summary of implemented QA/QC activities and key findings as a supplement to each country’s national inventory. However, it is not practical or necessary to report all the internal documentation that is retained by the inventory agency. The summary should describe which activities were performed internally and what external reviews were conducted for each source category and on the entire inventory in accordance with the QA/QC plan. The key findings should describe major issues regarding quality of input data, methods, processing, or archiving and show how they were addressed or plan to be addressed in the future.

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ANNEX 1

CONCEPTUAL BASIS FOR UNCERTAINTY ANALYSIS

CO-CHAIRS, EDITORS AND EXPERTS

Co-chairs of the Expert Meeting on Cross-sectoral Methodologies for Uncertainty Estimation and Inventory Quality

Taka Hiraishi (Japan) and Buruhani Nyenzi (Tanzania)

REVIEW EDITOR

Richard Odingo (Kenya)

Expert Group: Conceptual Basis for Uncertainty Analysis

CO-CHAIRS

Ian Galbally (Australia) and Newton Paciornik (Brazil)

AUTHORS OF BACKGROUND PAPERS

Ian Galbally (Australia), Newton Paciornik (Brazil), and Milos Tichy (Czech Republic)

CONTRIBUTORS

Wiley Barbour (USA), Leandro Buendia (IPCC-NGGIP/TSU), Franck Jacobs (Antigua), Naoki Matsuo (Japan), Richard Odingo (Kenya), Daniela Romano (Italy), and Milos Tichy (Czech Republic)

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ANNEX 1 CONCEPTUAL BASIS FOR UNCERTAINTY ANALYSIS

A1.1 INTRODUCTION

A structured approach to the development of a methodology to estimating inventory uncertainty is needed. The requirements include:

- A method of determining uncertainties in individual terms used in the inventory;
- A method of aggregating the uncertainties of individual terms to the total inventory;
- A method of determining the significance of year to year differences and long term trends in the inventories taking into account the uncertainty information;
- An understanding of the likely uses for this information which include identifying areas requiring further research and observations and quantifying the significance of year to year and longer term changes in national greenhouse gas inventories;
- An understanding that other uncertainties may exist, such as those arising from inaccurate definitions that cannot be addressed by statistical means.

This Annex is concerned with the basis for concepts used elsewhere in this report to discuss uncertainties in greenhouse gas inventories. Some issues concerned with uncertainties in inventories requiring further research are discussed at the end of this annex.

A1.2 STATISTICAL CONCEPTS

There is a number of basic statistical concepts and terms that are central to the understanding of uncertainty in greenhouse gas inventories. These terms have common language meanings, specific meanings in the statistical literature and in some cases other specific meanings with regard to uncertainty in inventories. For definition, the reader is referred to the Glossary in Annex 3; the definitions in SBSTA-UNFCCC (1999); and the International Standards Organisation Guide to Uncertainty (ISO, 1993).

The process of estimating uncertainties in greenhouse gas inventories is based on certain characteristics of the variable of interest (input quantity) as estimated from its corresponding data set. The ideal information includes:

- The arithmetic mean (mean) of the data set;
- The standard deviation of the data set (the square root of the variance);
- The standard deviation of the mean (the standard error of the mean);
- The probability distribution of the data;
- Covariances of the input quantity with other input quantities used in the inventory calculations.

A1.2.1 Expressing uncertainty

An important aspect of an uncertainty analysis concerns the ways on how to express the uncertainties associated with individual estimates or the total inventory. The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (*IPCC Guidelines*) specify the following: ‘Where there is sufficient information to define the underlying probability distribution for conventional statistical analysis, a 95 per cent confidence interval should be calculated as a definition of the range. Uncertainty ranges can be estimated using classical analysis (Robinson, 1989) or the Monte Carlo technique (Eggleston, 1993). Otherwise, the range will have to be assessed by national experts.’

This statement indicates that the confidence interval is specified by the confidence limits defined by the 2.5 percentile and 97.5 percentile of the cumulative distribution function of the estimated quantity. Put another way, the range of an uncertain quantity within an inventory should be expressed such that: (i) there is a 95%

probability that the actual value of the quantity estimated is within the interval defined by the confidence limits, and (ii) it is equally likely that the actual value, should it be outside the range quoted, lies above or below it.

A1.2.2 Individual sample, mean value and confidence interval

A key issue in the compilation of uncertainties within inventories is the distinction between the standard deviation of the data set and the standard deviation of the sample mean. The uncertainty associated with the information being analysed (emission rate, activity data or emission factor) can be either the standard deviation of the sample population or the standard deviation of the sample mean, depending on the context (ISO 1993).

The standard deviation of the mean, known also as the standard error of the mean, is the standard deviation of the sample data set divided by the square root of the number of data points. The standard deviation and variance of the data set do not change systematically with the number of observations, but the standard deviation of the mean decreases as the number of observations increase. Within much statistical and physical science literature the standard deviation of the mean is known as the standard error of the mean, but the ISO (1993) recommends the use of the term standard deviation of the mean for this quantity.

The use of the standard deviation to estimate the limits of the confidence interval (in this case the 95% confidence interval) is directly dependent on the probability distribution of the data set or the probability function chosen to represent the data set. For some probability distributions, including those discussed later, there are analytical relationships that relate the standard deviation to the required confidence intervals. Some examples are given in Annex 3 (Glossary), and ISO (1993). Usually, a normal distribution is assumed for the variable under consideration; in this case, the confidence limits are symmetric about the mean. For a 95% confidence interval, the confidence limits are approximately 2 standard deviations of the variable, above and below the mean.

It is probable that in many circumstances, the quantification of uncertainties for the input variables of the inventory will involve analyses of small amounts of data combined with expert judgement. For this reason it is important to review the information content of small data sets. There are useful studies of the amount of information on uncertainties contained in data sets with a small number of observations (Manly, 1997; Cullen and Frey, 1999). The term examined is the 95% confidence interval of the estimate of a standard deviation. This is the uncertainty in the estimate of the standard deviation: essentially, how the standard deviation might vary from one set of observations to another where both sets of observations are made on the same quantity. Cullen and Frey (1999) have presented data from which the limits of the 95% confidence interval of the standard deviation have been derived for a normally distributed variable where the sample used to calculate the standard deviation has a given number of observations. The limits of the 95% confidence interval for repeated determinations of the standard deviation are:

- 7 observations: 0.64 and 2.2 times the standard deviation estimated from a very large number of observations;
- 20 observations: 0.76 and 1.5 times the standard deviation estimated from a very large number of observations;
- 100 observations: 0.88 and 1.2 times the standard deviation estimated from a very large number of observations.

A similar analysis of the uncertainty in estimates of confidence intervals has been done on synthetic data samples for non-normal distributions using the bootstrap technique (Manly, 1997) with similar results to those above. What these calculations emphasise is that very large numbers of observations are required to precisely estimate the variance, standard deviation and standard error of the mean of any quantity. Essentially, the confidence intervals estimated from small numbers of observations via a variance (and an assumed probability distribution) have uncertainties associated with them, and in these cases, further observations may either increase or decrease these calculated uncertainty limits. Ultimately, large numbers of observations will decrease the uncertainty limits of the standard deviation.

A1.2.3 Choosing the appropriate measure of uncertainty

The following are two hypothetical worked examples illustrating the choice of the standard error of the mean and the standard deviation of the data set as the appropriate uncertainty:

In the first case, the emission factor for a greenhouse gas from biomass burning in savanna has been measured on 9 individual occasions and varies between 0 and 6 • 10^{-3} kg kg^{-1} (mass emitted per unit mass of biomass burned) with an arithmetic mean and standard deviation of the data set of 2 • 10^{-3} kg kg^{-1} and 1 • 10^{-3} kg kg^{-1} respectively, sometimes written as 2 ± 1 • 10^{-3} kg kg^{-1}. The emission factor used for that year in the IPCC inventory algorithm is the arithmetic mean, and the uncertainty appropriate to the inventory must be based on the standard error of the mean, which is $1 \bullet 10^{-3} / \sqrt{9}$ kg kg^{-1} or 3.3 • 10^{-4} kg kg^{-1}, a factor of three smaller than the standard deviation. The mean and 95% confidence interval is then encompassed by 2 ± 0.7 • 10^{-3} kg kg^{-1}.

The second case involves a component of an inventory, for which there is a single estimate for a particular year that has been calculated on more than one occasion. Such recalculations have occurred as a result of changes in agreed methodology, during audits of the inventory, or as a result of the emergence of new data. In this case, it is the standard deviation of the sample set that is appropriate and not the standard deviation of the mean.

An illustration of this point may be made using a set of national estimates of waste to landfill given in Table A1.1. These are the activity data needed to calculate greenhouse gas emissions from waste.

TABLE A1.1
NATIONAL ESTIMATES OF MASS OF WASTE TO LANDFILL FOR THE YEAR 1990

Source and year of estimate	Mass (kilotonnes)
Technology Commission, 1991	12,274
Consultant 1994	11,524
National inventory 1994	14,663
National inventory revision 1995	16,448
National inventory revision 1996	12,840
Academic review 1995	22,000
Mean	**14,958**
Standard deviation	**3,883**

We note that the mean and the 95% confidence interval based on the standard error of the mean of the six estimates is 14,958 ±3,107. However, in the case, where the 1996 inventory estimate is used, only a single estimate is used and the uncertainty appropriate for inventory is calculated from the standard deviation of the data set.

Specifically, based only on the evidence in Table A1.1, the 95% confidence interval associated with the 1996 estimate should be two standard deviations, namely 12,840 ± 7,610. As it is a single estimate, a re-evaluation of the data is needed. This happens because the 1996 estimate is not the mean value of many independent determinations.

Choosing the appropriate measure of uncertainty depends on the context of the analysis. If only one data point per inventory period is available, the uncertainty range should be based on the probability density function of the population if this is known or can be derived from other sources. The choices made should be reviewed as part of the expert review process for the inventory.

A1.2.4 Probability functions

When multiple determinations are made of a quantity that is an input to the inventory, a set of data is obtained that has variability. The issue is how to represent this variability in a compact way. One approach is to determine the following summary statistics (ISO, 1993; Cullen and Frey, 1999):

- Arithmetic mean;

- Variance;
- Skewness (asymmetry of the distribution);
- Kurtosis (peakedness of the distribution).

However, when focusing on the determination of uncertainty limits on the input data in terms of frequency (the 95% confidence limits) additional information about the data set is needed as well as summary statistics. This additional information can be obtained by representing the data as a probability distribution, either cumulative or as a density distribution (ISO, 1993; Cullen and Frey 1999). This is the approach adopted in Chapter 6, Quantifying Uncertainties in Practice. An empirical cumulative distribution provides a relationship between the percentiles and the data.[1] A percentile is the percentage of values in the data set that are less than or equal to a given value of the quantity.

For the subsequent task of calculating the propagation of errors in a complex system (using either analytical or computational approaches), empirical probability distributions are unwieldy. The common approach is to replace the empirical distribution with an analytical function, either a cumulative distribution function (CDF) or a probability density function (PDF) which is the first derivative of the CDF. These functions are, in fact, the first component of a model of the uncertainty process. Also, they are only an approximation to the real data. These probability functions are essential for two aspects of the uncertainty work. The functions are required for (i) the propagation of uncertainties and (ii) for the determination of the confidence interval of the quantity being considered.

There are many probability functions available in the statistical literature and often representing particular situations from the physical world. Examples of such functions and the situations they represent are:

- The normal distribution – human heights;
- The lognormal distribution – concentrations of chemicals in the environment.

These functions can also be expressed in truncated forms to represent the situation when there are known physical limits on the possible range of the data.

Other distributions are used to represent the absence of information on the processes. Examples are:

- The uniform distribution – all values in a given range have equal probability;
- The triangular distribution – upper and lower limits and a preferred value in this range are assigned.

The issue of identifying which function best fits a set of data can be difficult. One approach is to use the square of the skewness and the kurtosis to define functional forms that can fit the data (Cullen and Frey, 1999). The function is then fitted to the data by least squares fit or other means. Tests are available to assess the goodness of fit, including the chi-squared test and others (Cullen and Frey, 1999). In many cases, several functions will fit the data satisfactorily within a given probability limit. These different functions can have radically different distributions at the extremes where there are few or no data to constrain them, and the choice of one function over another can systematically change the outcome of an uncertainty analysis. Cullen and Frey (1999) reiterate the advice of previous authors in these cases that *it must be knowledge of the underlying physical processes that governs the choice of a probability function.* What the tests provide, in the light of this physical knowledge, is guidance on whether this function does or does not satisfactorily fit the data.

A1.2.5 Good practice guidance for selecting a probability density function

The criteria of comparability, consistency and transparency in emission inventories, as defined earlier, are best met when:

- The minimum number of probability functions are used;
- These probability functions are well known and well based.

Such probability functions would be the default probability functions.

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[1] A key point with regard to both data sets and their representation as empirical cumulative probability distributions is that no information is available on the likely values of the quantity for percentile probabilities either less than 50/*n*, or greater than (100-50/*n*) where *n* is the number of observations. In fact the probability data in the tails are very uncertain.

The criteria of accuracy are met when either:

- The default probability functions provide a good fit to the data; or
- A more appropriate probability function is used in the event that either the default probability functions fail to provide a good fit to the data or there is compelling scientific evidence to use another probability function.

The following *good practice guidance* describes how inventory agencies can meet these criteria:

(i) Where empirical data are available, the first choice should be to assume a normal distribution of the data (either in complete or truncated form to avoid negative values, if these would be unrealistic), unless the scatter plot of the data suggests a better fit to another distribution;

(ii) Where expert judgement is used, the distribution function adopted should be normal or lognormal as in (i), supplemented by uniform or triangular distributions as described in Annex 3;

(iii) That other distributions are used only where there are compelling reasons, either from empirical observations or from expert judgement backed up by theoretical argument.

A1.2.6 Characterising probability density functions for uncertainty analyses

The characteristics of PDFs that are relevant to the quantification and aggregation of uncertainties associated with quantities included in national greenhouse gas inventories, are:

- The mathematical form of the PDF;
- The parameters required as input values to specify the PDF;
- The relationships between these parameters that specify the PDF and available data about the quantity being described;
- The mean, variance and standard error of the mean, calculated from the data set that are used to determine the parameters of the PDF.

In selecting the input values and the PDF, the inventory compiler must distinguish between occasions where the appropriate uncertainty is the standard deviation or confidence intervals of the data set, or the appropriate uncertainty is the standard error of the mean value.

As previously mentioned, the wrong choice of the measure used to estimate the uncertainty would lead to spurious results.

A1.3 SOURCES OF UNCERTAINTY IN INVENTORIES

Some sources of uncertainty are addressable by statistical means, others are outside the scope of statistics (ISO 1993).

Uncertainty in inventories arises through at least three different processes:

- Uncertainties from definitions (e.g. meaning incomplete, unclear, or faulty definition of an emission or uptake);
- Uncertainties from natural variability of the process that produces an emission or uptake;
- Uncertainties resulting from the assessment of the process or quantity, including, depending on the method used,: (i) uncertainties from measuring; (ii) uncertainties from sampling; (iii) uncertainties from reference data that may be incompletely described; and (iv) uncertainties from expert judgement.

Uncertainties due to poor definitions are related to completeness and attribution to source categories and should be eliminated as far as possible before undertaking uncertainty analysis.

Uncertainties from natural variability are inherent to the emission process and can be assessed by statistical analysis of representative data.

Uncertainties that arise due to imperfect measurement include:

- Personal bias in measuring, recording and transmitting information;
- Finite instrument resolution or discrimination threshold;
- Inexact values of measurement standards and reference materials;
- Inexact values of constants and other parameters obtained from external sources and used in the data-reduction algorithm (e.g. default values from the *IPCC Guidelines*);
- Approximations and assumptions incorporated in the measurement method and estimation procedure;
- Variations in repeated observations of the emission or uptake or associated quantity under apparently identical conditions.

While continuous emission measurements can reduce overall uncertainty, it usually has limited application on the evaluation of GHG emissions. Periodic and random sampling are more frequently employed, introducing further uncertainties like:

- *Random sampling error*. This source of uncertainty is associated with data that are a random sample of a finite sample size and typically depends on the variance of the population from which the sample is extracted and the size of the sample itself (number of data points).
- *Lack of representativeness*. This source of uncertainty is associated with lack of complete correspondence between conditions associated with the available data and the conditions associated with real world emissions or activity. For example, emissions data may be available for situations in which a plant is operating at full load but not for situations involving start-up or load changes. In this case, the data are only partly relevant to the desired emission estimate.

Uncertainties due to expert judgement cannot, by definition, be assessed by statistical means since expert judgements are only used where empirical data are sparse or unavailable. However, expert judgements, provided they are treated according to the practical procedures summarised here and in Chapter 6, Quantifying Uncertainties in Practice, can be combined with empirical data for analysis using statistical procedures.

All of these sources of uncertainty need to be accounted for in the assessment of uncertainties in inventories.

The International Standards Organisation (ISO, 1993) stresses that with ‘natural materials’ the uncertainty due to sampling and due to the requirement to obtain a representative sample can outweigh the uncertainties due to the measurement technique. Sampling issues apply to the evaluation of inventory uncertainties. The achievement or failure to obtain representative sampling directly affects the uncertainty in an inventory. The overall problem of determining the uncertainty in these inventories is a mixture of a statistical problem in error analysis and a problem in matching the statistical and inventory concepts to occurrences in the real world.

