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Department of Climate Change, Energy,
the Environment and Water

National Inventory Report
2022

The Australian Government Submission to the United Nations Framework Convention on Climate Change

Australian National Greenhouse Accounts

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VOLUME 1

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Acknowledgement of Country

In delivering this National Inventory Report, we pay our respects to our First Nations people, their elders and their ancestors who cared for the lands before our time, their communities who continue to care for Country today, and the young ones who are following in their footsteps.

First Nations people have loved, cared for, and listened to Country for thousands of generations, so it is important to reflect on this ancient connection and guardianship. These enduring cultures are the oldest on Earth. They have used their traditional knowledge to adapt as Australia's climate has changed over the millennia, and the resilience of these cultures is a source of inspiration.

Aboriginal and Torres Strait Islander voices and knowledge are critical to addressing the impacts of climate change and responding to the challenges we all now face. In the spirit of reconciliation, we look forward to improving how these voices are heard and represented in Australian Government decision-making, especially in our current climate and environmental crisis.

Australia recognises and pays its respects to Aboriginal and Torres Strait Islanders as the Traditional Owners of Australia. We would like to thank the Traditional Owners for their continuing custodianship of the lands, waters, skies, and communities that we live and work within today.

Other acknowledgements

The Department of Climate Change, Energy, the Environment and Water acknowledges the many individuals and organisations that have contributed to the development of the national methods applied in successive editions of this Report over the years.

We would like to extend particular thanks to the National Greenhouse Gas Inventory Committee and National Inventory User Reference Group who provided quality assurance on the methods and emissions estimates contained in this Report.

The resources and expertise of the following Commonwealth agencies have also significantly contributed to the Report:

- Australian Bureau of Agricultural and Resource Economics and Sciences
- Australian Bureau of Statistics
- Bureau of Meteorology
- Clean Energy Regulator
- Commonwealth Scientific and Industrial Research Organisation
- Department of Agriculture, Fisheries and Forestry
- Department of Industry, Science and Resources
- Department of Infrastructure, Transport, Regional Development, Communications and the Arts
- Geoscience Australia

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Executive Summary

ES.1 Background information on greenhouse gas inventories and climate change

This document is Australia's *National Inventory Report 2022* ("this Report") and, in conjunction with associated Common Reporting Tables (CRTs), is Australia's second national inventory submission under the Paris Agreement (PA). In accordance with decision 1/CP.24 of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC), the submission of this Report and associated CRTs also fulfils Australia's annual national inventory reporting obligation under the UNFCCC.

This Report provides estimates of Australia's net greenhouse gas emissions for the period 1989–90 to 2021–22, and emissions estimates are classified using the UNFCCC classification system. That is, this Report includes emissions and removals from the energy, industrial processes and product use, agriculture, waste, and the land use, land use change and forestry (LULUCF) sectors.

This Report has been prepared in accordance with the *Modalities, procedures and guidelines for the transparency framework for action and support referred to in Article 13 of the Paris Agreement* agreed by the Conference of Parties (COP) serving as the meeting of the Parties to the Paris Agreement at its first session (decision 18/CMA.1) and known as MPG, and *Guidance for operationalizing the modalities, procedures and guidelines for the enhanced transparency framework referred to in Article 13 of the Paris Agreement* (decision 5/CMA.3).

Consistent with decision 18/CMA.1 and decision 5/CMA.3, emissions estimates provided in this Report have been compiled in accordance with the Intergovernmental Panel on Climate Change (IPCC) *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006 Guidelines), supplemented by aspects of the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (2019 IPCC Refinement), and the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013 Wetlands Supplement). Australia's methodologies have been improved over time and will continue to be refined as new information emerges, and as international practice evolves. The aim is to ensure that the estimates of emissions are accurate, transparent, complete, consistent through time and comparable with those produced in the inventories of other Parties.

The responsibility for Australia's greenhouse gas emissions reporting has been assigned to the Department of Climate Change, Energy, the Environment and Water (the Department). The Department is responsible for all aspects of the national inventory systems, including activity data coordination, emissions estimation, quality control, preparation of reports and their submission to the UNFCCC on behalf of the Australian Government.

In addition to this Report, the Department publishes a range of supporting emissions estimates that, together, constitute the Australian National Greenhouse Accounts, including:

- *Quarterly Updates of Australia's National Greenhouse Gas Inventory*, which provide a summary of Australia's national emissions, updated on a quarterly basis,
- *State and Territory Greenhouse Gas Inventories*, comprising emissions estimates for Australian states and territories, and
- the *National Inventory by Economic Sector,* comprising emissions estimates for industries and households rather than by IPCC sectors as in this Report.

These documents are available on the Department's website Tracking and reporting greenhouse gas emissions.

The Department also publishes annual emissions projections, which estimate Australia's future greenhouse gas emissions and help determine how Australia is tracking against its emissions reduction targets. Projections reports are published at Projecting greenhouse gas emissions.

Emissions data from the aforementioned reports are published in an interactive online database: Australia's National Greenhouse Accounts (ANGA). ANGA allows users to interrogate historical and projected emissions estimates by a wide range of variables. Data are presented in customised tables and charts and can be downloaded as images or Excel sheets. These supplementary reports and databases provide additional information with respect to Australia's emissions on a regional, industry, gas (raw and carbon dioxide equivalent), quarterly, scope 1 and scope 2 basis.

This Report presents emissions for each of the major greenhouse gases as carbon dioxide equivalents (CO_2-e) using 100-year global warming potentials (GWPs). As greenhouse gases vary in their radiative activity, and in their atmospheric residence time, converting emissions into CO_2-e allows the integrated effect of emissions of the various gases to be compared. In accordance with Paris Agreement requirements[1], this Report applies 100-year GWPs contained in Table 8.A.1 of Chapter 8: Anthropogenic and Natural Radiative Forcing of the 2014 IPCC Fifth Assessment Report (AR5) (IPCC 2014). These are different from those applied to National Inventory Reports (NIRs) submitted in previous years (except for the NIR 2021). NIRs submitted for the years 2013 to 2020 applied 100-year GWPs from the 2007 IPCC Fourth Assessment Report (AR4) (IPCC 2007).

A summary of the AR4 and AR5 GWPs and the differences between them is presented in Table ES.01.

Table ES.01 Comparison of global warming potentials (GWPs) between the 2020 (AR4), and 2021 and 2022 (AR5) National Inventory Reports (NIRs)

Greenhouse gas	AR4[1] GWPs NIR 2020 (t CO_2-e per t of gas)	AR5[2] GWPs NIR 2021 and 2022 (t CO_2-e per t of gas)	Difference (%)
CO_2	1	1	0
CH_4	25	28	12
N_2O	298	265	-11
SF_6	22,800	23,500	3
PFC[3] (tetrafluoromethane)	7,390	6,630	-10
PFC[3] (hexafluoroethane)	12,200	11,100	-9
HFCs[4]	dependent on HFC type[5]	dependent on HFC type[5]	dependent on HFC type[5]

Notes: 1) IPCC 2007 Fourth Assessment Report (AR4) (IPCC 2007), 2) IPCC 2014 Fifth Assessment Report (AR5) (IPCC 2014), 3) PFC = perfluorocarbons, 4) HFC = hydrofluorocarbons, 5) GWPs for the various HFCs are available in AR4 and AR5.

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[1] Decision 18/CMA.1, annex, paragraph 37, and decision 5/CMA.3, paragraph 25.

Emission estimates presented in this Report are provided on an Australian financial year basis (Jul-Jun) rather than on a calendar year basis (Jan-Dec) because key data sources for Australia's national greenhouse gas inventory are published on this basis. For example, the Australian financial year 1990 commences on 1 July 1989 and ends on 30 June 1990, and is commonly cited as "1989–90". This Report covers the Australian financial years 1989–90 to 2021–22. The use of financial year data is consistent with the IPCC 2006 Guidelines (IPCC 2006) as the use of these data conforms to the normal practice of Australia's national statistical agencies and leads to more accurate emissions estimates.

Information on Australia's national circumstances and climate change policies are detailed in Australia's 8th National Communication on Climate Change, the Climate Change Act 2022, and the Annual Climate Change Statement 2023.

ES.2 Summary of trends related to national emissions and removals

Australia's net greenhouse gas emissions from all sectors were 432.6 million tonnes (Mt) of carbon dioxide equivalent (CO_2-e) in 2021–22. Including the LULUCF sector, which is a net sink in 2021–22, this is a decrease of:

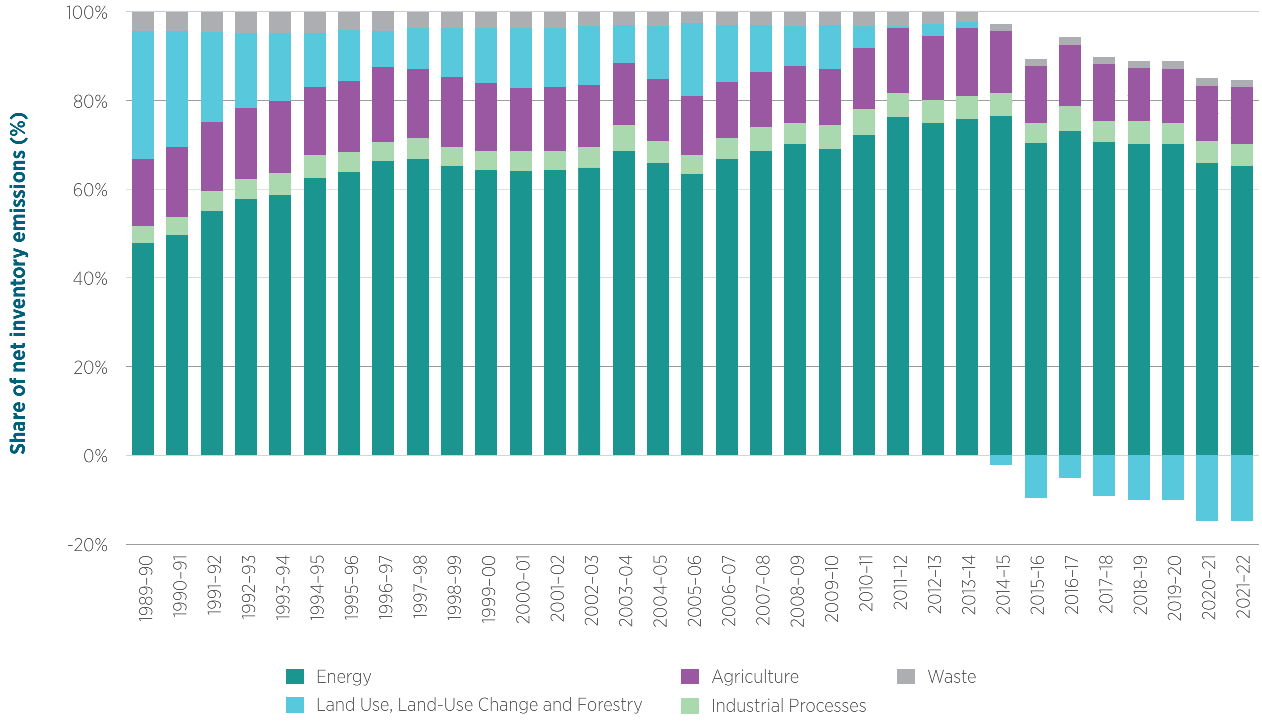
- 29.7 per cent (182.8 Mt CO_2-e) from 615.4 Mt CO_2-e in 1989–90,
- 29.0 per cent (176.8 Mt CO_2-e) from 609.4 Mt CO_2-e in 2004–05, and
- 1.4 per cent (6.1 Mt CO_2-e) from 438.7 Mt CO_2-e in 2020–21.

Emissions by sector for key years, including changes between 2021–22 and the years 1989–90, 2004–05, and the previous year (2020–21), are presented in Tables ES.02 and 2.1.

As the LULUCF sector is a net sink in 2021–22, emissions by sector are described with and without LULUCF in ES.2 and ES.3 and are largely described excluding LULUCF in Section 2.2 and sectoral Chapters 3–5 and 7. As presented in Figure ES.01, emissions as a share of Australia's total inventory by sector are outlined below:

- Energy sector emissions accounted for the largest proportion of Australia's emissions profile, contributing 91.7 per cent of Australia's net national emissions (or 76.1 per cent excluding LULUCF) in 2021–22. This is an increase in contribution from 48.3 per cent in 1989–90.
- Agriculture sector emissions accounted for the second largest proportion of Australia's emissions profile, comprising 17.9 per cent of Australia's net national emissions (or 14.9 per cent excluding LULUCF) in 2021–22. This is an increase in contribution from 14.8 per cent in 1989–90.
- Industrial processes and product use sector emissions accounted for 7.6 per cent of Australia's net national emissions (or 6.3 per cent excluding LULUCF) in 2021–22. This is an increase in contribution from 4.1 per cent in 1989–90.
- Waste sector emissions accounted for 3.2 per cent of Australia's net national emissions (or 2.7 per cent excluding LULUCF) in 2021–22. This is a decrease in contribution from 3.8 per cent in 1989–90.
- Land use, land use change and forestry (LULUCF) was a net sink of 20.4 per cent of Australia's net national emissions (or equivalent to 17.0 per cent of non-LULUCF emissions) in 2021–22. In contrast, LULUCF accounted for 29.0 per cent of Australia's net national emissions in 1989–90.

Figure ES.01 Contribution to total net emissions by sector, Australia, 1989–90 to 2021–22 (per cent)



Trends in emissions are discussed further in Chapter 2, and trends in emissions from each sector and their sub-sectors are discussed further in Chapters 3-7.

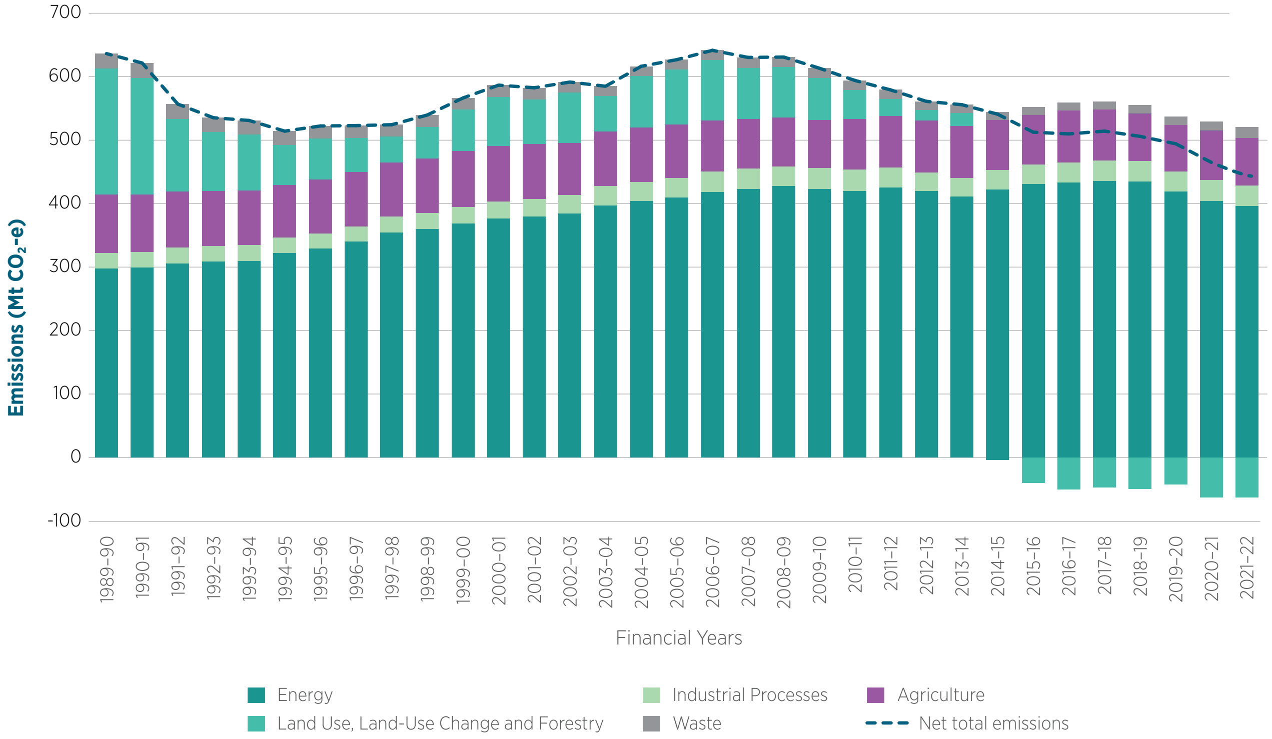
ES.3 Overview of source and sink category emissions estimates and trends

The full time series of the national inventory, including for major sectors, is presented in Figure ES.02. A summary table is presented in Table ES.02 containing annual emissions by sector and comparison between key years. As the LULUCF sector is a net sink in 2021–22, emissions by sector are described with and without LULUCF in ES.2 and ES.3 and are largely described excluding LULUCF in Section 2.2.

Table ES.02 Net greenhouse gas emissions by sector, Australia (Mt CO_2-e)

UNFCCC classification sector and subsector	**Net emissions (Mt CO_2- e)**							**% change in emissions between 2021–22 and:**		
	1989–90	**2004–05**	**2009–10**	**2014–15**	**2019–20**	**2020–21**	**2021–22**	**1989–90**	**2004–05**	**2020–21**
1 Energy (combustion + fugitive)	297.4	403.7	422.4	422.5	418.8	404.3	396.7	33.4	-1.7	-1.9
Stationary energy	195.7	278.9	288.2	278.7	271.7	265.6	258.9	32.3	-7.2	-2.5
Transport	61.4	82.0	88.6	95.2	93.2	90.1	89.8	46.3	9.4	-0.4
Fugitive emissions from fuel	40.3	42.8	45.5	48.6	53.9	48.6	48.1	19.3	12.3	-1.1
Carbon capture and storage	NO	NO	NO	NO	0.012	0.002	0.0003	NA	NA	-84.7
2 Industrial processes and product use	25.1	30.1	33.4	30.5	31.9	32.9	33.0	31.3	9.4	0.3
3 Agriculture	91.2	84.9	74.0	77.7	71.6	76.6	77.5	-15.0	-8.8	1.1
4 Land use, land use change and forestry	178.3	75.0	63.3	-9.7	-61.2	-88.5	-88.4	-149.6	-217.9	0.2
6 Waste	23.5	15.7	16.0	12.7	13.5	13.4	13.9	-40.9	-11.8	3.1
Total net emissions	**615.4**	**609.4**	**609.2**	**533.7**	**474.5**	**438.7**	**432.6**	**-29.7**	**-29.0**	**-1.4**
Memo: *Total net emissions without application of the natural disturbance provision*	615.4	577.9	584.9	516.9	1193.3	305.0	320.6	-47.9	-44.5	5.1

Figure ES.02 Greenhouse gas emissions by sector, Australia, 1989-90 to 2021-22 (Mt CO_2-e)



The *Energy* sector was the largest source of greenhouse gas emissions in 2021–22 comprising 91.7 per cent (367.7 Mt CO_2-e) of total net emissions (or 76.1 per cent excluding LULUCF). *Energy* emissions increased by 33.4 per cent (99.3 Mt CO_2-e) between 1989–90 and 2021-22 and decreased by 1.9 per cent (7.6 Mt CO_2-e) between 2020–21 and 2021–22. Trends for this sector and its sub-sectors are described in more detail in Chapter 3.