A1.4 ASSESSMENT, RECORDING AND PROPAGATION OF UNCERTAINTIES IN INVENTORIES

A1.4.1 Determination and recording of uncertainties in input data

The measure of every physical quantity that is input data into the inventory algorithms has some associated uncertainty. In some select cases, such as the ratio of molecular weights, the uncertainty is negligible for the purposes of the inventory, but in almost all other cases, the uncertainty requires evaluation.

There are several underlying principles that govern *good practice* with regard to the estimation of uncertainties in input data for inventories. The ideal situation is that there are hundreds of measurements of the input quantity and the confidence intervals can be estimated by classical statistical methods. However, in most cases, there are few or no data available. Four types of information that can be used to varying degrees to deal with specific situations are:

- Available measurements of the quantity;
- Knowledge of extreme values of the quantity;

- Knowledge of the underlying processes regulating the quantity and its variance;
- Expert judgement.

The collection and recording of information about the uncertainty in input data is critical to the success and transparency of the uncertainty analysis. Box A1.1 lists the information required for an extensive and transparent uncertainty analysis which is consistent with *good practice*. In practical terms, the full information may not be available and expert judgement may be required.

BOX A1.1

DESIRABLE INFORMATION FOR EACH INPUT QUANTITY IN A NATIONAL GREENHOUSE GAS INVENTORY FOR A TRANSPARENT UNCERTAINTY ANALYSIS

(i) Name of the quantity;

(ii) Units;

(iii) A description of the spatial, temporal and system domain that this quantity represents;

(iv) Input value of the quantity;

(v) Specification of whether this is a mean value from a set of data or a single observation;

(vi) Specification of whether the uncertainty required is the standard deviation of the sample mean or the standard deviation of the population;

(vii) Size of the sample or number of estimates of the quantity available;

(viii) The estimate of the standard deviation of the sample mean or the estimate of the standard deviation of the population;

(ix) Estimates of the variance of the quantity from knowledge about the controlling factors and processes influencing the quantity;

(x) Upper and lower limits to the values of the quantity based on scientific analyses and expert judgement;

(xi) The preferred probability density function;

(xii) The input parameters to specify the probability density function;

(xiii) Succinct rationale explaining the basis or cause of the uncertainty;

(xiv) References to the source of expert judgement and data used in this tabulation;

(xv) Documentation of the peer review of the analysis.

A1.4.1.1 EXPERT JUDGEMENT

In situations where it is impractical to obtain reliable data or where existing inventory data lack sufficient statistical information, it may be necessary to elicit expert judgements about the nature and properties of the input data. Experts may be reluctant to provide quantitative information regarding data quality and uncertainty, preferring instead to provide relative levels of uncertainty or other qualitative inputs. Elicitation protocols, discussed in Chapter 6, Quantifying Uncertainties in Practice, may be helpful in overcoming these concerns, and if necessary the experts should be made aware of the existence of IPCC default uncertainty ranges which would be used in the absence of their judgements.

The use of expert judgement to make these quantitative uncertainty estimates is acceptable, provided it takes into account all the available data and involves reasoned formation of opinions by someone with special knowledge or experience with the particular quantity being examined, and provided that the judgement is documented and can be explained with sufficient clarity to satisfy outside scrutiny (Cullen and Frey, 1999). The key requirement in making estimates of uncertainty by expert judgement or otherwise, is that all the possible sources of uncertainty are considered.

Frequently, there are few observations from which to determine input data into these inventories, and so there must be considerable reliance on expert judgement. There should be a recognition that the results of quantitative uncertainty analyses for inventories provide, at best, an estimate of their uncertainty, but that there are also substantial uncertainties attached to these confidence intervals.

A1.4.2 Representative sampling, algorithms and covariance

Issues of representative sampling and the development of adequate algorithms to represent emissions are closely linked. The issue of representative sampling arises because the inventory must capture all of the emissions (or uptake) within the national border and over the period of the inventory. However, measurements are limited by time and space. The emissions of the different activities are calculated as the product of activity data and the related emission factor. The data for both of these variables have to be representative of the reality of the spatial and temporal domain considered. An emission factor is considered representative if it is calculated as the weighted average of all the emission factors related to all the different typologies of processes or products, where the weights are the percentages that different productions/products are of the total. Activity data can be considered representative if they include all of the activities in the period considered. There are many cases in which activity data and emission factors are not available for a region or for a specific category of process so there is a need to estimate emissions using emission factors determined in a different region or different category of processes. This is the process of extrapolation. Otherwise, it may be possible to calculate the values using proxy variables. Whenever extrapolation or proxy variables are used, an evaluation of the representativeness of the values chosen is needed. The data are more representative and so more accurate if a similar condition or similar process is used.

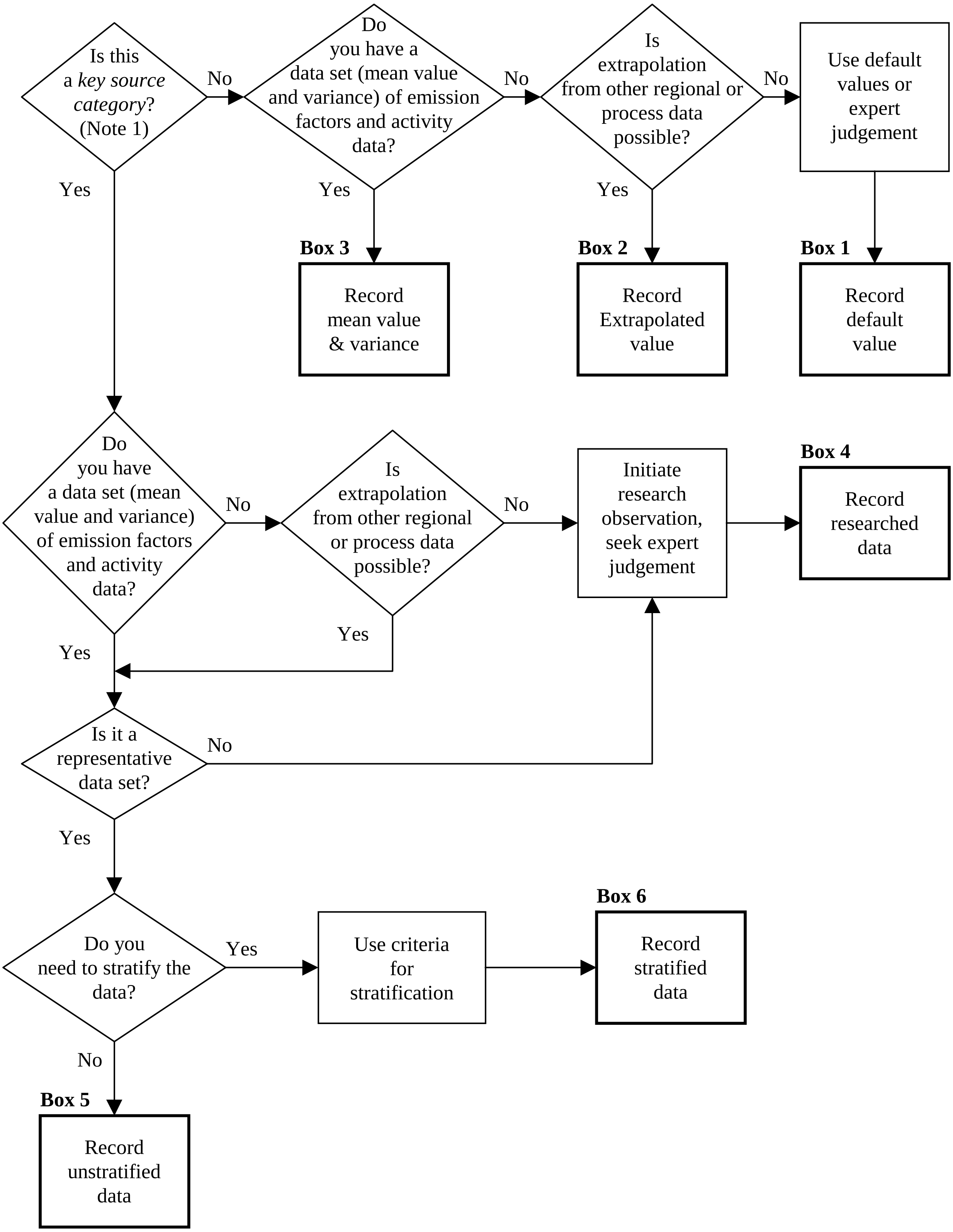
There are statistical methods to estimate the uncertainty associated with extrapolation provided the available data arise from random sampling. However, in the cases of national inventories, it is rare that data come from random sampling. Consequently, in view of the heterogeneous nature of greenhouse gas emissions and uptakes, the key issue with regard to extrapolation is that of the uncertainty associated with unrepresentative or representative sampling. For example, extrapolation of a known emission rate derived from irrigated rice to a countryside including rainfed rice will result in high uncertainty. In contrast, it is possible to stratify the activity data in the country into irrigated and rainfed rice and produce a far more reliable analysis. In the biosphere, homogeneity is rarely present and use of stratification is a powerful technique to manage and reduce the uncertainty in inventory estimates.

If there are sufficient resources, it may be possible to undertake a monitoring campaign and design a stratified sample of measurements choosing the most appropriate variables to stratify the sample (products, processes, plants, territory, population). The whole set of data can be used to estimate the probability density function and summary statistics. Then statistical tools can be used to calculate bias of the mean and variance, confidence intervals and the distribution of the errors. When data are missing at a regional level, it is possible to extrapolate information from existing literature provided that care is taken to choose data coming from sources with similar characteristics to those being estimated. In this case, expert judgement is needed.

This activity/process involves a minimal set of procedures outlined in the decision tree in Figure A1.1.

Firstly, one needs to ascertain whether or not the data are for a key emission source category (as described in Chapter 7, Methodological Choice and Recalculation). If the source category is not a key source then the use of the existing data set, extrapolated values, default values, or expert judgement is appropriate and these data can be recorded. If the source category is a key source then either there will be an existing complete data set, or it is possible to extrapolate a data set, or there is a need to initiate observations or gather data. Then there is a need to test the data set for representativeness which could require stratification (for refinement/improvement of accuracy). Finally, all data need to be recorded. These pathways are presented in Figure A1.1. It is necessary to consider the averaging time of the data versus the averaging time of the inventory, and the geographic applicability of the data. For example, data for a given emission factor may be based upon short-term (e.g. hourly, daily) measurements taken in one country under conditions that might be specific to that location, but there may be a need to use this data to estimate both annual emissions and their uncertainty in a different country. The analyst is encouraged to use reasonable judgements and methods to develop an appropriately representative estimate of uncertainty as input to an emission inventory. Such adjustments, although not always perfect, are preferable to using a non-representative data set. A corollary of this is that there is a burden on the analyst to justify the assumptions used in a particular assessment, and to be careful about using ‘defaults’ that in fact may not be directly applicable in a given situation.

Figure A1.1 A Flow Chart and Decision Tree for Actions Concerning the Representativeness of Data



Note 1: A *key source category* is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emission, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation, Section 7.2, Determining National Key Source Categories.)

In most cases, it is impossible to directly measure a significant portion of the emissions in a source category over a significant part of the year for a country. What is required for the inventory is the sum of the emissions and uptakes over the entire country and the whole inventory year whereas what is directly measured are the emissions and uptakes for a time much less than a year and for an area much smaller than the national domain. The observed emission is only a sub-set of the required inventory and so a method of extrapolation of the emissions is required.

The method of extrapolation is based on the algorithms in the *IPCC Guidelines* and knowledge of the input quantities throughout the country and over the inventory year. As interest in greenhouse gas emissions has only recently emerged, the measurements necessary to quantify the emissions have been made at only a limited number of locations under a limited range of conditions. The algorithm used for emission estimation is an approximation that includes only the major variables apparent from the available measurements and generally accounts for only a limited amount of the variance in the available data. At the same time many possibly important sources of covariance in the actual emissions disappear from the inventory calculations because of incomplete knowledge of the emission process.

An efficient method to collect further representative data and to simultaneously improve the quality of the algorithms is to conduct a programme of stratified sampling of the emissions and relevant supporting information. Stratified sampling is a common statistical technique (Cochran, 1963).

There are several steps in stratified sampling. The first step involves identifying variables (environmental, technological etc.) that are known to have a significant influence on the emissions in question. Knowledge about the influence of these variables can come from laboratory studies, theoretical modelling, field observations and elsewhere. Having identified the key variables, one must estimate the cumulative distributions for these variables over the inventory domain. Finally, one must check if the available observations constitute a representative sample from these distributions. If not, the distributions can be divided into strata, and a sampling programme designed and undertaken to get representative data. These representative data can be used to revise the emission algorithm. An emission algorithm based on a representative data set is an essential prerequisite for high inventory quality.

An example is presented to illustrate these issues about representative data. The example concerns the emissions of nitrous oxide (N_2O) from fertiliser application to dry land crops. Most of the data used to construct the current IPCC Inventory algorithm and default global emission factor comes from northern hemisphere temperate cropping systems. Bouwman (1996) presented an excellent systematic analysis of the data (available at that time) on the N_2O emissions arising from fertiliser application and derived an algorithm based solely on the amount of fertiliser nitrogen applied and an emission factor. However, as Bouwman (1996) acknowledged, soil science indicates that there are other key factors that can contribute to the variance in emissions including soil temperature, soil fertility, the frequency and amount of rainfall and waterlogging of the soil, and fertiliser composition. A consequence is that the emission factor, derived mainly from northern hemisphere temperate cropping systems may not be appropriate in hot tropical climates where the relevant environmental variables, such as soil temperature and rainfall frequency are entirely different from those in temperate latitudes. When the IPCC algorithm and emission factor (which are based on the best available data) are applied in tropical regions the resulting emission estimates may be unintentionally biased. The potential bias arises from the lack of adequate emission data in the tropics. Thus there is a problem concerning the representativeness of the underlying data for N_2O emissions from fertiliser application. What is needed, where there is a lack of representative data for a key emission or uptake, is the establishment of appropriate measurement, in this case of emissions of N_2O from fertiliser application in the tropics, and afterwards a review of the algorithm and emission factor. In some cases such as this, the global default emission factors should be replaced by regional ones, if more appropriate. This process of reviewing the representativeness of the data and acting to fill key data gaps should lead to a substantial increase in confidence of an inventory estimate. This is a key issue for reducing uncertainty in inventories and represents *good practice*. This example is only one of many cases where the representativeness of key data could be improved.

An associated issue concerning uncertainty and the review of algorithms, is that there may be considerable unexplained variance in an algorithm developed from a data set. This unexplained variance should be represented in uncertainty estimates for each parameter in the algorithm, including the exponents. Subsequent uncertainty analysis must include allowance for these uncertainties.

Stratified sampling is a useful technique in situations where covariance between activity data and emission factors is present. Covariance is reduced by stratifying activity data and emission factors into carefully selected sets. This approach has already been applied extensively within the IPCC inventory methodology.

Some numerical packages for Monte Carlo propagation of errors include covariances in their calculations, and require as input, the correlation matrix between all input quantities. Hence, it is important to have methods of either estimating these correlations or of circumventing the need for them.

The issue that arises in inventory compilation, and particularly in this step of calculation of uncertainty in an emission estimate, is the determination of the likely value of the covariance, or the related correlation coefficient between the various input quantities, in this case between the various activities and also between the activities and their associated emission factors. There is need for evaluation of these correlation coefficients for a range of inventory categories: stationary combustion, mobile sources, fugitive emissions, industrial processes, agriculture and land use change and forestry. Knowledge of correlation is required irrespective of the method used for the calculation of uncertainties, either the propagation of errors equation or the Monte Carlo method.

An example of a possible correlation between activity and emission factor for a single source category occurs when there is an elevated emission on start up of the equipment. In this case, there is an association of low local activity or frequent short periods of activity (in time or space) with high emissions, and fewer longer periods of local activity with lower emissions, this being negative correlation.

Similarly, with methane (CH_4) from animals, there will be a correlation between total animal numbers and average bodyweight over the course of the year which can produce a covariance affecting the animal CH_4 emissions. The effect of this covariance on the emissions can be minimised by disaggregating the calculations according to animal age and season of the year.

A1.4.3 Propagation of uncertainties

There are many methods that can be used for the propagation of uncertainties including those under the general descriptions of analytical methods, approximation methods and numerical methods. For the purpose of propagating uncertainties in national greenhouse gas inventories, we discuss two general methods: the approximation method based on a first order Taylor series expansion, often referred to as the error propagation equation, and the numerical Monte Carlo method.

A1.4.3.1 ERROR PROPAGATION EQUATION

In the first approach, an uncertainty in an emission can be propagated from uncertainties in the activity and the emission factor through the error propagation equation (Mandel 1984, Bevington and Robinson 1992). This method is presented in the current *IPCC Guidelines* where the conditions imposed for use of the method are:

- The uncertainties are relatively small, the standard deviation divided by the mean value being less than 0.3;
- The uncertainties have Gaussian (normal) distributions;[2]
- The uncertainties have no significant covariance.

Under these conditions, the uncertainty calculated for the emission rate is appropriate. The method can be extended to allow for covariances.

The error propagation equation is a method of combining variances and covariances for a variety of functions, including those used in inventories. In this approach, non-linear equations can be expanded using the Taylor expansion. This approach provides an exact solution for additive linear functions and an approximation for products of two terms. Most emission inventories are sums of emissions, E, that are the products of activity data, A, and emission factors, F. Assuming that both quantities have some uncertainty, such inventory equations are non-linear with respect to uncertainty calculations. Therefore the error propagation equation provides only an approximate estimate of the combined uncertainty that is increasingly inaccurate for larger deviations. Systematic error caused by neglecting this non-linearity in inventories can be assessed case by case. The method is very inaccurate with respect to functions containing inverse, higher power or exponential terms (Cullen and Frey, 1999). Terms can be included to allow for the effects of covariance.

When the activity and emission factor are mutually independent, their variances for a single source category can be combined according to Equation A1.1.

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[2] In fact, this condition that the uncertainties have Gaussian (normal) distributions is not necessary for the method to be applicable.

EQUATION A1.1

$$\sigma_E{}^2 = \sigma_A{}^2 F^2 + \sigma_F{}^2 A^2$$

Where $\sigma_E{}^2$ is the emission variance, $\sigma_A{}^2$ is the variance of the activity data, $\sigma_F{}^2$ is the variance of the emission factor, A is the expected value of the activity data, and F is the expected value of the emission factor.

When the variables are correlated, but the uncertainties are small, then the following approach is valid. The covariance, cov(x,y), between two variables can be derived from their correlation coefficient, r_{xy}, and the standard deviations as follows:

EQUATION A1.2

$$\mathrm{cov}(x,y) = r_{xy}\sigma_x\sigma_y$$

Equation A1.1 is expanded to:

EQUATION A1.3

$$\sigma_E{}^2 = \sigma_A{}^2 F^2 + \sigma_F{}^2 A^2 + 2r_{AF}\sigma_A\sigma_F AF$$

Inspection of Equation A1.3 shows that the variance of the product can, in the extreme case, double or go to zero if the correlation between the two components approaches its extreme values of +1.0 and –1.0 and the coefficients of variation are of equal value. In practical terms, correlation between emission factors and activity data should be dealt with by stratifying the data or combining the categories where covariance occurs, and these are the approaches adopted in the advice on source specific *good practices* in Chapter 6, Quantifying Uncertainties in Practice.

To estimate the uncertainty of an estimate which results from the sum of independent sources E_1 and E_2 where $E = E_1 + E_2$, one can apply the error propagation equation presented in Equation A1.4.

EQUATION A1.4

$$\sigma_E{}^2 = \sigma_{E_1}{}^2 + \sigma_{E_2}{}^2$$

If the source categories (or sinks) are correlated, the error propagation equation provided in Equation A1.4 does not hold and Equation A1.5 should be applied.

EQUATION A1. 5

$$\sigma_E{}^2 = \sigma_{E_1}{}^2 + \sigma_{E_2}{}^2 + 2r_{E_1E_2}\sigma_{E_1}\sigma_{E_2}E_1E_2$$

Once the summation exceeds two terms and covariance occurs, the use of the Monte Carlo approach is preferable where resources are available.

A1.4.3.2 MONTE CARLO APPROACH

Numerical statistical techniques, particularly the Monte Carlo technique, are suitable for estimating uncertainty in emission rates (from uncertainties in activity measures and emission factors) when:

- Uncertainties are large;
- Their distribution are non-Gaussian;
- The algorithms are complex functions;
- Correlations occur between some of the activity data sets, emission factors, or both.

Uncertainties in emission factors or activity data or both are often large and may not have normal distributions. In these cases, it may be difficult or impossible to combine uncertainties using the conventional statistical rules. Monte Carlo analysis can deal with this situation. The principle is to perform the inventory calculation many times by electronic computer, each time with the uncertain emission factors or model parameters and activity data chosen randomly (by the computer) within the distribution of uncertainties specified initially by the user. This process generates an uncertainty distribution for the inventory estimate that is consistent with the input uncertainty distributions on the emission factors, model parameters and activity data. The method is very data and computing time intensive, but is well suited to the problem of propagating and aggregating uncertainties in an extensive system such as a national greenhouse gas inventory. More detailed descriptions and applications of this method are presented in Annex 3, Glossary, and in Bevington and Robinson (1992), Manly (1997) and Cullen and Frey (1999).

A1.4.4 Propagation of uncertainties in the whole inventory

The task of propagation of uncertainties in the inventory, after the individual uncertainties for each class of emission are estimated, is simpler than the task of propagation of uncertainties in algorithms, because only addition and subtraction are used in aggregating the emissions and uptakes.

In aggregating uncertainties, two different processes occur. Firstly, there is the aggregation of emissions of a single gas which obeys the rules of propagation of uncertainties already discussed. The other case is the aggregation of uncertainties from several gases. In this case, the emissions and uptakes must be reduced to a common scale, and the process for this is the use of global warming potentials (GWPs). However, for the gases nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs) there is no IPCC accepted GWP. Consequently, the emissions and uptakes of these gases cannot be included in an aggregated uncertainty for an emissions inventory. Furthermore, it should be kept in mind that GWP values have a rather important uncertainty associated with them and that an overall scientific appraisal of the total equivalent emission should take this into account.

As some of the variables to be aggregated are non-Gaussian, have large variances, and are correlated with other variables, the use of a Monte Carlo approach to the aggregation of uncertainty is the preferred approach. The application of this method to inventory uncertainty calculations is presented in Chapter 6, Quantifying Uncertainties in Practice.

There is the option, as a working approximation, to estimate the overall uncertainty in an inventory using the Central Limit theorem (Cullen and Frey 1999). The assumptions relevant to the Central Limit theorem are:

- The number of emission and uptake terms are large;
- No single term dominates the sum;
- The emissions and uptakes are independent.

If this is the case then the sum of the variances of all the terms equals the variance of the total inventory, and the distribution of the total emissions is normal. Thus the interval defined by approximately two standard deviations either side of the mean is the 95% confidence interval of the inventory. As noted above this approach is a gross approximation. Its use in aggregating uncertainties is an option for use at the Tier 1 of an inventory uncertainty system. The simplified spreadsheet approach to uncertainty analysis described in Chapter 6 uses this approach.

A1.4.5 Covariance and autocorrelation

The subsequent discussions assume that the uncertainty propagation calculations are carried out by a Monte Carlo procedure.

The emissions (or uptake) estimates of two components of the inventory are represented by the functions $E_1(t)$ and $E_2(t)$ where t is the year of the inventory estimate. These estimates have uncertainties represented by $\delta_1(t)$ and $\delta_2(t)$ respectively.

There are at least four significant sources of covariance in the overall inventory. These arise from:

- Use of common activity data for several emissions estimates (as occurs in the suite of gases from combustion);

- Mutual constraints on a group of emission estimates (such as a specified total fuel usage or total manure production which provides input to a number of processes);
- The evolution of activities and emission factors associated with new processes, technology etc. decoupling the uncertainties from one time period to the next;
- External drivers that affect a suite of emissions or uptakes (economic, climatic, resource based).

For the purpose of calculating uncertainties, we are only interested in covariance between the uncertainties represented by $\delta_1(t)$ and $\delta_2(t)$. While covariance does occur between $E_1(t)$ and $E_2(t)$ and such covariance is relevant to the issues of understanding and projecting emissions and uptakes, it is not of primary relevance to the issue of aggregating uncertainties etc. Therefore of these four sources of covariance, the first three are central to determining uncertainties. The first source of covariance, the use of common activities over a range of inventory components occurs particularly when several gases are emitted from the same process, such as in fossil fuel combustion or biomass burning. The use of the same activity in two different emission estimates will lead to a positive covariance between two emission estimates. One effective way to remove this source of covariance is to combine the equations into a single formula, having one activity and the sum of several emission factors (expressed in CO_2 equivalent).

The second type of covariance occurs when there is a mutual constraint on a set of activities or emission factors, where a total activity is entered and proportions for each treatment pathway are prescribed to divide this activity amongst several emissions processes and algorithms. An example of this is the proportioning of animal manure between different manure waste management systems. In this case, the system can be over specified if all proportions and their uncertainties are solved simultaneously. The appropriate method of removing the covariance is to leave one of the proportions unspecified, and to determine it by the difference between the other proportions and the total fraction. This removes the necessity to specify the correlation of other terms with the residual component. However, if there are correlations between the specified proportions or between the specified proportions and the total activity, these need to be quantified and used in the uncertainty propagation calculations.

The third type of covariance arises when new measurement techniques, new methods of recording data, or new technologies remove existing uncertainties and introduce new uncertainties, reducing the degree of autocorrelation of the series over time. Autocorrelations will be high when technology, measurement techniques and the gathering of statistics are unchanging, and low when they change. Engineering and social sciences have a wealth of information to contribute on these rates of change (Grübler *et al.*, 1999). Now that the records of national inventories are approaching a decade in length, there is a need for analysis of these covariances.

A1.4.6 Systematic compilation of uncertainty in inventory components

The key features of *good practice* for the determination of uncertainty in an individual greenhouse gas emission or uptake in an inventory have been presented in the previous sections. These are presented in Box A1.2.

There is need for revision of the IPCC standard reporting tables to include information on uncertainties. In the summary tables, the information recorded could be limited to confidence intervals with limits at 2.5% and 97.5% respectively. The full information described in Boxes A1.1 and A1.2 should be recorded. The practice of uncertainty analysis in inventories is presented in detail in Chapter 6, Quantifying Uncertainties in Practice.

A1.5 APPLICATIONS

A1.5.1 Significance of year to year differences and trends in inventories

A major component of uncertainty analysis for inventories is the determination of year to year and longer-term differences in national emissions.

If two years, t_1 and t_2, in a time series are considered, the difference in the total emissions between these years can be represented using the symbols defined in Section A1.4.5 above, by:

EQUATION A1.6

$$\Delta E(t_1 - t_2) = E(t_1) - E(t_2)$$

and the variance of the difference is defined by:

EQUATION A1.7

$$\sigma^2_{\Delta E} = \sigma^2_{E_1} + \sigma^2_{E_2} - 2\,\mathrm{cov}(\delta E_1, \delta E_2)$$

or

EQUATION A1.8

$$\sigma^2_{\Delta E} = \sigma^2_{E_1} + \sigma^2_{E_2} - 2r_{\delta E_1 \delta E_2}\sigma_{E_1}\sigma_{E_2}$$

Where

$E_1 = E(t_1)$
$E_2 = E(t_2)$

Thus if the autocovariance or autocorrelation function of the estimated uncertainties in the inventory is known, then the significance of year to year differences can be determined. (Note that the term autocovariance is to autocorrelation as covariance is to correlation.) To estimate the correlation of the uncertainty between years in the total inventory, one may consider the addition of two autocorrelated series representing two of the many uncertainty components of the inventory. The autocovariance of the combined series includes the autocovariances of the individual terms plus a component to allow for the time lagged covariance between the two components of the inventory. For any evaluation beyond two terms, the use of a Monte Carlo analysis is recommended.

BOX A1.2

KEY FEATURES OF GOOD PRACTICE FOR THE DETERMINATION OF UNCERTAINTY IN EMISSION AND UPTAKE ESTIMATES

(i) Use of available observations and expert judgement to determine uncertainty in input quantities;

(ii) Systematic and transparent recording of this input data;

(iii) Examination of the available emission data to determine if representative sampling has occurred;

(iv) Design of further sampling and revision of parameters, default values and algorithms for key source categories if representative sampling has not taken place;

(v) Use of sectoral *good practice guidelines* to choose a probability density function to represent the data;

(vi) Evaluation of any significant correlations (covariances) between input quantities;

(vii) Propagation of uncertainties by the approximation method if the uncertainties are small and have Gaussian distributions; otherwise

(viii) Propagation of uncertainties by Monte Carlo method where resources are available; and

(ix) Recording of uncertainty.

Enting (1999) has presented a similar analysis for the uncertainty in the trend in a quantity over a specified time interval. As an example, consider emissions E(t), E(t + Δt), in two different years of a time-series separated by Δt years. The variance of the trend over this time period is given by:

EQUATION A1.9

$$\mathrm{var}(\Delta E) = 2\sigma_E{}^2(1 - r_{\delta E}(\Delta t))$$

This demonstrates that the uncertainty in the emission trend is smaller for positively autocorrelated estimated uncertainties, than for random uncertainties of equivalent size. There is a need for studies on autocorrelations of estimated uncertainties in inventories as well as of cross correlations of estimated uncertainties within one inventory year and between subsequent inventory years for related emissions and uptakes.

A1.5.2 Splicing of methods

In some cases as the compilation of national inventories continue, there will be a need to change the algorithm used for the calculation of a particular emission or uptake. This may come about either because of improved knowledge about the form of the algorithm or because of some change in the availability of activity data. In these cases, the best approach is to recalculate previous years' inventories using the new methods. In some cases, this will not be possible, and some means of 'splicing' or combining estimates prepared using different approaches into a consistent time series will be required. The statistical theory underlying *good practice* is described below, and practical guidance on how to apply this in inventories is found in Chapter 7, Methodological Choice and Recalculation. The emissions (or uptake) estimates by the two methods are represented by the functions P(t) and Q(t) where t is the year of the inventory estimate. In any particular year when both estimates are available, there will be a difference, and the task of splicing is to examine the difference. There are three likely possibilities: the two emissions estimates may differ by a constant amount, the two emissions estimates may be proportional to each other, or, they may be related by both a constant difference and a proportional term. In the case analysed here, the near constant difference is considered. (A similar analysis can be performed for the two other cases. In fact with the third case, a form of linear regression analysis is appropriate.)

The uncertainty in the difference between the two emission estimates at time t can be expressed as:

EQUATION A1.10

$$\text{uncertainty} = \delta\Delta_{P-Q}(t)$$

$$\text{where } \Delta_{P-Q}(t) = P(t) - Q(t)$$

The ideal situation is to determine this difference for many years, along with the uncertainty of the mean difference taking into account the uncertainties in P and Q. An overbar indicates the multiyear average of the difference over the years t_1–t_2 and δ indicates the uncertainty of this mean difference. In this case, an acceptable series of estimates can be made up by splicing the series P(t) and Q(t) by correcting Q(t) back to P(t) by adding $\overline{\Delta_{P-Q}}(t)$ as averaged over the period t_1 to t_2. A change in the estimation technique can be either an improvement or a diminishment in the quality of an estimate. If it is demonstrated that Q(t) is an improvement then Q(t) corrected back to P(t) should be used as long as possible. That is P(t) should be used up until t_1, and Q(t) + $\overline{\Delta_{P-Q}}(t)$ thereafter. Conversely, if P(t) is preferred, it should be used up until t_2 etc.

In practice in a national inventory, three situations may arise. There may be no years of overlap between P(t) and Q(t); there may be a limited number of years of overlap which are inadequate for the process of refinement of the difference between the two series as discussed above; and there may be sufficient number of years of overlap.

In the first two cases, some additional information is required to determine the effectiveness of the splicing. Several approaches may be possible. These are:

- Identify other locations (countries) where very similar time series exist and use these data to develop a global or regional estimate of the mean difference $\overline{\Delta_{P-Q}}(t)$ gathering all available data until $\delta\overline{\Delta_{P-Q}}(t)$ decreases to an acceptably small uncertainty, or all data sources are exhausted.
- When all data sources are exhausted and $\delta\overline{\Delta_{P-Q}}(t)$ is still above the cut off criterion, accept the time series noting that the time series, from beginning to end has an additional uncertainty that arises because of the uncertainty in the difference between the two series.
- Where there is no overlap of data, nor any data available from elsewhere, other splicing techniques are needed. One possibility is the use of time series techniques (Box and Jenkins, 1970) to forward forecast P(t) and to back forecast in time Q(t) and to see if in the immediate years around the splice, these forecasts agree with the other data set to within the 95% confidence interval. If so the splice could be accepted, if not then a discontinuity in the emissions (or uptake) estimates would have to be recorded. In both these cases, the

uncertainty applied throughout the time series would, at minimum, be the combined uncertainty arising from each of the estimates P(t) and Q(t).

Practical approaches to splicing are discussed in Chapter 7, Methodological Choice and Recalculation.

A1.5.3 Sensitivity analyses and the setting of national inventory research priorities

Given the objective of reducing uncertainties in an inventory, priorities for further research should be established based on three main characteristics:

- The importance of the source category or sink;
- The size of the uncertainty in the emission and uptake;
- The research cost and the expected benefit, measured as an overall reduction in the uncertainty of the inventory.

The importance of the source category should be established using the criteria described in Chapter 7, Methodological Choice and Recalculation. Among source categories of equal magnitude, priority should be given to those with larger uncertainties or greater effect on the trend.

For each source category, the options for research will depend on the origins of the uncertainty. In most cases, there are a number of variables that determine the activity and the emission factor. Priority should be given to those quantities which influence the overall uncertainty most. Among the research options, further stratification of the emissions and uptakes can lead to great benefit. In fact, many current default values are defined for a wide range of conditions which necessarily leads to large confidence intervals.

In the present context, the research cost includes financial cost, time involved and other components that cannot always be quantified.

There are sophisticated computational techniques for determining the sensitivity of a model (such as an inventory) output to input quantities. These methods rely on determining a sensitivity coefficient, λ, that relates the aggregated emissions E_T to an input quantity (or parameter) which in this case is represented by *a*. These methods determine the coefficient as:

Equation A1.11

$$\lambda = \partial E_T / \partial a$$

Some software packages for Monte Carlo analyses have an option for such analysis. This approach has been used for atmospheric chemical systems involving tens to hundreds of chemical reactions (NAS, 1979; Seinfeld and Pandis, 1998). However, one difference between these chemical models and greenhouse gas inventories is the state of knowledge. Chemical models generally represent a closed system with conservation of mass, well-defined relationships and a suite of rate constants that mostly have been well quantified. There is much less knowledge about the extent of interactions, and values of quantities and parameters in greenhouse gas inventories.