Industrial processes and product use comprised 7.6 per cent (33.0 Mt CO_2-e) of total net emissions (or 6.3 per cent excluding LULUCF) in 2021–22, increased 31.3 per cent (7.9 Mt CO_2-e) between 1989–90 and 2020–21, and increased by 0.3 per cent (0.1 Mt CO_2-e) between 2020–21 and 2021–22. Trends for this sector and its sub-sectors are described in more detail in Chapter 4.

Agriculture emissions made up 17.9 per cent (77.5 Mt CO_2-e) of total net emissions (or 14.9 per cent excluding LULUCF) in 2021–22, decreased 15.0 per cent (13.7 Mt CO_2-e) between 1989–90 and 2021–22, and increased by 1.1 per cent (0.8 Mt CO_2-e) between 2020–21 and 2021–22. Trends for this sector and its sub-sectors are described in more detail in Chapter 5.

The *Land use, land use change and forestry* (LULUCF) sector was a net sink of 88.4 Mt CO_2-e in 2021–22, equivalent to -20.4 per cent of total net emissions (including LULUCF). Between 1989–90 and 2021–22 there was a decrease of 149.6 per cent (266.6 Mt CO_2-e), with the sector changing from a net source to a net sink. The long-term trends including reductions in native forest harvesting and land clearing rates have continued in 2022 (see section 6.1 for more information). Net forest cover increased by around 300,000 hectares in 2022, reflecting increases in native vegetation in previously cleared forest lands and grasslands exceeding clearing rates (see Chapter 6, Table 6.2.1 — land transition matrix). These trends have contributed to the net LULUCF sink in 2021–22.

Between 2020–21 and 2021–22 there was a 0.2 Mt CO_2-e decrease in the net sink from the *LULUCF* sector. This reflects inter-annual variations in climate drivers, including the increasing sink in croplands and grasslands caused by high rainfall La Niña conditions, that was offset by emissions increases in forest lands due to wildfires and increased rates of soil carbon decay also caused by wetter conditions. Significant updates to the FullCAM Tier 3 emissions model have been made in this submission as part of ongoing improvement programs for soil carbon and native forest harvesting, as detailed in ES.6, and further updates to these model components are expected to continue in the next inventory submission reflecting roll out of new research on soils and access to additional activity data. Trends for this sector and its sub-sectors are described in more detail in Chapter 6.

The *Waste* sector contributed 3.2 per cent (13.9 Mt CO_2-e) of total net emissions (or 2.7 per cent excluding LULUCF) in 2021-22, decreased 40.9 per cent (9.6 Mt CO_2-e) between 1989-90 and 2021–22, and increased by 3.1 per cent (0.4 Mt CO_2-e) between 2020–21 and 2021–22. Trends for this sector and its sub-sectors are described in more detail in Chapter 7.

A full overview of emissions estimates by source, sink, and gas is given in Chapter 2.

ES.4 Other Information

The Australian Government submitted an updated Nationally Determined Contribution (NDC) (DISER 2022) under Article 4 of the Paris Agreement on 16 June 2022, as one of its first actions as a new Government. In this updated NDC, Australia increased the ambition of its 2030 target, committing to reduce greenhouse gas emissions 43 per cent below 2005 levels by 2030. Australia also reaffirmed its target to achieve net zero emissions by 2050.

Both targets are economy-wide emissions reduction commitments, covering all sectors and gases included in Australia's national inventory. The revised 2030 commitment is both a single-year target to reduce emissions 43 per cent below 2005 levels by 2030 and a multi-year emissions budget from 2021–2030. In September 2022, the Government passed the Climate Change Act 2022, enshrining these targets in legislation.

Descriptions of Australia's national circumstances and climate change policies are detailed in Australia's 8th National Communication on Climate Change, and the Annual Climate Change Statement 2023.

ES.5 Key category analysis

A key category is defined in the IPCC 2006 Guidelines (Volume 1, Chapter 4) (IPCC 2006) as an emissions source that is prioritised within the national inventory system because it has a significant influence on total, trend and uncertainties of total greenhouse gas emissions. In general, higher tier methods should be used for estimating emissions from key categories. Consistent with the IPCC 2006 Guidelines (section 4.1.2), Tier 1 methods can be used where application of a higher tier method is not possible.

Key categories are identified by undertaking the level and trend assessments described in the IPCC 2006 Guidelines (Volume 1, Chapter 4, Section 4.3) (IPCC 2006) by all inventory sub-categories by greenhouse gas. These approaches identify the emissions sources that contribute to 95 per cent of total emissions or of the trend of the inventory in absolute terms.

Australia's analyses have been undertaken using a disaggregation of sources, as recommended in Table 4.1 of the 2006 IPCC Guidelines (IPCC 2006).

With the exception of the three key categories below, all key categories, and a significant proportion of non-key categories, are reported using Tier 2 of Tier 3 methods. The full results are detailed in Volume 2, Annex I to this Report.

Three key categories estimated using Tier 1:

- **2.B.9 – IPPU, Chemical Industry / Fluorochemical Production – HFC-23**

  HFC-23 (trifluoromethane) is generated as a by-product of production of the refrigerant HCFC-22 (chlorodifluoromethane). The production of HCFC-22 last occurred in Australia in 1994-95, following international agreement of the Montreal Protocol on Substances that Deplete the Ozone Layer (the Montreal Protocol) in 1987.

  Emissions from this sub-category were identified as a key category on a trend basis. Emissions from this source have not occurred since 1994-95 and plant-specific (facility-specific) data are not available.

- **3.C – Agriculture, Rice Cultivation – CH_4 (methane)**

  CH_4 is produced by flooded rice fields, which causes anaerobic decomposition of organic material. A range of variables such as crop size, duration, water regimes, and soil amendments affect the CH_4 intensity of rice cultivation. In Australia, the capacities of water resources are highly variable based on fluctuating periods of strong drought and rain, which results in strong variability in rice cultivation trends.

  Australia applies a Tier 1 method using updated default emissions factors provided in the 2019 IPCC Refinement. The method is described in detail in Chapter 5, Section 5.4 (IPCC 2019). Historically, this sub-category was not considered a key category for Australia. It contributes 0.009 to 0.51 Mt CO_2-e per year from 2004-05 onwards, and 0.1 per cent of net emissions in 2021-22.

  In recent years this category fluctuates between key and not key category on a trend basis caused by strong declines towards the end of the millennium drought (which ended around 2008-09), drought conditions experienced from 2015-16 to 2018-19, and recovery driven by the start of wet La Nina conditions in 2020-21.

  As included in Chapter 5, Section 5.4.6, Australia is considering the development of Tier 2 emissions factors for this sub-category for inclusion in future submissions.

- **3.H – Agriculture, Urea Application – CO_2 (carbon dioxide)**

  Adding urea to soils leads to a loss of CO_2 that was fixed during the industrial process of urea manufacturing. Australia applies a Tier 1 method for this category. Historically, this sub-category was not considered a key category for Australia. It contributes 0.7 to 1.9 Mt CO_2-e per year from 2004–05 onwards, and 0.4 per cent of net emissions in 2021–22.

  This category only recently became a key category, due to lowering national emissions resulting in smaller sources now becoming a higher proportion of national emissions, and emissions from this source significantly increasing since 1989–90. As described in Section 5.9.6 of this Report, improvements to develop a Tier 2 method for this category are under consideration.

ES.6 Improvements introduced

Australia’s inventory is subject to continuous, incremental improvement to incorporate the latest verifiable research, data, technologies and practices.

ES.6.1 Improvements implemented in 2021-22

For this Report, UNFCCC Expert Review Team (ERT) recommendations from previous submissions were progressed or addressed. The status of these improvements are described in Chapter 10.4, as well as a summary of responses to the simplified review for the 2023 inventory submission. In addition, the following improvements were implemented:

Method improvements were applied to improve the accuracy and comparability of Australia’s emissions estimates

Improvements typically result in recalculations to Australia’s emissions. The impact of recalculations on national totals are summarised in ES.6.2 Recalculations and in Chapter 10, and the details are presented in sectoral Chapters 3-7. The main method improvements are described by sector, below.

Energy

Manufacturing Industries and Construction’: Additional plant-specific activity data and emissions factors reported under the National Greenhouse and Energy Reporting (NGER) scheme have been incorporated.

More detail on method improvements in the energy sector is provided in Chapter 3 of this Report.

LULUCF

Croplands and Grasslands: Revisions were made to the modelling of crop and grass yields, as well as the modelling of perennial and annual grasses within FullCAM, so that yields better reflect local climate. This has led to recalculations across cropland and grassland soils, as well as other land-uses that include crop and grass regimes. These changes have had an impact across the time series, particularly over the 2020 to 2022 La Niña period, which saw above average rainfall, below average pan evaporation and temperatures. The resulting recalculations and building of soil carbon across croplands and grasslands can be seen in Figure ES.03.

Figure ES.03 Comparison of combined emissions from cropland remaining cropland and grassland remaining grassland soils from the NIR 2021 submission vs NIR 2022 submission.

Harvested native forests: The spatially explicit modelling approach for public multiple use forests has now been extended to the state of Queensland, following on from similar modelling updates for multiple use forests in Victoria, New South Wales and Tasmania. In New South Wales, completeness of the harvesting activity data has been improved using updated spatial data.