There are other approaches that may fill the need for providing input on measurement and research priorities for inventory development. It is possible to develop simpler methods, using broad assumptions, to provide indication of research priorities. The advantage of these simpler schemes is that they can be used by all inventory compilers. Such information on research and measurement priorities arises from the evaluations of representative sampling as discussed in Section A1.4.2, Representative sampling, algorithms and covariances, the uncertainty analysis in Chapter 6, Quantifying Uncertainties in Practice, and Chapter 7, Methodological Choice and Recalculation, and from the *good practice guidance* for each sector (see Chapters 2 to 5). These various inputs combined with the expert judgement of inventory compilers provide the best guide to priorities for inventory development.

A1.6 RESEARCH REQUIREMENTS

While some of the assumptions that underpin IPCC inventories are self evident and already have been examined, the systematic investigation of the set of assumptions that underpin these inventories would facilitate a structured approach to the identification of uncertainties and the design of experiments to test and refine these assumptions. This work includes issues of definition and the theoretical basis of emission algorithms. Such work would strengthen the coupling of understanding, and exchange of information, between IPCC inventories and studies of the global cycles of trace gases incorporated in IPCC Working Group 1, to the benefit of both activities.

One currently unresolved aspect of the reporting of emissions and uptakes is the number of significant digits recorded (numerical precision). The approach in ISO (1993) is that the numerical values of the estimate and its standard deviation should not be given with an excessive number of digits. The Canadian National Greenhouse Gas Inventory has adopted the practice of only reporting data to the number of significant digits commensurate with the uncertainty of the inventory estimates. If care is taken to maintain this association throughout the inventory, it is possible to clearly visualise the uncertainty of the values and the difference between the uncertainty associated with the emissions from each source category. The other approach is to define the minimum unit for reporting as a fixed quantity, then inventories from all countries and all components of these inventories are reported with the same numerical unit. In practical terms there are probably advantages in this approach for ease of auditing the tables, but this issue will require further discussion.

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ANNEX 2

VERIFICATION

CO-CHAIRS, EDITORS AND EXPERTS

Co-chairs of the Expert Meeting on Cross-sectoral Metholodogies for Uncertainty Estimation and Inventory Quality

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Leo Meyer (Netherlands)

Expert Group: Checks and Verification at National and International Level

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Mike Woodfield (UK) and Faouzi Senhaji (Morocco)

AUTHORS OF BACKGROUND PAPERS

Jos Olivier (Netherlands), Wilfried Winiwarter (Austria), and Jean-Pierre Chang (France)

CONTRIBUTORS

William Breed (USA), Zhenlin Chen (China), Riccardo De Lauretis (Italy), Eilev Gjerald (Norway), Michael Strogies (Germany), Susan Subak (USA), Kiyoto Tanabe (IPCC-NGGIP/TSU), Karen Treanton (IEA), and Andre van Amstel (Netherlands)

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A2.1 INTRODUCTION

Verification processes are, in the present context, intended to help establish an inventory's reliability. These processes may be applied at either national or global levels of aggregation and may provide alternative information on annual emissions and trends. The results of verification processes may:

(i) Provide inputs to improve inventories;

(ii) Build confidence in emissions estimates and trends;

(iii) Help to improve scientific understanding related to emissions inventories.

Verification processes may also enhance international cooperation in improving inventory estimates.

There are different approaches to verification. One approach is to evaluate emissions estimates and trends, for example, as part of the United Nations Framework Convention on Climate Change (UNFCCC) review of emissions inventories. Another approach entails an evaluation of aggregate inventories on a global or regional basis, with the objective of providing further scientific insight.

A number of options or tools for verification are discussed in this Annex. Their application, as well as the types of information needed, will vary according to the role and intention of the verification process. International verification of inventories may include comparisons with international or independently compiled activity data, emissions factors, uncertainty estimates, atmospheric measurements, and global or regional budgets and source trends. International verification will usually occur following inventory preparation, including the quality assurance/quality control (QA/QC) process (see Section A2.2.1, National Inventories, in this Annex and Chapter 8, Quality Assurance and Quality Control). International verification may occur in the absence of national verifications. Verification activities require resources, time and technical and intellectual expertise.

Verification processes and results should be reported systematically and in a timely manner, in order to provide feedback to national inventory teams, and to the international community, as appropriate, depending on the role and reason for verification.

Techniques for Verification

Verification techniques include internal quality checks, inventory inter-comparison, comparison of intensity indicators, comparison with atmospheric concentrations and source measurements, and modelling studies. In all cases, comparisons of the systems for which data are available and the processes of data acquisition should be considered along with the results of the studies. These techniques, and their applicability at the national and international level, are discussed below.[1]

A2.1.1 National Level

Verification procedures can be conducted on parts of national inventories as part of the QA/QC process (see Chapter 8, Quality Assurance and Quality Control), or on parts or the whole inventory as a separate exercise.

A2.1.1.1 COMPARISONS WITH OTHER NATIONAL EMISSIONS DATA

Comparisons with other, independently compiled, national or regional emissions estimates are a quick option to verify completeness, approximate emission levels, or allocations to source categories or sub-source categories. The availability of such independently compiled inventories will vary, but possible resources include state or provincial inventories, as well as inventories prepared independently by research organisations. Specific steps for national comparison are similar to those for comparisons with international data, as described in Section A2.2.1, National Inventories.

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[1] Some of the options are described in more detail in EEA (1997), Lim *et al.* (1999a, b) and Van Amstel *et al.* (1999).

A2.1.1.2 DIRECT SOURCE TESTING

On-line stack measurements, in-plume measurements, remote measurements, and tracers have been used for direct testing of sources. All these approaches allow the direct attribution of observed concentrations to the emissions from a certain source. So long as it is representative, the uncertainty associated with the measurement and emission calculations in direct source testing is often considered to be lower than the uncertainty of inventory emissions estimates that may have been calculated by other methods. See Chapter 8, Quality Assurance and Quality Control, Section 8.7.1.3, Direct Emission Measurements, for further discussion of this topic.

A2.1.1.3 COMPARISON WITH NATIONAL SCIENTIFIC AND OTHER PUBLICATIONS

Although the inventory agency is responsible for the compilation and submission of the national greenhouse gas inventory, there may be other independent publications of relevance (e.g. scientific and technical literature). Examining such literature sources may identify areas for further research and inventory improvement.

A2.1.2 Additional international comparative tools

Comparison of national greenhouse gas inventories with international data sets may be an independent means to verify inventory estimates. Several types of comparisons can be made, including comparisons with independently compiled bottom-up emissions estimates, comparisons with atmospheric measurements, comparisons with international scientific literature sources, and comparisons with global or regional budgets. Comparisons with inventories from other countries enable cross-checking of assumptions regarding the use of emission factors, completeness of source categories and overall approaches. In addition to comparisons with single country emissions inventories, it is possible to make more systematic comparisons for larger groups of countries.

A2.1.2.1 BOTTOM-UP COMPARISONS

For a given source category, different types of bottom-up comparisons can be performed in parallel. These comparisons can examine overall emission levels, emission factors, or activity data. The broad types can include:

- Comparisons with other independently compiled datasets, in order to check for completeness, magnitude, and source allocation;
- Inter-country comparisons in which input data (i.e. activity levels, aggregated emission factors or other factors used in emission calculations) are compared for different countries for the same year;
- Inter-country comparisons in which trends in emissions or input data are compared for different countries.

These different types of comparisons can also assist in evaluating the uncertainty estimates of national inventories and global emission inventories, and evaluating differences at the country level. These comparison processes do not always represent verification of the data themselves, but instead verification of the reliability and the consistency of data (e.g. in trends and between countries). They can enable reviewers to identify inconsistencies or questions for which more detailed data verification may need to be performed. The time that inventory agencies are able to spend on these independent verification activities will depend upon the resources available and an assessment of the value of these activities compared to other means of improving inventory quality.

Several examples of the types of comparisons are described below:

- *Comparisons of Top-down and Bottom-up Estimates*: For carbon dioxide (CO_2) from fossil fuel combustion, a reference calculation based on apparent fuel consumption per fuel type is mandatory according to the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (*IPCC Guidelines*). This type of top-down completeness and order-of-magnitude check may also be applicable in other cases where the inventory is based on a bottom-up approach. In cases where emissions are calculated as the sum of sectoral activities based on the consumption of a specific commodity (e.g. fuels or products like hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) or sulfer hexafluoride (SF_6)), the emissions could be estimated using apparent consumption figures (e.g. national total production + import – export ± stock changes).

- *Comparisons of National Emission Inventories with Independently Compiled, International Datasets*: Some global databases already exist. For example, CO_2 emissions estimates associated with the combustion of fossil fuel are compiled by the International Energy Agency (IEA) and the Carbon Dioxide Information and Analysis Centre (CDIAC). Global total anthropogenic inventories of all greenhouse gases are compiled by the Global Emission Inventory Activity (GEIA, a component of IGAC/IGBP) and the Emission Database for Global Atmospheric Research (EDGAR), as compiled by TNO Institute of Environmental Science and National Institute of Public Health and the Environment (RIVM) in close cooperation with GEIA (IEA, 1999; Marland *et al.,* 1994; Graedel *et al.,* 1993; Olivier *et al.*, 1999). These comparisons can assist in checking completeness, consistency, source allocation and accuracy to within an order of magnitude. However, when evaluating the results of these comparisons, it should be remembered that the various data sources are often not completely independent of each other or from the data set used to calculate the national inventory. For example, EDGAR starts with IEA energy data to calculate CO_2 emissions from fuel combustion and CDIAC and GEIA datasets start with UN energy data. In addition, even the IEA and UN energy data are not completely independent. In order to avoid duplication of work, the IEA and the United Nations cooperate in the exchange of data and use common questionnaires for some countries.

- *Comparisons of Activity Data with Independently Compiled Datasets*: Similar comparisons may be made using the underlying activity data to check completeness and order-of-magnitude. These underlying data may be compared with independently compiled international statistics (e.g. maintained by the IEA, and the United Nations Food and Agriculture Organization). One should not, however, expect to find exact matches since the activity data used by the inventory agency may be taken from different data sources or be a different version to that used in the national data collected by international organisations; for examples see Schipper *et al.* (1992). When checking activity data, indicators could be defined for the purpose of international comparison (e.g. activity rate per inhabitant, per employee, per unit of GDP, per number of households or per number of vehicles, according to the source sectors). This could enable order-of-magnitude checks and indicate outliers that may be caused by data input or calculation errors.

- *Comparisons of Emission Factors Between Countries*: Different kinds of comparisons can be combined in practice. For example, between-country emission factor comparisons can be combined with historic trends by plotting, for different countries, the reference year data (e.g. 1990), the more recent year data, and the minimum and maximum values. This analysis could be made for each source category and possible aggregations. Sub-source categories such as fuel types may also be included when relevant (see Figure A2.1, Illustrative Plot for an Inter-country Comparison of Emission Factors). Comparisons between countries can also be made using implied emission factors (which are top-down ratios between emissions estimates and activity data). This type of comparison may enable outlier detection based on the statistical distribution of values from the sample of countries considered, bearing in mind that differences in national circumstances can significantly affect the implied emission factors. Since implied emission factors are ratios of emissions to activity data, comparisons based on them should help verify both the emission factors and the activity data in the original calculation. Finally, a comparison with the IPCC Tier 1 default values and with literature values may be informative in establishing the comparability or country-specificity of the emission factors used.

- *Comparisons Based on Estimated Uncertainties*: Comparisons based on the estimated uncertainties of emission factors, when such data are available, can also be useful. For example, Figure A2.2, Illustrative Plot for an Inter-country Comparison of Emission Factors and their Uncertainties, shows on a single plot current year's emission factor and the related uncertainty range for different countries. This can be done for a given source category and, when relevant, sub-source categories such as different fuel types. This type of comparison may help to identify data outliers where uncertainty ranges do not overlap.

- *Comparisons of Emission Intensity Indicators Between Countries*: Emission intensity indicators may be compared between countries (e.g. emissions per capita, industrial emissions per unit of value added, transport emissions per car, emissions from power generation per kWh of electricity produced, emissions from dairy ruminants per tonne of milk produced). These indicators provide a preliminary check and verification of the order of magnitude of the emissions. It is not expected that emission intensity indicators will be correlated across countries. Different practices and technological developments as well as the varying nature of the source categories will be reflected in the emission intensity indicators. However, these checks may flag potential anomalies at country or sector level.[2]

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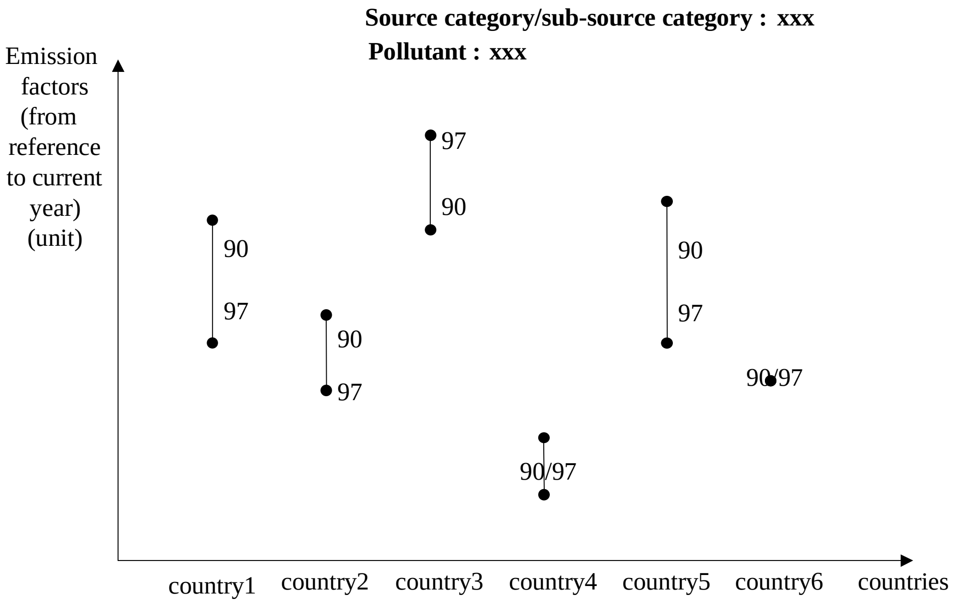
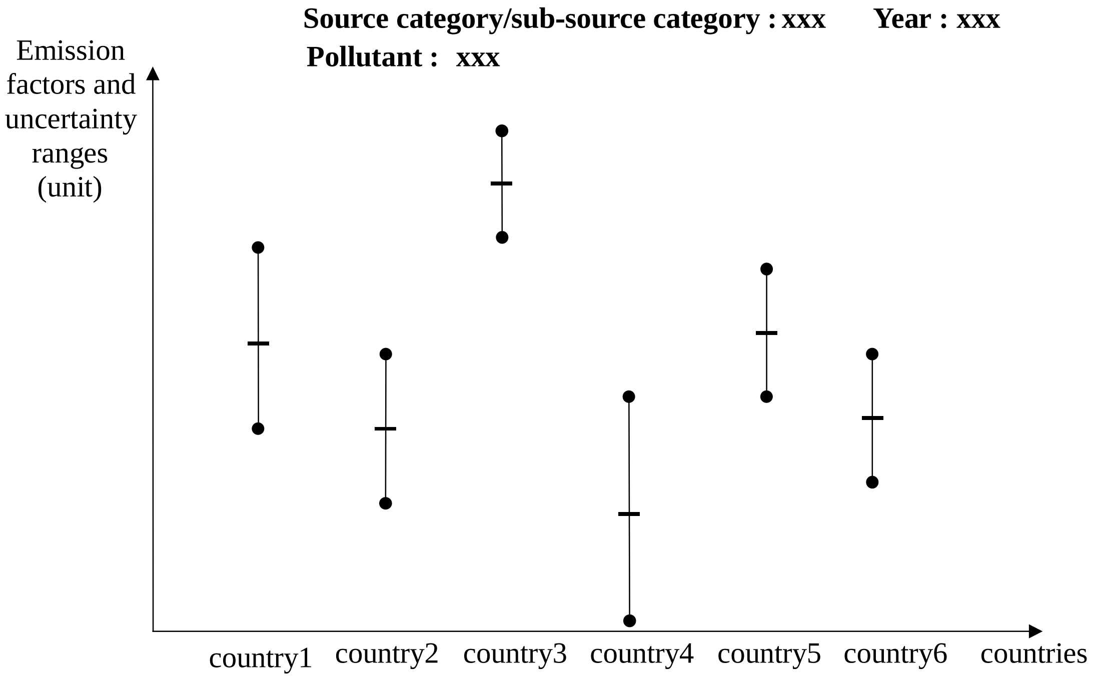
[2] More examples for energy indicators can be found in Schipper and Haas (1997) and Bossebeuf *et al.* (1997).

Figure A2.1 Illustrative Plot for an Inter-country Comparison of Emission Factors



N.B. : The E.F. range for a given country relates here to the minimum and maximum E.F. during the period 90-97.