Farm dams: Updates were made to the model for farm dam water surface area and methane emission rates based on the relationship with climate variables (by applying machine learning techniques), enabling updates to estimates of annual farm dam methane emissions.

More detail on method improvements in the LULUCF sector is provided in Chapter 6 of this Report.

Waste

Solid Waste Disposal: Revisions were made to the way that residual disposal and capture data, not covered by the mandatory NGER scheme, are estimated. This improves inventory alignment with state and territory reported data.

More detail on method improvements in the waste sector is provided in Chapter 7 of this Report.

ES.6.2 Recalculations

The impact of the method improvements and other recalculations across the time series ranged from 15.8 Mt CO_2-e (-3.0 per cent) to +1.1 Mt CO_2-e (+0.2 per cent) per year. Recalculations are presented in absolute and relative terms in Table ES.03.

Table ES.03 Recalculations for this submission (NIR 2022) compared with last year's submission (NIR 2021), AR5 GWPs

	NIR 2021	NIR 2022	Change	
	(Gg CO_2-e)		(Gg CO_2-e)	(%)
1989–90	636,268.6	615,387.3	-20,881.3	-3.3
1994–95	514,212.0	510,972.6	-3,239.4	-0.6
1999–00	566,358.3	569,826.4	3,468.1	0.6
2004–05	616,293.2	609,446.1	-6,847.0	-1.1
2005–06	626,790.5	644,924.3	18,133.8	2.9
2006–07	641,523.1	626,119.7	-15,403.4	-2.4
2007–08	630,251.3	614,649.1	-15,602.3	-2.5
2008–09	630,906.6	607,868.2	-23,038.4	-3.7
2009–10	613,332.7	609,168.6	-4,164.1	-0.7
2010–11	594,032.2	577,597.9	-16,434.3	-2.8
2011–12	579,077.4	554,652.2	-24,425.3	-4.2
2012–13	561,101.3	557,099.1	-4,002.2	-0.7
2013–14	555,817.5	538,319.3	-17,498.2	-3.1
2014–15	540,912.2	533,688.4	-7,223.8	-1.3
2015–16	512,483.0	491,065.0	-21,418.0	-4.2
2016–17	509,809.5	528,911.2	19,101.6	3.7
2017–18	514,226.4	501,666.1	-12,560.2	-2.4
2018–19	505,857.1	490,705.8	-15,151.3	-3.0
2019–20	494,233.0	474,544.3	-19,688.7	-4.0
2020–21	464,770.7	438,745.1	-26,025.6	-5.6

Method improvements, data corrections, and the incorporation of improved activity data are detailed in sectoral Chapters 3-7 and summarised in ES.6.1 and Chapter 10. Recalculations by sector are presented in Table ES.04.

Table ES.04 Recalculations for this submission (NIR 2022) compared with last year's submission (NIR 2021) by sector, Gg CO_2-e AR5 GWPs

	1 Energy	1.A.1, .2, .4, and .5 Stationary Energy	1.A.3 Transport	1.B Fugitive emissions	2 IPPU	3 Agriculture	4 LULUCF	5 Waste
1989–90	0.0	0.0	0.0	0.0	0.0	-936.6	-19,944.7	-0.1
1994–95	0.0	0.0	0.0	0.0	0.0	-787.8	-2,438.9	-12.7
1999–00	-0.1	0.0	0.0	-0.1	0.0	-1,117.2	4,604.4	-19.0
2004–05	-29.9	1.5	-31.3	-0.1	0.0	-1,057.4	-5,734.4	-25.3
2005–06	-77.9	-3.3	-74.3	-0.3	0.0	-1,219.7	19,453.5	-22.2
2006–07	-61.3	-44.2	-162.0	144.8	0.0	-742.0	-14,578.8	-21.2
2007–08	736.7	-23.0	614.3	145.3	0.0	-1,011.2	-15,310.2	-17.5
2008–09	-234.2	-353.9	-36.6	156.3	0.0	-1,247.9	-21,540.2	-16.0
2009–10	-207.0	-354.2	-34.1	181.4	10.7	-1,086.2	-2,866.6	-15.0
2010–11	-163.6	-373.9	-23.9	234.2	9.1	-1,299.6	-14,966.0	-14.2
2011–12	-188.1	-370.8	-23.3	206.1	-0.6	-1,507.7	-22,715.3	-13.6
2012–13	38.5	-207.9	-22.9	269.3	-3.9	-1,300.9	-2,722.4	-13.6
2013–14	-44.0	-299.2	-30.2	285.4	-6.7	-1,294.3	-16,138.8	-14.4
2014–15	396.6	130.9	-23.6	289.4	-0.4	-1,272.5	-6,331.7	-15.8
2015–16	438.6	146.8	-21.5	313.3	5.7	-1,193.2	-20,652.0	-17.2
2016–17	429.5	172.3	-24.3	281.5	13.4	-1,705.4	20,382.4	-18.3
2017–18	594.5	232.2	-2.2	364.5	13.4	-1,350.6	-11,763.7	-53.9
2018–19	320.1	-52.2	-0.2	372.5	-12.4	-1,319.0	-14,115.4	-24.6
2019–20	66.2	-229.7	3.4	292.5	-6.8	-1,067.4	-18,724.9	44.3
2020–21	303.9	568.1	-95.1	-169.1	-110.6	-1,637.1	-24,670.1	88.3

1. Introduction and inventory context

1.1 Background information on greenhouse gas inventories and climate change

1.1.1 Inventory reporting

Australia is Party to both the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement (PA). One of the principal commitments made by Parties to these treaties is to develop, publish, and regularly update national greenhouse gas inventories.

Australia's National Inventory Report 2022 (the Report) and associated Common Reporting Tables (CRTs) fulfil its national inventory reporting obligations for the year 2023 under both the UNFCCC and the PA, in accordance with decision 1/CP.24[2] of the Conference of the Parties to the UNFCCC. The Report provides estimates of Australia's net greenhouse gas emissions for the period from 1 July 1989 to 30 June 2021, i.e. from financial years 1989–90 to 2021–22.

This Report has been prepared in accordance with chapter II of the annex to the decision 18/CMA.1 *Modalities, procedures and guidelines for the transparency framework for action and support referred to in Article 13 of the Paris Agreement*[3] (known as the MPG) and decision 5/CMA.3 *Guidance for operationalizing the modalities, procedures and guidelines for the enhanced transparency framework referred to in Article 13 of the Paris Agreement*[4].

Consistent with the MPG and decision 5/CMA.3, emissions estimates provided in this Report have been compiled in accordance with the Intergovernmental Panel on Climate Change (IPCC) *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006 Guidelines) (IPCC 2006), supplemented by aspects of the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (2019 IPCC Refinement) (IPCC 2019), and the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013 Wetlands Supplement) (IPCC 2013). Australia's methodologies have been improved over time and will continue to be refined as new information emerges, and as international practice evolves. The aim is to ensure that the estimates of emissions are accurate, transparent, complete, consistent through time and comparable with those produced in the inventories of other Parties.

1.1.2 Gases

The Report covers sources of greenhouse gas emissions, and removals by sinks, resulting from human (anthropogenic) activities for the major greenhouse gases. Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3). Also covered in ancillary fashion for reporting under the UNFCCC are the indirect greenhouse gases; carbon monoxide (CO), oxides of nitrogen (NO_X), and non-methane volatile organic compounds (NMVOCs). Sulphur dioxide (SO_2), an aerosol precursor, is also included because emissions of this gas influence global warming. Australia voluntarily includes estimates of black carbon emissions in this Report.

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[2] FCCC/CP/2018/10/Add.1, paragraph 42, https://unfccc.int/sites/default/files/resource/10a1.pdf

[3] FCCC/PA/CMA/2021/10/Add.2, chapter II, https://unfccc.int/sites/default/files/resource/CMA2021_L10a2E.pdf

[4] FCCC/PA/CMA/2021/10/Add.2, https://unfccc.int/sites/default/files/resource/CMA2021_L10a2E.pdf

This Report presents emissions for each of the major greenhouse gases as carbon dioxide equivalents (CO_2-e) using the 100-year global warming potentials (GWPs) contained in the 2014 *IPCC Fifth Assessment Report* (IPCC 2014)[5]. As greenhouse gases vary in their radiative activity, and in their atmospheric residence time, converting emissions into CO_2-e allows the integrated effect of emissions of the various gases to be compared.

1.1.3 Sectors

Emissions and removals have been grouped under five sectors, in accordance with those included in the IPCC 2006 Guidelines (IPCC 2006). These represent the main human activities that contribute to the release or capture of greenhouse gases into, or from, the atmosphere:

- Energy,
- Industrial processes and product use (IPPU),
- Agriculture,
- Land use, land use change and forestry (LULUCF), and
- Waste.

1.1.4 Reporting year

The Australian greenhouse gas inventory is reported for Australian financial years as key data sources, such as data collected under the National Greenhouse and Energy Reporting (NGER) scheme and energy and agricultural statistics obtained from national statistical agencies, are published on this basis. The Australian financial year runs from 1 July of a given year to 30 June of the following year. This Report covers the Australian financial years 1989–90 to 2021–22. The use of financial year data is consistent with the IPCC 2006 Guidelines as the use of these data conforms to the normal practice of Australia's national statistical agencies and leads to more accurate emissions estimates.

1.1.5 Structure of the National Inventory Report

The structure of this Report has been organised to conform to the requirements of Annex V to decision 5/CMA.3 on the *outline of the national inventory document, pursuant to the modalities, procedures and guidelines for the transparency framework for action and support referred to in Article 13 of the Paris Agreement*.