Figure A2.2 Illustrative Plot for an Inter-country Comparison of Emission Factors and their Uncertainties



N.B. : The E.F. range for a given country relates here to the uncertainty range of the current E.F.

A2.1.2.2 COMPARISONS OF UNCERTAINTY ESTIMATES BETWEEN COUNTRIES

Chapter 6, Quantifying Uncertainties in Practice, describes how to estimate and report uncertainties. The uncertainty estimates developed for various source categories may be compared in several ways, including:

- Comparing the uncertainty estimates of various source categories and gases within a country's inventory;
- Comparing the uncertainty of a given gas for specific source categories between countries;
- Comparing the uncertainty estimates reported in the national inventory with those provided in related regional or other national inventories or other documents used for verification purposes.

Many factors influence the uncertainty estimates for different gases in different source categories and these are not expected to be identical. However, such comparisons may alert the inventory agency to possible areas for improvement.

A2.1.3 Comparisons with atmospheric measurements at local, regional and global scales

For some regions, emission source categories, or compounds, comparisons with atmospheric measurements may provide useful information on the validity of the emissions estimates in the context of overall atmospheric trends. Several options may be employed, including:

- *Local and Regional Atmospheric Sampling*: At a given site, background concentrations may be inferred from low concentration levels, and enhanced concentrations (plumes) from high concentration levels. Measurements can be performed at several fixed sites upwind and downwind thus allowing the comparison of measured concentrations with modelled concentrations. In terms of emission assessment, however, it is more appropriate to perform inverse modelling (i.e. estimate emissions from measured concentrations). As an example, markers (^{13}C) have been used to assess methane (CH_4) emissions (Levin *et al.*, 1999) in atmospheric sampling. Such methods are not limited to areas defined by national boundaries. Indeed, they are best suited to regions where emissions are concentrated in a small area. As industrial and population centres are frequently situated at both sides of a national boundary, an evaluation for just one country may not be possible because emissions can only be assessed for the whole area. In such cases, the methods are only useful at a bilateral or international level.
- *Continental Plumes*: A strong difference between source and non-source (sink) regions may generally be found between a continent and an ocean. Routine measurements may be performed close to an ocean, at offshore islands, or on ships. The difference between background air concentrations and the offshore plume concentrations, taking advantage of wind vector analysis or trajectory analysis, may provide an indication of emissions on a broad scale. For example, a number of greenhouse gases, including chlorofluorocarbons (CFCs), nitrous oxide (N_2O) and CH_4 from the European continental plume, have been detected at Mace Head, Ireland. These results have then been used for subsequent quantification of the European emission source strength by inverse modelling (Derwent *et al.*, 1998a, b; Vermeulen *et al.*, 1999).
- *Satellite Observations*: Satellite observations allow users to retrieve quasi-continuous concentration profiles for all or part of the globe.
- *Global Dynamic Approaches*: Trends over time in the atmospheric concentration of particular compounds may also indicate a change in the global balance between sources and sinks. This may be particularly useful where the background concentration of the gas in the atmosphere is low. Such approaches have been taken for CH_4 (Dlugokencky *et al.*, 1994) and SF_6 (Maiss and Brenninkmeijer, 1998).

These methods allow a large proportion of global emissions to be covered and monitoring is possible on a routine basis. However, it is almost impossible to trace emissions back to individual sources or source categories if their emissions do not contain some sort of 'fingerprint' that characterises them. This 'fingerprint' may be a specific type of carbon isotope in the case of CO_2 and CH_4 emissions from fossil fuels, or a typical temporal profile (seasonality or diurnal variation) or zonal variation (e.g. latitudinal distribution).

A2.1.4 Comparisons with international scientific publications, global or regional budgets and source trends

The international scientific literature may provide other estimates or analyses to compare with national inventory estimates. Comparison of these estimates with such literature is a valuable check on the quality of the official national inventory that can be used when comparing or integrating the greenhouse gas emissions of various countries.

Comparisons of national inventories with independently compiled global inventories and with global or regional emission levels included as part of a more comprehensive analysis are a means to update global budgets or provide feedback to national inventory developers or both. Provided that sufficient information is available on spatial and temporal distribution of the sources, including natural sources, it may be possible to trace the reasons for inconsistencies between different reports of emissions for major sources (Heimann, 1996, for CO_2; Janssen *et al*., 1999, and Subak, 1999, for CH_4; Bouwman and Taylor, 1996, for N_2O).

A2.2 PRACTICAL GUIDANCE FOR VERIFICATION OF EMISSIONS INVENTORIES

There is value in independent verification of individual national greenhouse gas inventories at the international level (e.g. inter-country comparisons). Such verification activities could serve the following purposes:

- Support the national verification activities;
- Improve efficiency by avoiding duplication of effort at the national level;
- Provide input to evaluation of the *IPCC Guidelines*;
- Inform the public, scientists and government reviewers.

A2.2.1 National inventories

If an independent verification is considered a valuable means for improving inventory estimates, it would be *good practice* to have the following:

- Availability of sufficient independent expertise;
- National inventory report;
- Uncertainty estimates and QA/QC documentation included in the report;
- Reports of existing national verifications.

It is also useful to identify gaps in the inventory prior to undertaking any verification process.

The list in Box A2.1, Verification of a National Inventory, summarises and ranks the tools in order of approximate ease of implementation. The best combination for a particular user will depend upon the available data, and resource constraints (e.g. funding, time, expertise).

BOX A2.1

VERIFICATION OF A NATIONAL INVENTORY

A. Checks:

- Check for discontinuities in emission trends from base year (usually 1990) to end year.

B. Comparisons of emissions and other such features:

- Compare the Reference Approach for CO_2 emissions from fuel combustion with other approaches.
- Compare inventory emissions estimates by source category and gas against independently compiled national estimates from international databases.
- Compare activity data against independently compiled estimates and perhaps activity data from countries with similar source categories and sectors.
- Compare (implied) emission factors for source categories and gases with independent estimates and estimates from countries with similar source categories and sectors.
- Compare sector intensity estimates of selected source categories with estimates from other countries with similar source categories and sectors. If necessary, calculate emission intensity estimates based on international statistical compendia.

C. Comparisons of uncertainties:

- Compare uncertainty estimates with those from reports of other countries and the IPCC default values.

D. On-site measurements:

- Perform direct source testing on *key source categories*, if possible.

Some of these activities may have been conducted as part of the QA/QC processes and results may be included in the inventory report. After the selected processes in Box A2.1 have been completed and issues to be reviewed in more detail have been identified, the following information may also support the verification processes:

- National reports;
- Additional tools such as scientific literature on emission factors;
- Results from atmospheric sampling relevant to *key source categories* and sectors.

Findings should be summarised and feedback sought from the inventory agency. Findings of the verification process should be made publicly available wherever possible.

A2.2.2 Aggregated global or regional inventories

There is also value in examining emissions inventory information between countries and as totals of groups of countries. Such evaluations could, for example, compare global or regional totals and trends against atmospheric concentrations and changes in concentrations. Comparison of global or regional totals of selected source categories against isotopic signature analysis may provide additional information. This type of verification may provide an indicative range for emissions estimates.

The explicit steps, and the data required, will be determined by the intent and scope of the verification effort and analysis. Discrepancies identified by verification processes on aggregate national inventories and comparisons with atmospheric concentrations may guide future priorities for research on national inventories and atmospheric science.

A2.3 REPORTING

For the verification process to be most useful, findings should be made publicly available.

The report should include the following items:

- What has been verified;
- How the verification was performed;
- What criteria were used for the selection of verification priorities;
- Limitations in the processes that have been identified;
- What feedback was received from external reviewers summarising key comments;
- Actions taken by the inventory agency as a result of the verification process;
- Recommendations for inventory improvements or research at an international level arising from the findings.

To facilitate use of the reports and wide dissemination, verification reports should use the common units recommended by the *IPCC Guidelines* and the official languages of the United Nations.

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ANNEX 3

GLOSSARY

CO-CHAIRS, EDITORS AND EXPERTS

Co-chairs of the Expert Meeting on Cross-sectoral Methodologies for Uncertainty Estimation and Inventory Quality

Taka Hiraishi (Japan) and Buruhani Nyenzi (Tanzania)

REVIEW EDITOR

Richard Odingo (Kenya)

AUTHORS

Milos Tichy (Czech Republic) and Simon Bentley (Australia)

REVIEWERS

Roberto Acosta (UNFCCC Secretariat), Simon Eggleston (UK), Ian Galbally (Australia), Katarina Mareckova (Slovak Republic), Thomas Martinsen (IPCC/OECD), Jos Olivier (Netherlands), Jim Penman (UK), and Kristin Rypdal (Norway)

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ANNEX 3 GLOSSARY

A3.1 INTRODUCTION

The Glossary provides a convenient reference for inventory compilers and policy makers covering general statistical terms and terms that have a particular meaning in the context of emission inventories.

A3.1.1 Selection of entries

The main purposes for the selection of terms and the formulation of entries were to:

- Distinguish between terms that have different meanings when used in the context of greenhouse gas inventory compilation and when used in a technical, statistical, or mathematical sense – e.g. the term ‘consistency’;
- Provide unified notation for the basic terms (mostly statistical) considered fundamental to the practical reporting of inventories;
- Define other terms that assist in the understanding and development of good practice guidelines for uncertainties in national inventories.

A3.1.2 Formulation of entries

The Glossary takes a pragmatic approach and provides one or more of the following types of definitions for each entry. First, any definition developed specially for inventory applications is marked ‘Inventory definition.’ In some cases, examples are used to illustrate specific meanings for inventory preparation. The second type is ‘statistical definition,’ that are used to explain the statistical or common mathematical definition for a certain term. Again, in some cases, examples are provided to clarify the application of these meanings for inventory use. The final type of definitions are those that come from other sources – including pre-existing SBSTA or IPCC definitions agreed by the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the United Nations Framework Convention on Climate Change (UNFCCC) (indicated by FCCC/SBSTA/1999/6 Add. 1), the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, and the International Standardization Organization (ISO). The clauses, that fall under the following definitions: arithmetic mean, expectation, population, probability, probability distribution, random variable, statistic and uncertainty include a definition indicated by [7] are taken from the publication *Guide to the Expression of Uncertainty in Measurement* and have been reproduced with permission from the International Organization for Standardization (ISO). This ISO publication can be obtained from any member body or directly from the Central Secretariat, ISO, Case Postale 56, 1211 Geneva 20, Switzerland. Copyright remains with the ISO.

The definitions provided in this Glossary are not rigorous in a full mathematical or statistical sense. Most of the statistical definitions given here lie within the context of ‘classical’ frequency-based statistical inference, although it is acknowledged that this is not the only theory of statistical inference. As with any reference manual, compromises have been made between understandability, clarity, exactness, and brevity. To this end, mathematical notation has been kept to a minimum.

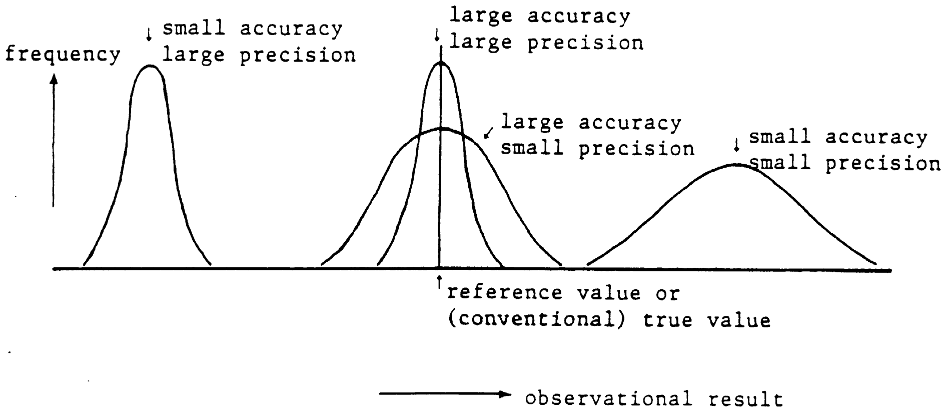
A3.2 GLOSSARY

ACCURACY

Inventory definition: Accuracy is a relative measure of the exactness of an emission or removal estimate. Estimates should be accurate in the sense that they are systematically neither over nor under true emissions or removals, as far as can be judged, and that uncertainties are reduced as far as practicable. Appropriate methodologies conforming to guidance on good practices should be used to promote accuracy in inventories. (FCCC/SBSTA/1999/6 Add. 1)

Statistical definition: Accuracy is a general term which describes the degree to which an estimate of a quantity is unaffected by bias due to systematic error. It should be distinguished from precision as illustrated on Figure A3.1.

Figure A3.1 Accuracy and Precision (from [3]*)



ACTIVITY DATA

Inventory definition: Data on the magnitude of human activity resulting in emissions or removals taking place during a given period of time. In the energy sector for example, the total amounts of fuel burned is annual activity data for fuel combustion sources, and the total number of animals being raised, by species, is annual activity data for methane emissions from enteric fermentation. (*Revised 1996 IPCC Guidelines* [9]*)

ARITHMETIC MEAN

Statistical definition: The sum of the values divided by the number of values. [7]*

AUTO-CORRELATION

Statistical definition: The correlation coefficient calculated for two data items in a time series.

Example: Observed animal numbers in two successive years are usually highly auto-correlated when the lifetime of the animals significantly exceeds two years.

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* See references (p A3.21).

AUTO-COVARIANCE

Statistical definition: The covariance calculated for two data items in a time series.

BIAS

Inventory definition: A systematic error of the observation method, whose value in most cases is unknown. It can be introduced by using measuring equipment that is improperly calibrated, by selecting items from a wrong population or by favouring certain elements of a population, etc.

Statistical definition: The difference between the expected value of a statistic and the parameter which it estimates. See **Unbiased estimator**.

Example: Estimating the total fugitive emission from gas transport and distribution using only measurements of leakage from high/medium pressure pipelines can lead to bias if the leakage in the lower pressure distribution network (which is significantly more difficult to measure) is neglected.

BOOTSTRAP TECHNIQUE

Statistical definition: Bootstrap technique is a type of computationally intensive statistical methods which typically use repeated resampling from a set of data to assess variability of parameter estimates.

CENTRAL LIMIT THEOREM

Statistical definition: A general name for the class of mathematical/statistical theorems which, very broadly stated, says that the arithmetic mean of *n* independently distributed and random variables approximates a normal distribution as *n* tends to infinity. This is true for underlying distributions of variables likely to be encountered in practice, and certainly for any distributions likely to be encountered in the context of greenhouse gas inventories. For inventories, the theorem gives a guide to the interpretation of combined variances of total emission (which is the sum of sectoral emissions). Also, under some conditions, the central limit theorem can justify the approximation that the total emissions from a bottom-up inventory has a normal distribution.

COEFFICIENT OF VARIATION

Statistical definition: The coefficient of variation, v_x is the ratio of the population standard deviation, σ_x , and mean, μ_x, where $v_x = \sigma_x/\mu_x$. It also frequently refers to the sample coefficient of variation, which is the ratio of the sample standard deviation and sample mean.[1]

COMPARABILITY

Inventory definition: Comparability means that estimates of emissions and removals reported by Parties in inventories should be comparable among Parties. For this purpose, Parties should use the methodologies and formats agreed by the Conference of the Parties (COP) for estimating and reporting inventories. The allocation of different source/sink categories should follow the split of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* at the level of its summary and sectoral tables.

COMPLETENESS

Inventory definition: Completeness means that an inventory covers all sources and sinks as well as all gases included in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* in addition to other existing relevant source/sink categories which are specific to individual Parties (and therefore may

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[1] ‘Coefficient of variation’ is the term, which is frequently replaced by ‘error’ in a statement like ‘error is 5%’.

not be included in the *IPCC Guidelines*). Completeness also means full geographic coverage of sources and sinks of a Party[2].

CONFIDENCE

Inventory definition: The term 'confidence' is used to represent trust in a measurement or estimate. Having confidence in inventory estimates does not make those estimates more accurate or precise; however, it will eventually help to establish a consensus regarding whether the data can be applied to solve a problem [6].* This usage of confidence differs substantially from the statistical usage in the term confidence interval.

CONFIDENCE INTERVAL

Statistical definition: A confidence interval is the range in which it is believed that the true value of a quantity lies. The level of belief is expressed by the probability, whose value is related to the size of the interval. It is one of the ways in which uncertainty can be expressed (see Estimation).

In practice a confidence interval is defined by a probability value, say 95%, and confidence limits on either side of the mean value $\overline{x}$. In this case the confidence limits $L1$ and $L2$ would be calculated from the probability density function such that there was a 95% chance of the true value of the quantity being estimated by $\overline{x}$ lying between $L1$ and $L2$. Commonly $L1$ and $L2$ are the 2.5 percentile and 97.5 percentile respectively.

Example: 'An emission is between 90 and 100 kt with a probability of 95%.' Such a statement can be provided when the confidence interval is calculated (the numerical values in this example are arbitrarily chosen).

CONSISTENCY

Inventory definition: Consistency means that an inventory should be internally consistent in all its elements over a period of years. An inventory is consistent if the same methodologies are used for the base and all subsequent years and if consistent data sets are used to estimate emissions or removals from sources or sinks. Under certain circumstances referred to in paragraphs 10 and 11 of FCCC/SBSTA/1999/6 Add.1, an inventory using different methodologies for different years can be considered to be consistent if it has been recalculated in a transparent manner taking into account any good practices.

Statistical definition: A statistical estimator for a parameter is said to be consistent, if the estimator tends towards the parameter as the size of the sample used for the estimator increases – i.e. precision is improved by an increasing number of observations.

CORRELATION

Statistical definition: Mutual dependence between two quantities. See Correlation coefficient.

CORRELATION COEFFICIENT

Statistical definition: A number lying between –1 and +1 which measures the mutual dependence between two variables which are observed together. A value of +1 means that the variables have a perfect direct straight line relation; a value of –1 means that there is a perfect inverse straight line relation; and a value of 0 means that there is no straight line relation. It is defined as the covariance of the two variables divided by the product of their standard deviations.

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[2] According to the instruments of ratification, this is the acceptance, approval or accession of the Convention by a given Party.

* See references (p A3.21).

COVARIANCE

Statistical definition: The covariance between two variables is a measure of the mutual dependence between two variables.

The sample covariance of paired sample of random variables X and Y is calculated using the following formula: $s^2_{xy} = \frac{1}{n} \sum_i^n (x_i - \bar{x})(y_i - \bar{y})$ where x_i, y_i, $i = 1,\dots,n$ are items in the sample and $\bar{x}$ and $\bar{y}$ are sample means.

CUMULATIVE DISTRIBUTION FUNCTION

See Distribution function.

DECISION TREE

Inventory definition: A decision tree is a flow chart describing the specific ordered steps which need to be followed to develop an inventory or an inventory component in accordance with the principles of good practice.

DISTRIBUTION FUNCTION

Statistical definition: A distribution function or cumulative distribution function $F(x)$ for a random variable X specifies the probability $\Pr(X \le x)$ that X is less than or equal to x.

ELASTICITY

Statistical definition: Elasticity (or normalised sensitivity) is a measure of how responsive one quantity is to a change in another related quantity. The elasticity of a quantity Y that is affected by changes in another quantity X is defined as the percentage change in Y divided by the percentage change in X which caused the change in Y.

EMISSION FACTOR

Inventory definition: A coefficient that relates the activity data to the amount of chemical compound which is the source of later emissioms. Emission factors are often based on a sample of measurement data, averaged to develop a representative rate of emission for a given activity level under a given set of operating conditions (*Revised 1996 IPCC Guidelines* [9]*).

ERROR

Statistical definition: In statistical usage, the term 'error' is a general term referring to the difference between an observed (measured) value of a quantity and its 'true' (but usually unknown) value and does not carry the pejorative sense of a mistake or blunder.

ESTIMATION

Statistical definition: Estimation is the assessment of the value of a quantity or its uncertainty through the assignment of numerical observation values in an estimation formula, or estimator. The results of an estimation can be expressed as follows:

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* See references (p A3.21).

- a point estimation which provide a number which can be used as an approximation to a parameter (such as the sample standard deviation which estimates the population standard deviation), or
- an interval estimate specifying a confidence level.

Example: A statement like 'The total emission is estimated to be 100 kt and its coefficient of variation is 5%' is based upon point estimates of the sample mean and standard deviation, whereas a statement such as 'The total emission lies between 90 and 110 kt with probability 95%' expresses the results of estimation as a confidence interval.

ESTIMATOR

Statistical definition: An estimator is a formula specifying how to calculate a sample estimate value of a population parameter from the sampled data. For example, emission factors are often estimated as the sample means of sets of measurements. There can be more than one estimator for a population parameter, and each estimator in general has its own sampling properties with consistency and unbiasedness being among the most important.

Examples of point estimators include the arithmetic mean $\overline{x}$, which is a commonly used estimator for the expected value (mean), and the sample variance s^2, which is a commonly used estimator for the variance.

EXPECTATION

Statistical definition: 1. For a discrete random variable X taking the values x_i with the probabilities p_i, the expectation is $\mu = \mathrm{E}(X) = \Sigma\, p_i\, x_i$; and 2. For a continuous random variable X having the probability density function $f(x)$, the expectation, if it exists, is $\mu = \mathrm{E}(X) = \int x\, f(x)\, dx$, the integral being extended over the interval(s) of variation of X. [7]*

EXPECTED VALUE

Statistical definition: See Mean.

EXPERT JUDGEMENT

Inventory definition: A carefully considered, well-documented qualitative or quantitative judgement made in the absence of unequivocal observational evidence by a person or persons who have a demonstrable expertise in the given field.

EXTREME VALUE

Statistical definition: The extreme values of a sample are the maximum and minimum values of the sample. The statistical theory of extreme values is concerned with estimating the distributions of these extreme values for large values of n.

GOOD PRACTICE

Inventory definition: Good Practice is a set of procedures intended to ensure that greenhouse gas inventories are accurate in the sense that they are systematically neither over nor underestimates so far as can be judged, and that uncertainties are reduced so far as possible.

Good Practice covers choice of estimation methods appropriate to national circumstances, quality assurance and quality control at the national level, quantification of uncertainties and data archiving and reporting to promote transparency.

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* See references (p A3.21).

INDEPENDENCE

Statistical definition: Two random variables are independent if there is a complete absence of association between how their sample values vary. The most commonly used measure of the lack of independence between two random variables is the correlation coefficient.

KEY SOURCE CATEGORY

Inventory definition: A key source category is one that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both. (See Chapter 7, Methodological Choice and Recalculation.)

KURTOSIS

Statistical definition: Kurtosis is a measure of the flatness of a PDF. It is a simple function of two moments.

Kurtosis is given by: $\gamma = \frac{\mu_4}{\mu_2^2} = \frac{\mu_4}{\sigma^2}$ where μ_2 and μ_4 are the second and fourth population central moments. For the normal distribution, kurtosis equals 3. The sample kurtosis has a corresponding definition, with sample moments replacing population moments; it is very sensitive to 'outlier' points.

LATIN HYPERCUBE SAMPLING

Statistical definition: Latin hypercube sampling is a technique of selecting values for inputs to computer realisation runs of a model by stratifying the range of each of the model inputs, and ensuring that input values across the whole of each model input range are selected.

LAW OF LARGE NUMBERS

Statistical definition: A mathematical theorem which formalises the generally known wisdom that an average becomes a better approximation to the mean as the number of observations is increased.

LINEAR MODEL

Statistical definition: A variable y is said to be linearly related to (or a linear function of) variables x_1, x_2, … if y can be expressed by the formula $y= b_0 + b_1x_1 + b_2x_2 +$ … where the b terms are constant numbers.

Whether a function is considered to be linear or not can vary depending upon the context in which it is applied.

Example: An emission E is usually expressed as the product of an emission factor F and an activity level A. In the case where F is a fixed constant and E only varies when A does, E is linearly related to A. However, when both F and A are considered to be variables (such as when applying the error propagation equation to estimate the variance of E as a function of the variances and covariance of A and F) E is not a linear function of F and A.

LINEAR REGRESSION

Statistical definition: Linear regression provides a way of fitting a straight line to a set of observed data points, taking into account the effects of observational variability.

Example: If emissions observations are plotted against corresponding activity levels, the slope of the line fitted by a linear regression provides an estimate of the appropriate emission factor. The technique can also be used for estimating a straight-line trend for a quantity which varies over time.

LOGNORMAL DISTRIBUTION

Statistical definition: The lognormal distribution is an asymmetric distribution, which starts from zero, rises to a maximum and then tails off more slowly to infinity. It is related to the normal distribution: *X* has a lognormal distribution if ln (*X*) has a normal distribution.

The PDF of the lognormal distribution is given by:

$$f(x) = \frac{1}{\sigma_l x\sqrt{2\pi}} e^{-\frac{(\ln x - \mu_l)^2}{2\sigma_l^2}} \quad , \ \text{for } 0 \le x \le \infty$$

The parameters required to specify the function are: μ_l the mean of the natural log transform of the data; and $\sigma_l{}^2$ the variance of the natural log transform of the data. The data and information that the inventory compiler can use to determine the input parameters are: mean = μ; variance = σ^2; and the relationships:

$$\mu_l = \ln \frac{\mu^2}{\sqrt{(\sigma^2 + \mu^2)}}$$

and

$$\sigma_l = \sqrt{\ln\left(\frac{\sigma^2}{\mu^2} + 1\right)}$$

MEAN

Statistical definition: The mean, population mean, expectation or expected value is, broadly speaking, a measure of a central value around which values sampled from a probability distribution tend to lie. The sample mean or arithmetic average is an estimator for the mean. It is an unbiased and consistent estimator of the population mean (expected value) and itself is a random variable with its own variance value. The **sample** mean is the sum of values divided by the number of values:

$$\bar{x} = \frac{1}{n}\sum_{i}^{n} x_i \quad (x_i \, , \, i = 1,..,n \text{ are items of a sample})$$

MEDIAN

Statistical definition: The median or population median is a value which divides the integral of a PDF into two halves. For symmetric PDFs, it equals the mean. The median is the 50th population percentile.

The sample median is an estimator of the population median. It is the value that divides an ordered sample into two equal halves. If there are 2*n* + 1 observations, the median is taken as the (*n* + 1)th member of the ordered sample. If there are 2*n*, it is taken as being halfway between the nth and (*n* + 1)th.

MODE

Statistical definition: Distributions can have one or more modes. In practice, we usually encounter distributions with only one mode. In this case, **the mode or population mode of a PDF is the measure of a central value around which values sampled from a probability distribution tend to lie and is broadly speaking, the value which has the highest probability of occurrence**.

The sample mode is an estimator for the population mode calculated by subdividing the sample range into equal subclasses, counting how many observations fall into each class and selecting the centre point of the class (or classes) with the greatest number of observations.

MODEL

Statistical definition: A model is a quantitatively-based abstraction of a real-world situation which may simplify or neglect certain features to better focus on its more important elements.

Example: the relationship that emissions equal an emission factor times an activity level is a simple model. The term 'model' is also often used in the sense of a computer software realisation of a model abstraction which calculates a set of output values for a given set of input values – e.g. numerical global climate models.

MOMENTS (OF RANDOM VARIABLE)

Statistical definition: A population moment of a variable X about a given constant α is defined as the expected value of the random variable $(X - \alpha)^k$, i.e. $E(X - \alpha)^k$. For the case where α equals the population mean, μ, the moment $E(X - \mu)^k$ is termed the k^{th} central moment of X. They are important because statistical calculations are usually based upon the moments of the PDF rather than the PDF itself. The most commonly encountered moments are the mean and the variance.

The sample mean is the first moment around zero and the variance is the second central moment. Skewness and kurtosis are two frequently used functions of central moments which characterise the shape of the PDF.

The sample moments are estimators of population moments. The sample moment of k^{th} order is the arithmetic mean of the k^{th} power of the difference between the observed values and their average.

MONTE CARLO METHOD

Inventory definition: The principle of Monte Carlo analysis is to perform the inventory calculation many times by electronic computer, each time with the uncertain emission factors or model parameters and activity data chosen randomly (by the computer) within the distribution on uncertainties specified initially by the user. Uncertainties in emission factors and/or activity data are often large and may not have normal distributions. In this case the conventional statistical rules for combining uncertainties become very approximate. Monte Carlo analysis can deal with this situation by generating an uncertainty distribution for the inventory estimate that is consistent with the input uncertainty distributions on the emission factors, model parameters and activity data.

NON-LINEAR MODEL

Statistical definition: A model is non-linear if the relationship between its inputs and its outputs is non-linear (see Linear model).

NORMAL DISTRIBUTION

Statistical definition: The normal (or Gaussian) distribution has the PDF given in the following equation and is defined by two parameters (the mean μ and the standard deviation σ):

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \text{, for } -\infty \le x \le \infty$$

PARAMETERS OF POPULATION

Statistical definition: Parameters of the probability distribution that characterise the population. The most commonly used population parameters are the moments – e.g. the mean and the standard deviation for the normal distribution. A quantity used in describing the probability distribution of a random variable. [7]*

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* See references (p A3.21).

PDF

See Probability density function.

PERCENTILE

Statistical definition: The k^{th} percentile or population percentile is a value which separates the lowest k^{th} part of the integral of the PDF – i.e. an integral of a PDF tail from the k^{th} percentile towards lower probability densities.

The k^{th} population percentile ($0 \leq k \leq 100$) of a population with a distribution function $F(x)$ equals to z where z satisfies $F(z) = k/100$

Sample k^{th} percentile is an approximation for the population percentile which is derived from a sample. It is the value below which *k* percent of the observations lie.

POPULATION

Statistical definition: The population is the totality of items under consideration. In the case of a random variable, the probability distribution is considered to define the population of that variable [7]*.

Example: all conceivable experiments or events of a given type.

PRECISION

Inventory definition: Precision is the inverse of uncertainty in the sense that the more precise something is, the less uncertain it is.

PROBABILITY

Statistical definition: A probability is a real number in the scale 0 to 1 attached to a random event. ([7]*, C.2.1) There are different ways in which probability can be interpreted. One interpretation considers a probability as having the nature of a relative frequency (i.e. the proportion of all outcomes corresponding to an event), whilst another interpretation regards a probability as being a measure of degree of belief. The probability that a random event E occurs is often denoted as $\Pr(E)$. Probabilities may also be expressed in percentage terms. Probability theory is a branch of mathematics developed from axiomatic foundations, whose results underlay statistical inference.

PROBABILITY DENSITY FUNCTION – PDF

Statistical definition: A probability density function (PDF) is a mathematical function which characterises the probability behaviour of population. It is a function $f(x)$ which specifies the relative likelihood of a continuous random variable X taking a value near x, and is defined as the probability that X takes a value between x and $x+dx$, divided by dx where dx is an infinitesimally small number. Most PDFs require one or more parameters to specify them fully.

The probability that a continuous random variable X lies in between the values a and b is given by the interval of the PDF, $f(x)$, over the range between a and b.

$$\Pr(a \leq x < b) = \int_b^a f(x)dx$$

The PDF is the derivative (when it exists) of the distribution function:

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* See references (p A3.21).

$$f(x) = \frac{dF(x)}{dx}$$

In practical situations, the PDF used is chosen from a relatively small number of standard PDFs and the main statistical task is to estimate its parameters. Thus, for inventory applications, a knowledge of which PDF has been used is a necessary item in the documentation of an uncertainty assessment.

PROBABILITY DISTRIBUTION

Statistical definition: A function giving the probability that a random variable takes any given value or belongs to a given set of values. The probability on the whole set of values of the random variable equals 1. [7]*

PROPAGATION OF UNCERTAINTIES

Statistical definition: The rules for propagation of uncertainties specify how to algebraically combine the quantitative measures of uncertainty associated with the input values to the mathematical formulae used in inventory compilation, so as to obtain corresponding measures of uncertainty for the output values. See Chapter 6, Quantifying Uncertainties in Practice, and Annex 1, Conceptual Basis for Uncertainty Analysis.

QUALITY ASSURANCE (QA)

Inventory definition: Quality Assurance (QA) activities include a planned system of review procedures conducted by personnel not directly involved in the inventory compilation/development process to verify that data quality objectives were met, ensure that the inventory represents the best possible estimate of emissions and sinks given the current state of scientific knowledge and data available, and support the effectiveness of the quality control (QC) programme.

QUALITY CONTROL (QC)

Inventory definition: Quality Control (QC) is a system of routine technical activities, to measure and control the quality of the inventory as it is being developed. The QC system is designed to:

- **(i) Provide routine and consistent checks to ensure data integrity, correctness, and completeness;**
- **(ii) Identify and address errors and omissions;**
- **(iii) Document and archive inventory material and record all QC activities.**

QC activities include general methods such as accuracy checks on data acquisition and calculations and the use of approved standardised procedures for emission calculations, measurements, estimating uncertainties, archiving information and reporting. Higher tier QC activities include technical reviews of source categories, activity and emission factor data, and methods.

RANDOM ERROR

See Systematic and random errors.

RANDOM VARIABLE

Statistical definition: A variable that may take any of the values of a specified set of values and with which

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* See references (p A3.21).

is associated a probability distribution. A random variable which may take only isolated values is said to be ‘discrete.’ A random variable that may take any value within a finite or infinite interval is said to be ‘continuous’. [7][*]

RESIDUAL

Statistical meaning: For an observed value whose behaviour is modelled by a statistical model, the residual is the difference between the observed value and the value predicted by the model, e.g. by linear regression. The residual is thus the component of an observation that cannot be explained by the model.

SAMPLE

Statistical meaning: A sample is a finite set of observations drawn from a population.

SENSITIVITY

Statistical definition: A sensitivity is a measurement of how responsive one quantity is to a change in another related quantity. The sensitivity of a quantity Y that is affected by changes in another quantity X, is defined as the change in Y divided by the change in X that caused the changes in Y.

SENSITIVITY ANALYSIS

Statistical definition: Sensitivity analysis is a study of a model algorithm to determine how sensitive (or stable) it is to variations of its input data or underlying assumptions. It is performed by varying input values or model equations and observing how the model output varies correspondingly. The aim of such a sensitivity analysis can include:

- observing the range of output values corresponding to input variables lying within ‘reasonable’ ranges; and
- calculating finite difference approximations for elasticities and sensitivities as required by some methodologies for studying error propagation within a system.

SIGMA INTERVAL

Statistical definition: A *c*-sigma interval is a symmetric confidence interval centred on the mean and extending *c* times the standard deviation on either side.

SIMPLE RANDOM SAMPLE

Statistical definition: A sample of *n* items chosen from a population such that every possible sample has the same probability of being chosen.