This Report provides estimates of Australia's total net emissions and identifies trends in emissions for each of the sectors and for the main greenhouse gases. It also provides, *inter alia*, comprehensive information on estimation methodologies and data quality; details of recalculations of emissions estimates and background on the national system and the inventory preparation processes to facilitate international review and comparison with the inventories of other countries.

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[5] GWPs used are, 1 for CO_2, 28 for CH_4, 265 for N_2O, 6,630 for the PFC perfluoromethane (CF4), 11,100 for the PFC perfluoroethane (C2F6), 23,500 for SF_6 and 16,100 for nitrogen trifluoride (NF_3). The full list of GWPs can be found in Table 8.A.1 of Chapter 8: Anthropogenic and Natural Radiative Forcing of the 2014 IPCC Fifth Assessment Report (AR5). GWPs are not available for the indirect greenhouse gases and in accordance with the Paris Agreement reporting guidelines, are reported but are not included in the inventory total.

1.1.6 National Greenhouse Accounts

In addition to this Report, the Department publishes a range of supporting emissions estimates that, together, constitute the Australian National Greenhouse Accounts, including:

- *Quarterly Updates of Australia's National Greenhouse Gas Inventory*, which provide a summary of Australia's national emissions, updated on a quarterly basis,
- State and Territory Greenhouse Gas Inventories, comprising emissions estimates for Australian states and territories, and
- the *National Inventory by Economic Sector,* comprising emissions estimates for industries and households rather than by IPCC sectors as in this Report.

These documents are available on the Department's website: Tracking and reporting greenhouse gas emissions. They provide additional information with respect to Australia's emissions on both a regional and industry basis.

The Department also publishes annual emissions projections, which estimate Australia's future greenhouse gas emissions and help determine how Australia is tracking against its emissions reduction targets. Projections reports are published at Projecting greenhouse gas emissions.

Emissions data from the aforementioned reports are published through an interactive online database: Australia's National Greenhouse Accounts (ANGA). It allows users to interrogate historical and projected emissions estimates by a wide range of variables. Data are presented in customised tables and charts and can be downloaded as images or Excel sheets. These supplementary reports and databases provide additional information with respect to Australia's emissions on a regional, industry, gas (raw and CO_2-e), quarterly, scope 1, and scope 2 basis.

1.2 A description of national circumstances and institutional arrangements

1.2.1 National entity and focal point

On 1 July 2022 responsibility for Australia's national inventory was assigned to a single agency, the Department of Climate Change, Energy, the Environment and Water (the Department). The Department has responsibility for all aspects of the national inventory systems, including activity data co-ordination, emissions estimation, quality control, improvement planning, preparation of reports, and submission of reports to the UNFCCC on behalf of the Australian Government.

The designated representative with overall responsibility for the national inventory is:

Branch Head
National Inventory Systems and International Reporting Branch
Department of Climate Change, Energy, the Environment and Water
Australian Government
Ngunnawal Country
GPO Box 3090
Canberra ACT 2601
AUSTRALIA

The Department can be contacted at nationalgreenhouseaccounts@dcceew.gov.au

1.2.2 Inventory preparation process

Australia's inventory is prepared following a rigorous annual process which includes planning, methodology improvement, data collection and entry, the implementation of quality control and assurance measures, emissions estimation, report preparation, emissions and report review and report publication.

To meet the objectives of quality and timeliness Australia has invested significant financial and human resources through the development of capital assets, training of Department staff and the contracting of expert consultants as needed.

Estimation of emissions is conducted by the Department, using the Australian Greenhouse Emissions Information System (AGEIS) and, for the *LULUCF* sector, the Full Carbon Accounting Model (FullCAM) (see section 1.2.2.a and Figures 1.1 and 1.2).

Where possible, data sources reported under Australia's legislated NGER scheme (see section 1.2.2.b and Annex V.I) are used for the *energy, industrial processes and product use* and *waste* sectors, supplemented by the use of other published data sources only where necessary. The collection process for other data is well-integrated, with the objectives of other programmes with a strong reliance on data collected and published by Australia's principal economic statistics agencies; the Australian Bureau of Statistics (ABS), and the Department's Energy Statistics & Analysis team in the Office of Energy Economics Branch. The EIA team has collected energy statistics for over 40 years and use these data to meet Australia's reporting commitments to the International Energy Agency (IEA). The ABS is the national statistical agency with legislative backing for its collection powers. The ABS, in conjunction with the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), is the major source of agricultural activity data.

The Department employs consultants to help process the satellite imagery used to determine land cover change for the *LULUCF* sector. Satellite imagery is sourced from Geoscience Australia (Australia's principal satellite ground station and data processing facility). Data to support estimates of HFCs are sourced from compulsory reporting by importers under licensing arrangements under the *Ozone Protection and Synthetic Greenhouse Gas Management Act 1989* (Cwlth). Solid waste disposal data are provided by the Circular Economy Division of the Department. Disposal data are collected annually as part of the National Waste Reporting initiative.

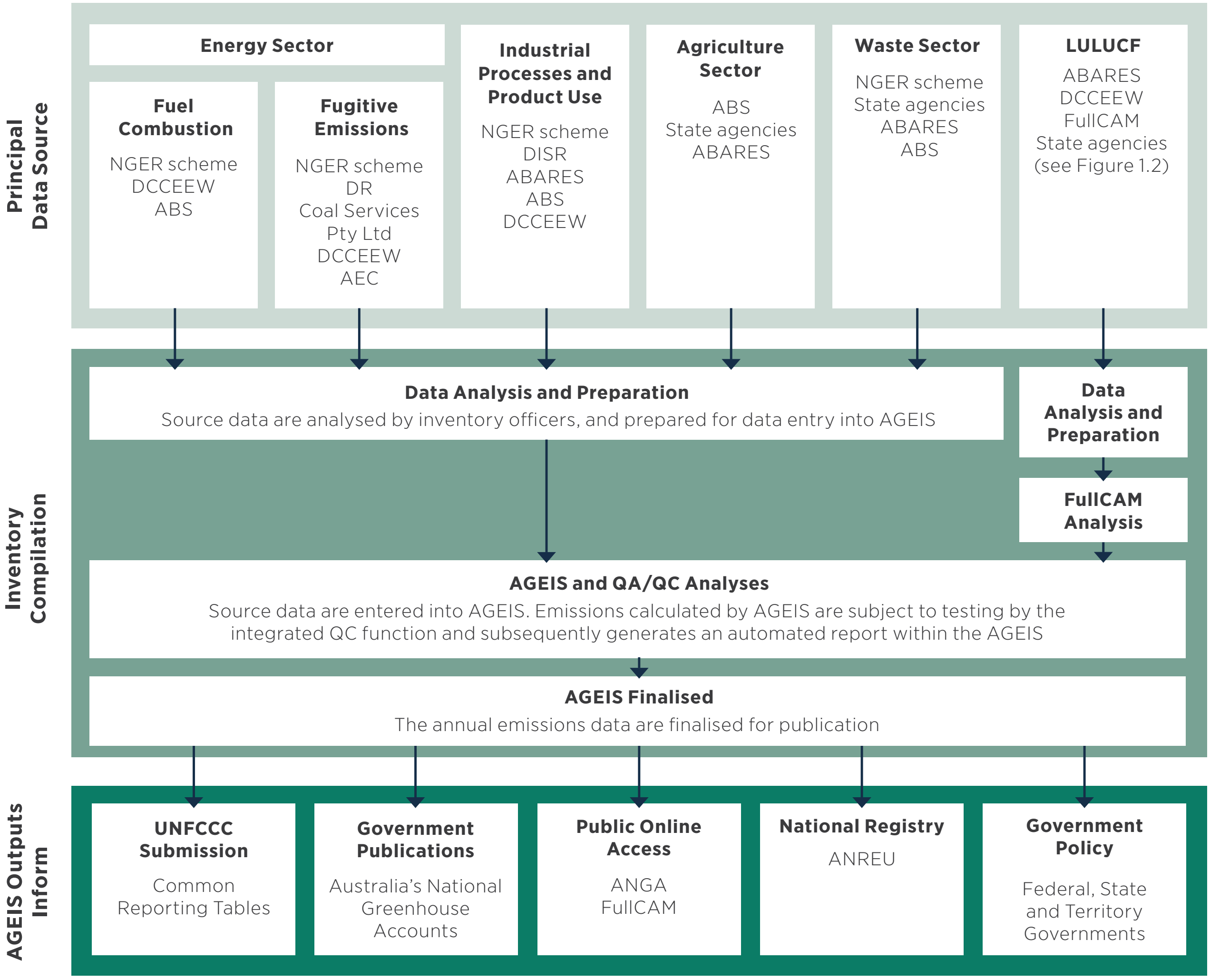
1.2.2.a IT Software Systems

AGEIS has been designed to meet the requirements for national inventory systems and is an integral part of the inventory preparation and publishing processes. In particular, it integrates numerous quality control procedures into the compilation process as well as centralising emissions estimation, inventory compilation and reporting, and data storage activities. AGEIS provides high transparency levels for the inventory, with emissions data for the *National Greenhouse Accounts* publicly accessible through an interactive web interface: Australia's National Greenhouse Accounts (ANGA).

The AGEIS continues to be expanded and refined to support the range of National Greenhouse Accounts in accordance with the AGEIS 2.0 Enhancements Work Plan 2020–2024. Recent investment includes development to support emission estimation in accordance with Paris Agreement requirements, track facility emissions and integration of models to estimate Australia's emissions projections and historical emissions on a quarterly basis.