SKEWNESS

Statistical definition: Skewness is a measure of asymmetry of a PDF. It is a simple function of two moments of the PDF, given by: $\gamma = \frac{\mu_3}{\mu_2^{3/2}} = \frac{\mu_3}{\sigma^3}$ where μ_2, μ_3, and σ, are central moments. Symmetric distributions have $\gamma = 0$. The same name is frequently used for sample skewness, in which case both population moments are replaced by sample moments.

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[*] See references (p A3.21).

STANDARD DEVIATION

Statistical definition: The population standard deviation is the positive square root of the variance. It is estimated by the **sample standard deviation** that is the positive square root of the sample variance.

STANDARD ERROR OF THE MEAN

Statistical definition: A term often used to signify the sample standard deviation of the mean.

STATISTIC

Statistical definition: A statistic is a function of the sample random variables. [7]*

STATISTICS

Statistical definition: Statistics can refer either in a general sense to the compilation of data, frequently about human activities, or in a more specific sense to the branch of science concerned with the systematic numerical treatment of data derived from aggregates of items.

SYSTEMATIC AND RANDOM ERRORS

Statistical definition: Systematic error is the difference between the true, but usually unknown, value of a quantity being measured, and the mean observed value as would be estimated by the sample mean of an infinite set of observations. The random error of an individual measurement is the difference between an individual measurement and the above limiting value of the sample mean.

SYSTEMATIC ERROR

Statistical definition: See Systematic and random errors.

TIME SERIES

Statistical definition: A time series is series of values which are affected by random processes and which are observed at successive (but usually equidistant) time points.

TRANSPARENCY

Inventory definition: Transparency means that the assumptions and methodologies used for an inventory should be clearly explained to facilitate replication and assessment of the inventory by users of the reported information. The transparency of inventories is fundamental to the success of the process for the communication and consideration of information.

TREND

Inventory definition: The trend of a quantity measures its relative trend over a time period, with a positive trend value indicating growth in the quantity, and a negative value indicating a decrease. It is defined as the ratio of the change in the quantity over the time period, divided by the initial value of the quantity, and is usually expressed either as a percentage or a fraction.

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* See references (p A3.21).

TRIANGULAR DISTRIBUTION

Statistical definition: An asymmetric triangular distribution function has a PDF

$f(x) = 2(x - a) / \{(b - a)\,(m - a)\}$ when $a \le x \le m$ and $a < m \le b$

$= 2(b - x) / \{(b - a)\,(b - m)\}$ when $m \le x \le b$ and $a \le m < b$

$= 0$ elsewhere,

where the parameters which specify the distribution are the minimum value a, the maximum value b, and the most likely position (i.e. mode) m, subject to $a \le m \le b$.

UNBIASED ESTIMATOR

Statistical definition: An unbiased estimator is a statistic whose expected value equals the value of the parameter being estimated. Note that this term has a specific statistical meaning and that an estimate of a quantity calculated from an unbiased estimator may lack bias in the statistical sense, but may be biased in the more general sense of the word if the sample has been affected by unknown systematic error. Thus, in statistical usage, a biased estimator can be understood as a deficiency in the statistical evaluation of the collected data, and not in the data themselves or in the method of their measurement or collection. For example, the arithmetic mean (average) $\overline{x}$ is an unbiased estimator of the expected value (mean).

UNCERTAINTY

Statistical definition: An uncertainty is a parameter, associated with the result of measurement that characterises the dispersion of the values that could be reasonably attributed to the measured quantity. [7]* (e.g. the sample variance or coefficient of variation)

Inventory definition: A general and imprecise term which refers to the lack of certainty (in inventory components) resulting from any causal factor such as unidentified sources and sinks, lack of transparency etc.

UNCERTAINTY ANALYSIS

Statistical definition: An uncertainty analysis of a model aims to provide quantitative measures of the uncertainty of output values caused by uncertainties in the model itself and in its input values, and to examine the relative importance of these factors.

UNIFORM DISTRIBUTION

Statistical definition: A random variable with a uniform or rectangular distribution is confined to lie within a range over which all values are equally probable. If the upper and lower limits of the range are a and b respectively, the PDF is a flat function from a to b (the two parameters defining the PDF).

The PDF of a uniform distribution is given by:

$$f(x) = \begin{cases} \dfrac{1}{b-a} & \text{for } a \le x \le b \\ 0 & \text{elsewhere} \end{cases}$$

where

$$\mu = \frac{a+b}{2}$$

is the mean and

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* See references (p A3.21).

$$\sigma^2 = \frac{(b-a)^2}{12}$$

is the variance.

VALIDATION

Inventory definition: Validation is the establishment of sound approach and foundation. In the context of emission inventories, validation involves checking to ensure that the inventory has been compiled correctly in line with reporting instructions and guidelines. It checks the internal consistency of the inventory. The legal use of validation is to give an official confirmation or approval of an act or product. [6]*

VARIABILITY

Statistical definition: This refers to observed differences attributable to true heterogeneity or diversity in a population. Variability derives from processes which are either inherently random or whose nature and effects are influential but unknown. Variability is not usually reducible by further measurement or study, but can be characterised by quantities such as the sample variance. [6]*

VARIANCE

Statistical definition: The variance or population variance is a parameter of a PDF, which expresses the variability of the population. It is the second central moment of a random variable. The **sample variance** is defined as a measure of dispersion, which is the sum of the squared deviations of observations from their average, divided by one less than the number of observations. [7]* $s^2 = \frac{1}{n-1}\sum_i^n (x_i - \bar{x})^2$

VARIANCE OF SAMPLE MEAN

Statistical definition: The mean of a sample taken from a population is itself a random variable with its own characteristic behaviour and its own variance. For such sample means, the appropriate estimate of the variance is not the sample variance, which estimates the variability associated with a single simple value, but a lower value, equal to the sample variance divided by the sample size.

VERIFICATION

Inventory definition: Verification refers to the collection of activities and procedures that can be followed during the planning and development, or after completion of an inventory that can help to establish its reliability for the intended applications of that inventory. Typically, methods external to the inventory are used to check the truth of the inventory, including comparisons with estimates made by other bodies or with emission and uptake measurements determined from atmospheric concentrations or concentration gradients of these gases. [6]*

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* See references (p A3.21).

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ANNEX 4

LIST OF PARTICIPANTS

PARTICIPANT	INSTITUTION	COUNTY	MEETING
ABEL, Kay	Australian Greenhouse Office	Australia	Industrial Processes Agriculture Uncertainty Finalisation
ABUBAKAR, Osman	Sudan Meteorlogical Authority	Sudan	Uncertainty
ADAMKOVA, Juliana	Slovak Hydrometeorological Institute	Slovak Republic	Waste
AGARWAL, Radhy .S.	Mechanical Engineering Department, Indian Institute of Technology Delhi	India	Industrial Processes
AGUIAR PEIXOTO, Roberto de	Department of Mechanical Engineering, Instituto Mauá De Tecnologia	Brazil	Industrial Processes
AGYEMANG-BONSU, William	Environmental Protection Agency	Ghana	Industrial Processes Uncertainty
AITCHISON, Kenneth	Novellus Systems, Inc.	USA	Industrial Processes
ALVES, Joao W. da Silva	CETESB	Brazil	Waste
AMON, Barbara	Institute of Agricultural, Environmental, and Energy Engineering, University of Agricultural Sciences	Austria	Agriculture
AMOUS, Samir	Apex-EBBD Consulting Co	Tunisia	Energy
ARMSTRONG-BROWN, Sue	UK Ministry of Agriculture, Fisheries, and Food	UK	Agriculture
ASHFORD, Paul	Caleb Management Services	UK	Industrial Processes
ATKINSON, Mike	Diamantina Technology	Australia	Industrial Processes Finalisation
ATKINSON, Ward	Sun Test Engineering	USA	Industrial Processes
BAKER, James A.	Delphi Automotive Systems	USA	Industrial Processes
BAKSHI, Vikram	ICF, Inc.	USA	Industrial Processes
BALDASANO, Jose	Dpto. de Proyectos de Ingenieria, Universidad Politecnica de Cataluna	Spain	Waste Finalisation
BARBOUR, Wiley	Office of Policy, Planning & Evaluation, US Environmental Protection Agency, Climate Change Division	USA	Industrial Processes Energy Uncertainty Finalisation
BARRY, Simon	Bureau of Rural Sciences	Australia	Finalisation
BARTOS, Scott	US Environmental Protection Agency	USA	Industrial Processes
BEEVER, David	CEDAR, Dept. of Agriculture, The University of Reading	UK	Agriculture
BENTLEY, Simon	CSIRO Atmospheric Research	Australia	Uncertainty Finalisation
BERRA, Guillerm	Instituto de Patobiologia	Argentina	Agriculture

BEU, Laurie	Motorola	USA	Industrial Processes
BHIDE, A. D.	National Environmental Engineering Research Institute	India	Waste
BIGG, Martin	Environment Agency	UK	Waste
BITSCH, Rainer	Siemens AG EV DE	Germany	Industrial Processes
BJERKE, Willy	International Primary Aluminium Institute	UK	Industrial Processes
BOECKX, Pascal	University of Ghent	Belgium	Waste Finalisation
BOGDANOV, Stanislav	National Institute of Meteorology, and Hydrology	Bulgaria	Industrial Processes
BOILEAU, Pierre	Environment Canada	Canada	Industrial Processes
BOUCHARD, Guy	Alcan International Limitée, Centre de recherche et de développement Arvida	Canada	Industrial Processes
BOUWMAN, A.F.	National Institute of Public Health and the Environment (RIVM)	Netherlands	Agriculture
BRAATZ, Barbara	ICF Consulting Group	USA	Agriculture
BRANSCOME, Marvin	Research Triangle Institute	USA	Industrial Processes
BREED, William	US Department of Energy	USA	Uncertainty
BRENNAN, Jean	Office of Global Change, US Department of State	USA	Agriculture Energy
BROTHERS, Lowell	Southern Company Services	USA	Industrial Processes
BROWN, Keith	AEA Technology Environment	UK	Waste
BUJIDMAE, B	Institute of Meteorology and Hydrology	Mongolia	Agriculture
BURTON, C. Shepherd	ICF Kaiser Consulting Group, Systems Applications International, Inc.	USA	Industrial Processes
CAHYONO ADI, Agus	Agency for Assessment and Application of Technology (BPP Technology)	Indonesia	Energy Finalisation
CAMPBELL, Nick	ICI Klea	UK	Industrial Processes
CARRUTHERS, Ian	Australian Greenhouse Office	Australia	Finalisation
CICERO, Anita	International Pharmaceutical Aerosol Consortium (IPAC)	USA	Industrial Processes
CHANG, Jean-Pierre	CITEPA	France	Uncertainty Finalisation
CHRISTMAS, Mark	DuPont Fluoroproducts	USA	Industrial Processes
CLARKE, Rachael	Australian Greenhouse Office	Australia	Finalisation
CLODIC, Denis	Ecole des Mines de Paris	France	Industrial Processes
DARRAS, Marc	Gaz de France	France	Energy

DE LAURETIS, Riccardo	Environmental Protection Agency (ANPA)	Italy	Uncertainty Finalisation
DENIER VAN DER GON, Hugo	Lab of Soil Science and Geology, Wageningen Agricultural University	Netherlands	Agriculture
DOLIN, Eric	US Environmental Protection Agency	USA	Industrial Processes
DOMINGOS MIGUEZ, José	Ministry of Science and Technology	Brazil	Energy
DONG, Hongmin	Chinese Academy of Agricultural Sciences	China	Agriculture
DOORN, Michiel	ARCADIS Geraghty & Miller	Netherlands	Waste Finalisation
DU TOIT, Pieter	SASTECH Research and Development	South Africa	Industrial Processes Finalisation
EGGLESTON, Simon	AEA Technology, National Environmental Technology Centre (NETCEN)	UK	Energy Uncertainty Finalisation
ELLERTON, Kathryn	Allied Signal, Inc.	USA	Industrial Processes
El-MOWAFY, Smair Attia	Egyptian Environmental Affairs Agency	Egypt	Energy
ESALA, Martti	Plant Production Research, Crops and Soil, Agricultural Research Centre	Finland	Agriculture
FALK, Robert S.	Department of Trade and Industry	UK	Energy
FAY, Kevin	International Climate Change Partnership	USA	Industrial Processes
FERNÁNDEZ, Marcelo Rodrigo	The National Commission for the Environment, Metropolitan Region Department, Air Decontamination Area	Chile	Uncertainty
FONTELLE, Jean-Pierre	CITEPA	France	Energy Uncertainty Finalisation
FORTE, Reynaldo	US Environmental Protection Agency	USA	Industrial Processes Finalisation
FOTT, Pavel	Czech Hydrometeorological Institute	Czech Republic	Energy Uncertainty Finalisation
FREY, Christopher	Dept. of Civil Engineering, North Carolina State University	USA	Uncertainty
FUJIMOTO, Yuichi	Japan Industrial Conference for Ozone Layer Protection	Japan	Industrial Processes
GALBALLY, Ian	CSIRO Atmospheric Research	Australia	Agriculture Uncertainty Finalisation
GASCA, Jorge	Mexican Petroleum Institute	Mexico	Uncertainty Finalisation
GERBENS, Sybren	Department of Manure and Agricultural Byproducts, Institute of Agricultural and Environmental Engineeering	Netherlands	Agriculture
GERMON, Jean-Claude	INRA	France	Agriculture

GIBBS, Michael	ICF Consulting Group	USA	Industrial Processes Agriculture Finalisation
GILLENWATER, Michael	US Environmental Protection Agency	USA	Industrial Processes Energy Uncertainty Finalisation
GILLET, Marc	Mission Interministérielle de l'Effet de Serre	France	Finalisation
GJERALD, Eilev	Norwegian Pollution Control Authority (SFT)	Norway	Energy Uncertainty Finalisation
GNAPELET, Lambert	Ministry of Environment, Water, Forest, Hunting, and Fisheries	Central African Republic	Agriculture
GOMEZ, Dario	Comision Nacional de Energia Atomica, Unidad de Actividad Quimica	Argentina	Energy
GREEN, David	National Institute of Standards and Technology	USA	Industrial Processes
GREENE, Dave	Oak Ridge National Laboratory (ORNL)	USA	Energy
GROENESTEIN, Karin	Institue of Agricultural and Environmental Engineering (IMAG-DLO)	Netherlands	Agriculture
GRONFORS, Kari	Statistics Finland	Finland	Energy Uncertainty Finalisation
GRUNCHARD, Francis	Solvay	Belgium	Industrial Processes
GYTARSKY, Michael	Institute of Global Climate and Ecology	Russia	Agriculture Uncertainty Finalisation
HABTETSION, Semere	Department of Energy	Eritrea	Uncertainty
HANNA, Javier	Programa Nacional de Cambios Climaticos	Bolivia	Energy Finalisation
HAO, Wei Min	USDA Forest Service	USA	Agriculture
HARNISCH, Jochen	ECOFYS Energy and Environment	Germany	Industrial Processes Agriculture
HARPER, Lowry	US Department of Agriculture	USA	Agriculture
HEINEMEYER, Otto	FAL/BML	Germany	Agriculture
HENRY, Beverley	Queensland Department of Natural Resources	Australia	Finalisation
HEROLD, Anke	Oeko-Institut	Germany	Energy Waste Uncertainty Finalisation
HIRAISHI, Taka	National Institute for Environmental Studies (NIES), Environment Agency	Japan	Industrial Processes Energy Waste Uncertainty Finalisation

HIRATA, Toshio	Denso Corporation	Japan	Industrial Processes
HOBSON, John	Water Research Centre	UK	Waste
HOSSAIN, Ijaz	Bangladesh University of Engineering and Technology	Bangladesh	Energy
IRPOLA, Eliisa	Finnish Environment Institute	Finland	Industrial Processes
IRVING, William	US Environmental Protection Agency	USA	Industrial Processes Agriculture Energy Waste Uncertainty Finalisation
JACOBS, Cindy	Office of Mobile Sources, US Environmental Protection Agency	USA	Energy
JACOBS, Franck Morgen	Statistics Division, Ministry of Planning	Antigua	Uncertainty
JACQUES, Art	Environment Canada	Canada	Uncertainty Finalisation
JANSSEN, Leon	National Institute of Public Health and the Environment (RIVM)	Netherlands	Agriculture
JARVIS, Stephen	Institute of Grassland and Environmental Research	UK	Agriculture
JEFFS, Mike	ICI Polyurethanes	Belgium	Industrial Processes
JENSEN, Jens F. Frøiland	Norconsult	Norway	Waste
JOHNSON, Don	Colorado State University	USA	Agriculture
JUBB, Charles	Burnbank Consulting Pty.Ltd.	Australia	Waste Uncertainty
JUN, Paul	ICF Consulting Group	USA	Agriculture
KELLER, Fred	Carrier Corporation	USA	Industrial Processes
KERR, Thomas	SCS Engineers	USA	Waste
KILDE, Niels	RISOE National Laboratory	Denmark	Agriculture
KIPONDYA, Wilfred	Centre for Energy, Environment, Science and Technology	Tanzania	Energy
KLEFFELGAARD, Tore	Norwegian Pollution Control Authority (SFT)	Norway	Waste
KOCH, Dietmar	Federal Environmental Agency	Germany	Energy
KOCH, Jean	SOREQ Nuclear Research Center	Israel	Agriculture Finalisation
KOHV, Natalja	Estonian Environment Information Centre	Estonia	Uncertainty
KOKORIN, Alexey	Institute of Global Climate and Ecology	Russia	Industrial Processes Finalisation
KRANJC, Andrej	Hydrometeorological Institute of Slovenia	Slovenia	Waste
KROEZE, Carolien	Wageningen Institute for Environment and Climate Research (WIME), Wageningen Agricultural University	Netherlands	Agriculture