While AGEIS is used for final preparation of the National Greenhouse Accounts, the inventory uses FullCAM to estimate emissions and removals from the *LULUCF* sector. FullCAM is a spatially explicit, process-based ecosystem model which uses inputs from a range of national datasets including on vegetation cover and climate. FullCAM's capability now covers nearly all aspects of LULUCF and continues to be expanded.

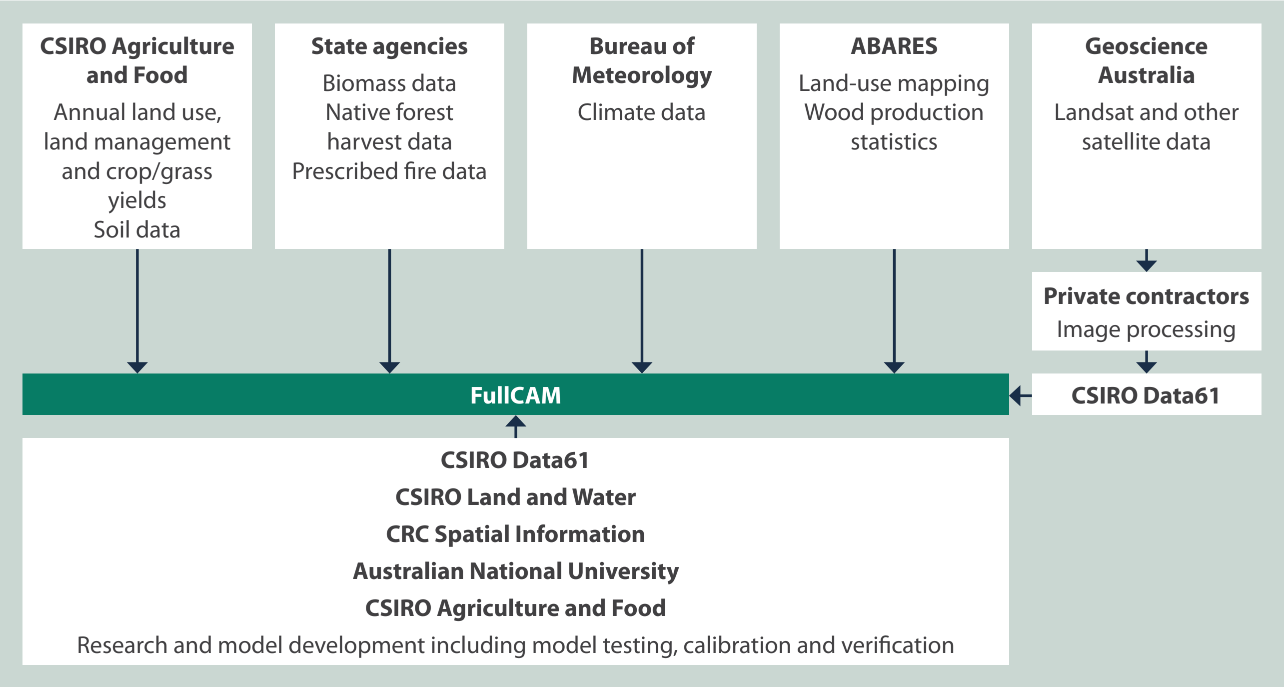
Figure 1.1 Department of Climate Change, Energy, the Environment and Water inventory asset structures and relationship



Acronym Key

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Australian Bureau of Statistics
AEC	Australian Electoral Commission
AGEIS	Australian Greenhouse Emissions Information System
ANGA	Australia's National Greenhouse Accounts
ANREU	Australian National Registry of Emissions Units
CRC	Cooperative Research Centres
DCCEEW	Department of Climate Change, Energy, the Enviroment and Water
DISR	Department of Industry, Science and Resources
DR	Department of Resources (Queensland)
FullCAM	Full Carbon Accounting Model
LULUCF	Land use, land use change and forestry
QA	Quality assurance
QC	Quality control

Figure 1.2 FullCAM institutional arrangements



1.2.2.b National Greenhouse and Energy Reporting (NGER) scheme

The NGER scheme, established by the *National Greenhouse and Energy Reporting Act 2007* (Cwlth) (NGER Act), is a single national framework for reporting and disseminating company information about greenhouse gas emissions, energy production, energy consumption and other information specified under NGER scheme legislation. Several legislative instruments sit under the NGER Act, providing greater detail about corporations' obligations, including:

- The *National Greenhouse and Energy Reporting (Measurement) Determination 2008* (Cwlth) (the Determination) — describes the methods, standards and criteria to be applied when estimating greenhouse gas emissions, energy production and energy consumption, and
- The *National Greenhouse and Energy Reporting Regulations 2008* (Cwlth) (the Regulations) — sets out the details that establish compliance rules and procedures for administering the NGER Act.

The NGER scheme is administered by the independent Clean Energy Regulator (CER), which manages the process of NGER scheme data collection from companies, verification, auditing, and the dissemination of this data to relevant agencies. The CER's online Emissions and Energy Reporting System (EERS) is used for collecting data directly from companies.

An explicit objective of the NGER Act is to collect information to support the development of the national inventory. The NGER scheme is one of the most critical assets in the preparation of the inventory, collecting data on emissions from the energy, industrial processes and product use and waste sectors. NGER scheme data are used to estimate approximately 72 per cent of total inventory emissions.

Under the NGER scheme, companies whose energy production, energy use, or greenhouse gas emissions (from the *energy, industrial processes and product use* and *waste* sectors) meet certain thresholds must report facility-level data to the CER. The NGER scheme provides activity data inputs, such as fuel combustion, emissions factors (EF) at facility level and, in some cases, directly measured emissions.

Annual reports have been submitted by companies under the NGER scheme for Australian financial years since 2008–09. Data collected through these annual reports have been used in the preparation of this Report. The NGER Act requires the CER to publish summaries of NGER scheme data on its website, which is published a financial year ahead of the most recent NIR. The CER publishes data highlights and data on corporate emissions and energy, electricity sector emissions and generation, and net energy consumption: National greenhouse and energy reporting data. The CER also publishes summaries and more detailed data on Australia's largest emitting facilities on its website: Safeguard data.

The rules for the estimation of activity data, emissions factors, and emissions by companies are well specified and set out in the Determination.

The methodologies used by facilities under the NGER scheme are estimated within the *National Greenhouse Accounts* framework ensuring consistency among the relevant accounts: national, state and territory, industry, company and facility-level inventories. Integration of the estimation methods and data is critical for ensuring that changes in emissions at the facility level are captured efficiently and accurately in the national inventory. The default methods used by companies are derived from the national inventory methods.

There are four methods available for estimating emissions under the Determination, noting that not all methods are available under all activities. These are described in more detail in Annex V.I. Most data collected through the NGER scheme adheres to an IPCC Tier 2 approach using either country- or facility- specific approaches. Some data are also collected using an IPCC Tier 3 approach, and a small minority of emissions are estimated using an IPCC Tier 1 approach using defaults.

There are four measurement criteria used to describe how activity data was collected through the NGER scheme. The vast majority of emissions data collected under the NGER scheme are supported by commercial transactions, stockpile change estimation and invoices, or high-quality measurements at the point of sale, consumption, or production of a fuel.

Each year the Department reviews and makes improvements to NGER scheme rules for the estimation of activity data, EFs and emissions based on latest available research, data, technologies and practices, and feedback from stakeholders and the CER. In addition, every five years the Climate Change Authority, an independent statutory authority, is required by law to review the operation of the NGER scheme legislation and may make recommendations to the Australian Government for its improvement.

Further information on the design, operation, and quality assurance of the NGER scheme is included in Annex V.I.

1.2.2.c Compilation procedures

Key steps in the annual inventory preparation process (with indicative dates in parentheses) are determined by the needs of the system and output and quality objectives. The timing is determined by the UNFCCC submission timelines and data availability. Steps 1–17 below provide an overview of a typical inventory cycle. The cycle commences with a review of emissions estimation methods, allocation of tasks, selection of external consultants, and the preparation of AGEIS for the compilation of the forthcoming inventory.

Planning and methodology improvement

1. Preparation of the Evaluation of Outcomes document for the previous year (March–April). See section 1.5.
2. Preparation of QA/QC and Inventory Improvement plans, taking into account the Department's review of methodologies and activity data; technical expert review recommendations and the Evaluation of Outcomes document (May).
3. Development of investment and maintenance plan for AGEIS, incorporating the QA/QC plan (June).
4. Methodology development, review, and incorporation into AGEIS, in consultation with the National Inventory Users Reference Group and the National Greenhouse Gas Inventory Committee (June–February).

Data collection and entry

5. Activity data collection, conducted annually by the Department. This is heavily reliant on NGER scheme data and published data from Australia's national, state, and territory statistical agencies and industry bodies. Activity data collection is subject to quality control checks (June–October).
6. Activity data entry into the AGEIS input database, by the Department, through predefined data entry templates (August–December).

Implementation of quality control measures

7. Activity data verification and quality control – the Department uses AGEIS to systematically report a range of diagnostic statistics on the activity data to facilitate identification and correction of anomalous entries to ensure time series consistency and consistency across sectoral emissions estimates (November-January).
8. A designated analyst (known as a Supervisory user) investigates anomalies and records an assessment of the quality of the activity data in AGEIS (December-January).
9. The data quality is checked and internally audited by a designated analyst in AGEIS, known as the Database Operations Manager (DOM), to provide quality control. Only when the DOM is satisfied is the input data transferred to the core database where emissions estimation is undertaken (December–January).
10. AGEIS is used to generate final emissions estimates for all inventory years using time series consistent methodologies (February).

Emissions and report review

11. Emissions estimates verification is undertaken by Department analysts by repeating the range of tests on emissions estimates generated by AGEIS to ensure time series consistency, consistency across sectoral emissions estimates, and accuracy of recalculations (December–February).
12. Emissions trends, anomalies, and recalculations by sector, national, state and territory, and greenhouse gas dimensions are reviewed, explained, and documented by Department analysts. Emissions trends are compared with a range of external contextual factors (for example, economic, technological, policy, regulatory, etc) to ensure emissions results are consistent with observed real-world activity. IEFs are compared with those of other Parties and significant anomalies are understood (December–February).
13. Completion of quality control measure tests to ensure estimates meet quality criteria (February).
14. Disaggregation of the national inventory by state and territory are circulated to the National Greenhouse Gas Inventory Committee of state and territory government representatives for comment prior to public release (December–February).

Report publication

15. Automated population of CRTs (February–March).

    Note: At the time of publication of this Report, online tools for submitting the CRTs remain under development by the UNFCCC Secretariat. As a result, the tables have been manually populated. Last year's manually populated CRT tables provided a useful basis for beta testing the online tools as part of a trial conducted by the UNFCCC Secretariat. Australia was grateful for the opportunity to support the development and implementation of the Paris Agreement Enhanced Transparency Framework. It is expected that Australia's CRTs will be resubmitted using the online tools once they are publicly released.

16. Following approval by the Deputy Secretary of the Department, the inventory is submitted to the UNFCCC and Paris Agreement secretariat and made available for public release (April).
17. Release of Australia's National Greenhouse Accounts and the AGEIS database of emissions estimates and background data at https://greenhouseaccounts.climatechange.gov.au/ (April–May).

1.2.3 Archiving of information

The Australian documentation systems aim to both manage and retain all data used in the estimation of emissions to provide a means for knowledge management, ensuring continuity and security of the National Inventory Systems.

AGEIS is at the heart of Australia's documentation systems. It allows efficient electronic data management and archiving of the significant quantities of data needed to generate an emissions inventory. AGEIS data management functions include:

- archival and storage within the AGEIS database of the emissions estimates of past submissions,
- archival and storage within the AGEIS of past activity data, EFs, and other parameters and models,
- archival and storage of data source descriptions, methodology descriptions, and source reference materials, and
- integrated access to the documentation of data sources; methodology description and source reference materials.

The aims of these systems include giving inventory staff ready access to all related materials that underpin the emissions estimates and to provide the means for replication of emissions estimates from past submissions.

The AGEIS functions are supported by some additional and important elements of the documentation system:

- documentation of the inventory's emissions estimation methodologies in this Report; and
- maintenance of a National Inventory Library of source material documents.

FullCAM, through which spatial simulations are run for estimating LULUCF emissions and activity data, also contains archiving functionality. FullCAM data management functions include:

- archival and storage of data utilised for spatial simulations for estimating LULUCF emissions for past simulations,
- version control of application coding of the FullCAM spatial simulator used for past simulations,
- records of key decisions for modifying the FullCAM spatial simulator coding, and
- storage of output SQL & SASS databases used to record spatial simulator results.

1.2.4 Process for official consideration and approval of the Inventory

The draft method improvements and estimates are considered by the National Greenhouse Gas Inventory Committee, which comprises representatives of the Australian, state and territory governments. Key domestic users of national inventory data are also engaged in the formal review arrangements through the National Inventory Users Reference Group. This group includes Australia's premier science organisation (CSIRO), academics, sectoral experts from the consulting sector, and industry representatives.

The National Greenhouse Gas Inventory Committee and the National Inventory Users Reference Group are the principal mechanisms for formal external review of key aspects of the Report prior to its release.

Release of each year's inventory and submission to the UNFCCC is approved by the Deputy Secretary of the Department.

1.3 Brief general description of methodologies and data sources

1.3.1 Estimation methods

The Australian methodology for estimating greenhouse gas emissions and sinks uses a combination of country-specific (CS) and IPCC methodologies and EFs. These methods are consistent with the IPCC 2006 Guidelines (IPCC 2006), supplemented by aspects of the 2019 IPCC Refinement (IPCC 2019) and the IPCC 2013 Wetlands Supplement) (IPCC 2013). They are consistent with international practice.

In accordance with the IPCC 2006 Guidelines (Volume 1, Chapter 4), Australia's national inventory predominantly uses a mix of Tier 2 and Tier 3 estimation methods that incorporate:

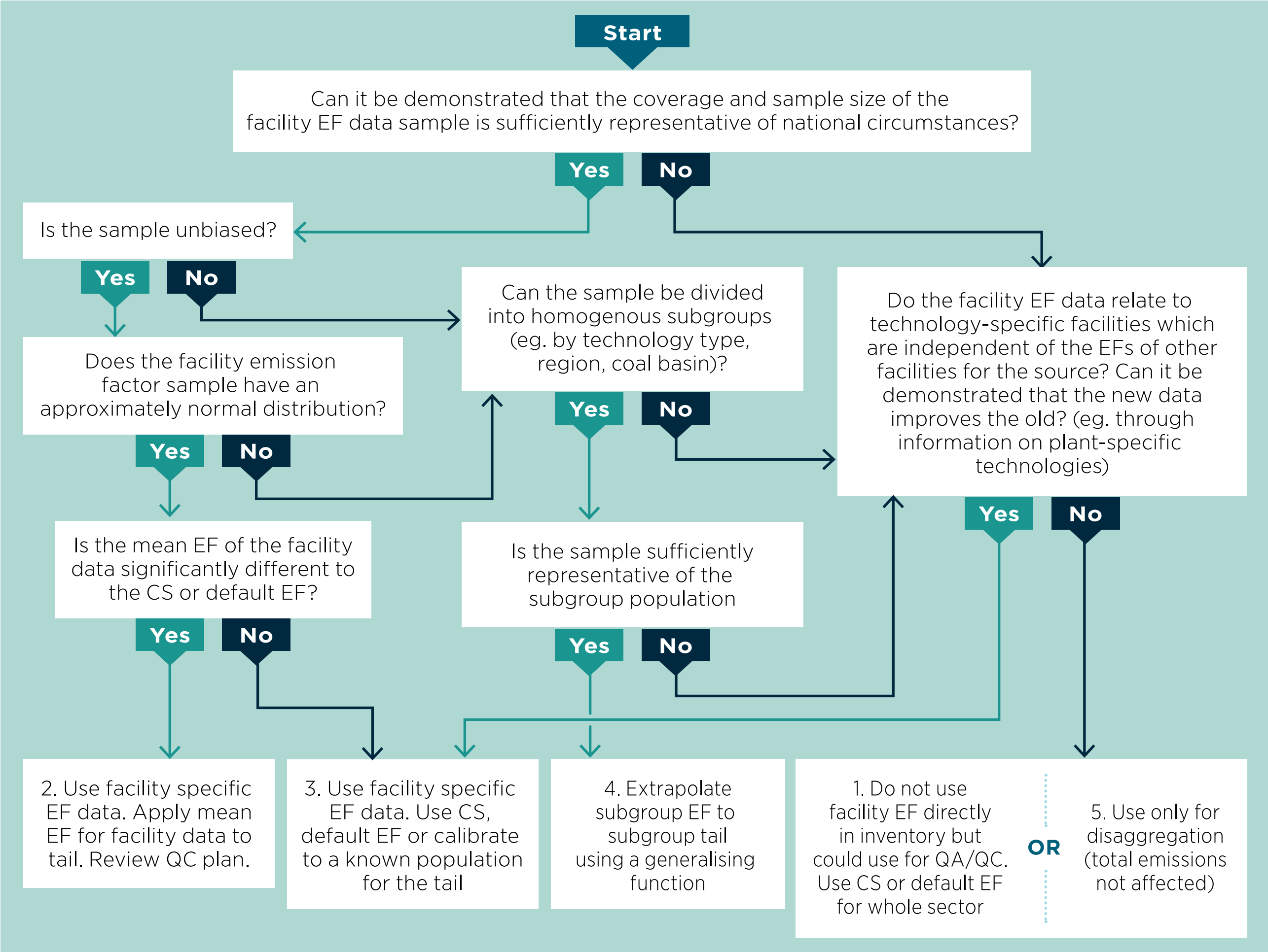
- plant-specific emissions estimation processes,
- characterisations of the capital and technology types at the point of emissions,
- dynamic relationships that link current emissions outcomes with the activity levels of previous years, and
- spatial differences in emissions processes across Australia.

The additional complexity of these methods and preferential use of country-specific and plant-specific data allows emissions to be estimated more accurately. Detailed descriptions of the methods used are set out in the Chapters 3-7 of this Report.

Tier 3 approaches are in place for fuel combustion in the electricity industry, non-CO_2 emissions in road transport, fugitive emissions from underground coal mining sources, fugitive emissions from oil and natural gas extraction (production, processing, and natural gas distribution leakage emissions, venting and flaring), carbon capture and storage, and vegetation modelling in LULUCF. For a range of additional categories, a mix of Tier 2 and Tier 3 approaches will continue to be implemented over time as methods for plant-specific measurement of emissions or key data inputs are adopted by reporters under the NGER scheme and as key pre-conditions for implementation of the new methods are met. These conditions include: the data must comply with prescribed data standards (in this case, set out in the Determination); there is a timely and comprehensive data collection system in place; and the resulting emissions estimates for the source pass the inventory quality criteria set out in the QA/QC plan (for example, in relation to completeness and international comparability).

Consistent decision making with respect to the use of facility specific EFs has been ensured through the application of a decision tree, as set out in Figure 1.3.