KRUGER, Dina	US Environmental Protection Agency	USA	Industrial Processes Agriculture Energy Waste Uncertainty Finalisation
KUNWAR, Purushottam	Ministry of Population and Environment	Nepal	Industrial Processes
KUTAS, Jozef	IEM's Institute for Environmental Protection	Hungary	Waste
KWASI ADU, Joseph	Animal Research Instittute	Ghana	Agriculture Finalisation
LAMOTTA, Sergio	ENEA	Italy	Energy
LANTIN, Rhoda	International Rice Research Institute	Philippines	Agriculture
LARA, Scarlette	INIA-La Platina, Instituto de Investigaciones Agropecuarias	Chile	Waste
LASSEY, Keith	National Institute of Water and Atmospheric Research (NIWA)	New Zealand	Agriculture Finalisation
LEBER, Bernard	Kaiser Aluminum	USA	Industrial Processes
LEVAVASSEUR, Philippe	SGS-Thompson Microelectronics	France	Industrial Processes
LIEBERMAN, Elliot	US Environmental Protection Agency	USA	Energy
LINDH, Nils	Swedish Environmental Protection Agency	Sweden	Uncertainty
LOPEZ, Carlos	Instituto de Meteorologia	Cuba	Finalisation
LOTT, Robert	Gas Research Institute	USA	Energy
LUCON, Oswaldo	CETESB	Brazil	Waste
LYCK, Erik	National Environmental Research Institute	Denmark	Agriculture
MAGEZI-AKIIKI, B. James	Department of Meteorology	Uganda	Uncertainty
MAHRENHOLZ, Petra	Federal Environmental Agency	Germany	Industrial Processes
MAINHARDT, Heike	ICF, Inc.	USA	Industrial Processes
MANGINO, Joe	Eastern Research Group	USA	Industrial Processes Uncertainty Finalisation
MARECKOVA, Katarina	Slovak Hydrometeorological Institute, Department of Environment	Slovak Republic	Industrial Processes Agriculture Energy Waste Uncertainty Finalisation
MARKS, Jerry	ALCOA	USA	Industrial Processes
MARTINEZ, Julia	Instituto Nacional de Ecologia/SENARNAP	Mexico	Industrial Processes
MATSUO, Naoki	Institute for Global Environmental Strategies (IGES)	Japan	Uncertainty

MAUSCHITZ, Gerd	Vienna University of Technology	Austria	Waste
MCCULLOCH, Archie	ICI Chemicals and Polymers, Ltd.	UK	Industrial Processes Finalisation
McFARLAND, Mack	DuPont Fluoroproducts	USA	Industrial Processes
McNAMARA, Pauline	Swiss Agency for the Environment, Forest and Landscape	Switzerland	Uncertainty
MEYER, Leo	Department of Climate Change Ministry of Housing, Physical Planning, and the Environment	Netherlands	Finalisation
MIDAGLIA, Carmen	CETESB	Brazil	Waste
MIGUEZ, José Domingos	Ministry of Science and Technology	Brazil	Finalisation
MILTON, Martin	National Physical Laboratory	UK	Waste
MIROSLAV, Markvart	Institute of Inorganic Chemistry, Czech Academy of Sciences	Czech Republic	Energy
MOCELLA, Michael	DuPont Fluoroproducts	USA	Industrial Processes
MOHAMED, Yahaiya	Ministère de l'Environnement	Comores	Agriculture
MONDSHINE, Michael	Science Applications International Corporation (SAIC)	USA	Waste
MOSIER, Arvin	U.S.Department of Agriculture Agricultural Research Service (USDA/ARS)	USA	Agriculture Finalisation
MUPETA, Bart	Henderson Research Station	Zimbabwe	Agriculture
MYERS, Jerry	Intel Corporation	USA	Industrial Processes
NAKHUTIN, Alexander	Institute of Global Climate and Ecology	Russia	Uncertainty Finalisation
NAUJOCK, Art	Calsonic North America	USA	Industrial Processes
NEITZERT, Frank	Environment Canada	Canada	Energy Uncertainty Finalisation
NEVISON, Cindy	National Center for Atmospheric Research (NCAR)	USA	Agriculture
NGARA, Todd	Climate Change Office, Ministry of Mines and Environment	Zimbabwe	Uncertainty
NYENZI, Buruhani	Drought Monitoring Centre (DMC)	Tanzania	Energy Waste Uncertainty Finalisation
OBATA, Yutaka	Calsonic Corporation	Japan	Industrial Processes
ODINGO, Richard	University of Nairobi	Kenya	Uncertainty Finalisation
OENEMA, Oene	AB-DLO	Netherlands	Agriculture Finalisation

OGHITA, Toshiaki	Institute for Techno-Economics	Japan	Industrial Processes Finalisation
OI, Michihiro	Environment Agency	Japan	Energy
OLIVIER, Jos	National Institute of Public Health and the Environment (RIVM)	Netherlands	Industrial Processes Uncertainty Finalisation
OLSEN, Kenneth	Environment Canada	Canada	Agriculture Waste
OLSSON, Astrid	Swedish Environmental Protection Agency	Sweden	Industrial Processes Energy
OONK, Hans	TNO-MEP	Netherlands	Waste
OSMAN, Nejib	National Agency of Renewable Energy	Tunisia	Energy
OTTINGER SCHAEFER, Deborah	US Environmental Protection Agency	USA	Industrial Processes
OWENS, John	3M Chemicals	USA	Industrial Processes
PACIORNIK, Newton	Ministry of Science and Technology, Furnas Centrais Eletricas	Brazil	Industrial Processes Energy Waste Uncertainty Finalisation
PALMER, Bill	Cheminfo Services, Inc.	Canada	Industrial Processes
PARADIZ, Bostjan	Hydrometeorological Institute of Slovenia	Slovenia	Waste Uncertainty Finalisation
PARASYUK, Natalya	Agency for Rational Energy Use and Ecology	Ukraine	Industrial Processes
PENMAN, Jim	Global Atmosphere Division Department of the Environment, Transport and the Regions	UK	Industrial Processes Agriculture Energy Waste Uncertainty Finalisation
PETITJEAN, Christophe	Valeo Thermique Habitacle	France	Industrial Processes
PETTERSEN, Marit Viktoria	Norwegian Pollution Control Authority	Norway	Industrial Processes
PHILLIPS, Marc	Enron Gas Pipeline Group	USA	Energy
PICARD, David	Clearstone Engineering, Ltd.	Canada	Energy Finalisation
PIPATTI, Riitta	VTT Energy	Finland	Agriculture Waste Uncertainty Finalisation
PREISEGGER, Ewald	Solvay	Germany	Industrial Processes

PRETEL, Jan	Czech Hydrometeorological Institute	Czech Republic	Energy Finalisation
PULLEN, John	Alcoa of Australia, Ltd.	Australia	Industrial Processes
PULLES, Tinus	Institute of Environmental Sciences, Energy Research and Process Innovation TNO-MEP	Netherlands	Energy Uncertainty Finalisation
RAJARATHNAM, Uma	Tata Energy Research Institute (TERI)	India	Energy
RAMOS-MANE, Cecilia		Uruguay	Agriculture
RAND, Sally	US Environmental Protection Agency	USA	Industrial Processes
RASMUSSEN, Erik	Danish Energy Agency	Denmark	Industrial Processes Agriculture Energy
RECHBAUER, Gabriele	GTZ Deutsche Gesellschaft fûr Technische, Zusammenarbeit GmbH, Proklima/Measures	Germany	Industrial Processes
REUCK, Karin	INIA-La Platina, Instituto de Investigaciones Agropecuarias	Chile	Waste
REYENGA, Penny	Australian Greenhouse Office	Australia	Finalisation
RIBACKE, Sara	Swedish Association of Local Authority	Sweden	Energy
RIVIERE, Emmanuel	CITEPA	France	Industrial Processes Uncertainty
RODE, Bojan	Hydrometeorological Insitutute of Slovenia	Slovenia	Energy Uncertainty Finalisation
ROMANO, Daniela	Environmental Protection Agency (ANPA)	Italy	Uncertainty Finalisation
ROSLAND, Audun	Norwegian Pollution Control Authority	Norway	Finalisation
RUIZ-SUAREZ, Luis Gerardo	Centro de Ciencias de la Atmosfera (UNAM)	Mexico	Agriculture
RUYSSENAARS, Paul	Ministry of Housing, Spatial Planning and the Environment, Air and Energy	Netherlands	Agriculture
RYPDAL, Kristin	Statistics Norway	Norway	Industrial Processes Agriculture Energy Uncertainty Finalisation
RYPINSKI, Arthur	Energy Information Administration, US Department of Energy	USA	Industrial Processes Energy Uncertainty Finalisation
SABURI, Masataka	Ministry of International Trade and Industry	Japan	Industrial Processes
SALWAY, Geoff	AEA Technology, National Environmental Technology Centre (NETCEN)	UK	Uncertainty
SASS, Ronald L..	Dept. of Ecology and Evolutionary Biology, Rice University	USA	Agriculture

SCHMID, Martin	Institute of Environmental Protection and Agriculture	Switzerland	Agriculture
SEIDEL, Stephen	US Environmental Protection Agency	USA	Industrial Processes
SENHAJI, Faouzi	Groupe d'Etudes et de Recherches sur les E.R. et l'Environnement (GERERE)	Morocco	Waste Uncertainty Finalisation
SHENGCHU, Huang	China Coalbed Methane Clearinghouse	China	Energy
SIMMONS, Tim	AVONLOG Limited	UK	Energy
SISKA, Bernard	Slovak Agricultural University	Slovak Republic	Agriculture
SMITH, Jeffery	USDA-ARS	USA	Agriculture
SMITH, Keith	Institute of Ecology and Resource Management (IERM), University of Edinburgh	UK	Agriculture Finalisation
SOUZA LOMBA NETO, Candido	TEIXEIRA, Egle Novaes	Brazil	Industrial Processes
SPAKMAN, Jan	National Institute of Public Health and the Environment (RIMV)	Netherlands	Energy
STECZKO, Katarzyna	Oil and Gas Institute	Poland	Waste
STIRPE, Dave	Alliance for Responsible Atmospheric Policy	USA	Industrial Processes
STROGIES, Michael	Federal Environmental Agency	Germany	Industrial Processes Agriculture Uncertainty Finalisation
SUBAK, Susan	NRDC	USA	Uncertainty
SUIZU, Takuya	Federation of Electric Power Companies	Japan	Industrial Processes
SULLIVAN, Rory	Pacific Air and Environment	Australia	Finalisation
SVENSSON, Ingvar	Swedish Environmental Protection Agency	Sweden	Waste
SWATKOWSKI, Len	Appliance Research Consortium	USA	Industrial Processes
TAILAKOV, Oleg	Russian Coalbed Methane Center	Russia	Energy
TAYLOR, Dwayne	Denso	USA	Industrial Processes
TAYLOR, Gary	Taylor/Wagner, Inc.	Canada	Industrial Processes
TEIXEIRA, Egle Novaes	Fac. Engenharia Civil – UNICAMP	Brazil	Waste
TICHY, Milos	SUJB	Czech Republic	Industrial Processes Energy Uncertainty Finalisation
TOWPRAYOON, Sirintornthep	Joint Graduate School of Energy and the Enviornment King Mongkut's University of Technology	Thailand	Waste
TRIPP, Tom	Magnesium Corporation of America	USA	Industrial Processes
TSARUKYAN, Martiros	Ministry of Nature Protection	Armenia	Uncertainty

TSURUTA, Haruo	National Institute of Agro-Environmental Sciences	Japan	Agriculture Finalisation
TUHKANEN, Sami	Technical Research Centre of Finland	Finland	Energy
VAN AARDENNE, John A.	Wageningen Center for Environment and Climate Studies (CMKW)	Netherlands	Agriculture
VAN AMSTEL, Andre	Wageningen Agricultural University/WIMEK	Netherlands	Agriculture Uncertainty
VAN BRUMMELEN, Margreet	ECOFYS	Netherlands	Industrial Processes
VAN OSS, Hendrik	U.S. Geological Survey	USA	Industrial Processes
VERHILLE, Maurice	ELF - Atochem	France	Industrial Processes
VICHULATA, Pravee	Department of Animal Science, Kasetsart University	Thailand	Agriculture
VIERA, Sonia Manso	CETESB	Brazil	Waste
WALSH, Mike	Technical Consultant	USA	Energy
WANG, Minxing	Institute of Atmospheric Physics Chinese Academy of Science	China	Finalisation
WEI, Zhihong	Tsinghua University	China	Industrial Processes Finalisation
WERKEMA, Tom	ELF Atochem	USA	Industrial Processes
WILLIAMS, David J.	CSIRO Energy Technology Urban and Industrial Air Quality	Australia	Energy Finalisation
WILLIAMSON, Matthew	US Environmental Protection Agency	USA	Industrial Processes
WINIWARTER, Wilfried	Austrian Research Centers	Austria	Uncertainty
WIRTH, Thomas	US Environmental Protection Agency	USA	Agriculture Finalisation
YAGI, Kazuyuki	Japan International Research Center for Agricultural Sciences (JIRCAS)	Japan	Agriculture Finalisation
YASUDA, Kenji	Kanagawa Environmental Research Center	Japan	Finalisation
YELLEN, Duncan	March Consulting Group	UK	Industrial Processes
YESSERKEPOVA, Irina	Kazakh Research Institute of Environment Monitoring and Climate	Kazakhstan	Waste
ZEEMAN, Grietje	Department of Environment Technology, Wageningen Agricultural University	Netherlands	Agriculture
ZHANG, Jim	Environmental and Occupational Health Sciences Institute	USA	Energy
ZHENLIN, Chen	Department of Forecasting Services and Disaster Mitigation, China Meteorological Administration	China	Industrial Processes Uncertainty Finalisation
ZHOU, Peter	EEGC CONSULTANTS Pty	Botswana	Uncertainty

PARTICIPANTS FROM INTERNATIONAL ORGANISATIONS

PARTICIPANT	**INSTITUTION**	**MEETING**
ACOSTA MORENO, Roberto	UNFCCC Secretariat	Energy Agriculture Uncertainty Finalisation
BUENDIA, Leandro	IPCC-NGGIP/TSU	Uncertainty Finalisation
DOBBIE, Leonie	IATA	Energy
EMMANUEL, Sal	IPCC-NGGIP/TSU	Energy Waste Uncertainty Finalisation
HOEHNE, Niklas	UNFCCC Secretariat	Industrial Processes Uncertainty
HOPPAUS, Robert	IPCC-NGGIP/TSU	Industrial Processes Agriculture Energy Waste Uncertainty Finalisation
MARTINSEN, Thomas	OECD, Environment Directorate	Industrial Processes Agriculture Energy Waste Uncertainty Finalisation
MEIJER, Jeroen	IPCC-NGGIP/TSU	Energy Uncertainty Finalisation
MIWA, Kyoko	IPCC-NGGIP/TSU	Waste Uncertainty Finalisation
SUNDARARAMAN, Narasimhan	IPCC	Industrial Processes
TANABE, Kiyoto	IPCC-NGGIP/TSU	Industrial Processes Agriculture Waste Uncertainty Finalisation
TREANTON, Karen	International Energy Agency (IEA)	Energy Uncertainty Finalisation
WILLEMS, Stephane	OECD, Environment Directorate	Energy
WOODFIELD, Mike	UNECE-Task Force on Emission Inventory	Uncertainty

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INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

NATIONAL GREENHOUSE GAS INVENTORIES PROGRAMME

UNEP

GPGAUM-Corr.2001.01

CORRIGENDUM

(15 June 2001)

Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories

1. Discard the following pages:

- ➢ BASIC INFORMATION: Page vii
- ➢ Chapter 1 INTRODUCTION: Page 1.4
- ➢ Chapter 3 INDUSTRIAL PROCESSES: Pages 3.42 to 3.44

2. Insert the enclosed pages as follows:

➢ BASIC INFORMATION: Page vii

("Sulfer hexafluoride" was replaced with "Sulfur hexafluoride".)

➢ Chapter 1 INTRODUCTION: Page 1.4

("practible" was replaced with "practicable" in first and second paragraphs of Section 1.3.)

➢ Chapter 3 INDUSTRIAL PROCESSES: Pages 3.42 to 3.44

Page 3.42, Box 3.3: (Definitions of all parameters were transferred inside the box and added the terms "expressed as a fraction rather than a percentage" in the CE definition.)

Page 3.42, Equation 3.11: ("as a fraction" was replaced with "in percent" in the CE definition.)

Page 3.44, Table 3.9: (Presentation of units for “Slope” and “Overvoltage coefficient” was improved by adding brackets and parentheses. The denominator of the unit of “Overvoltage coefficient” was changed from "mV/day" to "mV/cellday".)

IPCC National Greenhouse Gas Inventories Programme
Technical Support Unit
C/o Institute for Global Environmental Strategies, 1560-39 Kamiyamaguchi, Hayama, Kanagawa, JAPAN 240-0198
Phone: +81 468 55 3750   Fax: +81 468 55 3808
E-mail: tsu@iges.or.jp
Website: http://www.ipcc-nggip.iges.or.jp