Figure 1.3 Consistent decision making in method selection



In particular, Tier 3 methods incorporating plant-specific EF data obtained from the NGER scheme have been used where the sample size of the available NGER scheme data is sufficiently large and when there is no evidence of bias in the distribution of the NGER scheme EF data. For the balance of a source where there are facilities for which no plant- specific data are available, a country-specific factor is applied.

Tier 3 methods incorporating NGER scheme plant-specific data are also able to be used in two other cases where large samples displaying characteristics of an approximately normal distribution cannot be obtained.

The first additional case relates to the situation where, within one source, several homogenous sub-samples can be discerned. Data for facilities with unknown characteristics can be determined by the extrapolation of information from the relatively homogenous sub sample or through calibration to a known, unbiased distribution for the population.

The second additional case relates to the situation where facility data are heavily technology dependent, and where the data for each facility are likely to be independent of one another. In particular, this is the case in the industrial wastewater category where knowledge of the technology deployed at one facility does not affect the likelihood of a certain technology being deployed at another facility where no facility data is available. In these cases, it is possible to use the facility data, where available, and it may not be appropriate to extrapolate information from the NGER scheme sample to the remainder of a particular source. Consequently, in these cases, the original Tier 2 EF has been retained for the tail of the source where NGER scheme data has not yet been collected.

1.3.1 Data sources

The inventory is prepared using a mix of sources for activity data, including published data from national statistical agencies. The principal data sources are set out in Table 1.1.

Table 1.1 Principal data sources for the estimation of Australia's inventory

Category (UNFCCC sector)	Principal data sources	Principal collection mechanism
Energy sector (1.A.1, 1.A.2, 1.A.4, 1.A.5)	Australian Energy Statistics (DCCEEW)	Published
	NGER scheme (CER)	Mandatory data reporting system
Energy sector (1.A.3)	Australian Energy Statistics (DCCEEW)	Published
	Various national statistics (ABS, BITRE)	
Energy sector (1.B)	NGER scheme (CER)	Mandatory data reporting system
	Australian Energy Statistics (DCCEEW)	Published
	Australian Petroleum Statistics	Published
	Various national, state, and territory statistics (QLD DNRM, WA DMP SA DSD, NSW DIRE)	Published
	Various industry statistics (Coal Services Pty Ltd, AEP, AEC)	Published
1.C Carbon Capture and Storage	NGER scheme (CER)	Mandatory data reporting system
Industrial processes and product use (2)	NGER scheme (CER)	Mandatory data reporting system
	Import data of HFC gases (DCCEEW)	Mandatory reporting of HFCs under import licensing arrangements
Agriculture (3)	Various national statistics (ABS and ABARES)	Published
	Various statistics provided by industry	Published and unpublished
Land use, land use change and forestry (4)	Geosciences Australia, ABARES, CSIRO	Memorandum of Understanding, published
	Western Australian Land Information Authority (Landgate)	Data Supply Licence Agreement, published
	Forestry Corporation of New South Wales	Data Supply Licence
	VicForests	Published
	Sustainable Timber Tasmania	Data Supply Licence
Waste (5)	NGER scheme (CER)	Mandatory data reporting system
	National Waste Report (DCCEEW)	Published

Detailed descriptions of the NGER scheme, Australian Energy Statistics, and satellite data processing are provided in Volume 2, Annex V, Sections A5.1, A5.2, and A5.6 of this Report. The data sources presented in Table 1.1 along with additional data sources are described in more detail in Chapter 3-7 of this Report.

1.4 Brief description of key source categories

A key source category has a significant influence on a country's total inventory of direct greenhouse gases in terms of absolute level of emissions, the trend in emissions, or both. Australia has identified the key categories for the inventory using the Tier 1 level and trend assessments as recommended in the IPCC 2006 Guidelines (Volume 1, Chapter 4) and adopted by the MPGs. This approach identifies sources that together contribute to 95 per cent of the total emissions or 95 per cent of the trend of the inventory in absolute terms.

When the LULUCF sector is included in the analysis, Australia has identified *public electricity (solid fuel), road transportation (liquid fuels)* and *land converted to forest land* as the most significant of the key categories (i.e. contributing more than 10 per cent of the level).

When the LULUCF sector is excluded from the analysis the most significant key categories are *public electricity (solid fuel), road transportation (liquid fuels) and enteric fermentation (cattle).*

Australia's key category analyses use a relatively high degree of disaggregation of sources, as recommended in table 4.1 of the IPCC 2006 Guidelines. The full analyses are detailed in Annex I, Volume 2 of this Report.

1.5 Brief general description of QA/QC plan and implementation

This section outlines the major elements of the quality assurance/quality control (QA/QC) plan. Australia's QA/QC plan is documented in full in the *National Inventory Systems: Quality Assurance/Quality Control Plan* (QA/QC plan).

The IPCC defines a QC as a system of routine technical activities to measure and control the quality of the inventory as it is being developed. A basic QC system:

- ensures data integrity,
- identifies and addresses errors and omissions,
- documents and archive inventory materials, and
- records all QC activities and results.

A QA system consists of a series of review procedures conducted by personnel not directly involved in the inventory compilation and development process.

The QA/QC processes aim to conform to the IPCC 2006 Guidelines. These processes further aim to contribute to the production of inventories which are accurate transparent, documented, consistent over time, complete, comparable, and uncertainties are reduced to the extent practicable.

The QA/QC plan identifies key risks to the achievement of these objectives and sets out the mitigation strategies employed to ensure that they are attained. Systems have been established to monitor the outcomes of risk mitigation strategies and control measures, principally managed through the AGEIS which integrates QC operations directly with inventory compilation. AGEIS can conduct Tier 1 and Tier 2 quality controls based on user- defined selections of QC activities. It can also populate the *National Inventory Systems: Evaluation of Outcomes* report to record the results of the monitoring program designed to implement the risk mitigation strategies and quality control measures detailed in the QA/QC plan.

Principal risk mitigation strategies are discussed in Annex IV. This includes a discussion on the QC operations undertaken on principle data sources and the outcomes of the national carbon balance. Australia's QA systems operate at a number of levels. QA controls that are implemented annually include:

- the review of key data from the Report, prior to submission to the UNFCCC, by the National Greenhouse Gas Inventory Committee, which comprises representatives of state and territory governments. This is the principal formal external review mechanism for the report before it is finalised,
- the prioritisation and review of inventory improvements by the National Inventory Users Reference Group, which comprises representatives from Australia's premier science organisation, academics, sectoral experts from the consulting sector and industry representatives,
- review by external consultants for specified sectors,
- the inventory is potentially subject to audit by the Australian National Audit Office (ANAO). The ANAO is an independent office established under the *Auditor-General Act 1997*. It conducts performance audits of government agencies operating under the Standard on Assurance Engagements ASAE 3500 Performance Engagements issued by the Australian Auditing and Assurance Standards Board (AUASB). ANAO reports are tabled in the Australian parliament and subject to review by the Joint Committee of Public Accounts and Audit (JCPAA). The ANAO undertook a performance audit of the national inventory in 2009-10 and 2016-17,
- opening the inventory emissions estimates and methods for public review through the release of transparent and easily accessible information via the Department and the Australia's National Greenhouse Accounts webpage. Industry and public feedback is accepted through the inventory e-mail facility nationalgreenhouseaccounts@dcceew.gov.au, and
- Paris Agreement technical expert review processes conducted in accordance with the MPGs (chapter VII, annex to decision 18/CMA.1).

This Report is also informed by the valuable feedback provided by successive UNFCCC expert review teams. Australia's inventory has been reviewed by in-country expert review teams in 2002, 2005, 2008, 2010, 2015 and 2022, by a desktop review in 2017, with centralised reviews in other years. A simplified Paris Agreement review under the MPGs by the UNFCCC Secretariat was undertaken in 2023.

Further information on Australia's quality assurance and quality control plan and implementation, including Tier 1 and 2 and source-based quality control checks, are set out in Annex IV.

1.6 General uncertainty assessment, including data pertaining to the overall uncertainty of inventory totals

Uncertainty is inherent within any kind of estimation, be it an estimate of the national greenhouse gas emissions, or the national gross domestic product. Managing these uncertainties, and reducing them over time, is recognised by the IPCC 2006 (IPCC 2006) as an important element of inventory preparation and development. Uncertainty can arise from the limitations of measuring instruments, sampling processes and the complexity of modelling highly variable sources of emissions over space and time, particularly for some biological sources.

Emissions estimate uncertainties are typically low for CO_2 from energy consumption as well as from some *industrial process and product use* emissions. Uncertainty surrounding estimates of emissions were higher for *agriculture, LULUCF* and synthetic gases. A medium band of uncertainty applied to estimates from *fugitive emissions*, most *industrial processes* and non-CO_2 gases in the *energy* sector.

The sectoral estimates presented in Annex II of this Report show that the uncertainty ranges reported for the various components of the Australian inventory are largely consistent with the typical uncertainty ranges expected for each sector, as identified in the IPCC 2006 Guidelines.

At an aggregate level, using IPCC good practice Tier 1 uncertainty methods, the overall uncertainty surrounding the Australian inventory estimate for 2021–22 is estimated at ± 5.4 per cent. The reported uncertainty for the trend in total inventory emissions is estimated to be ± 5.1 per cent. When the LULUCF sector is excluded from the analysis, national inventory uncertainty is estimated at ± 3.5 per cent for 2021–22 emissions and ± 3.3 per cent for the trend in emissions.

	2021–22	
	Including LULUCF	Excluding LULUCF
Uncertainty (%)	±5.4	±3.5
Trend Uncertainty (%)	±5.1	±3.3

The IPCC approach provides accurate estimates of uncertainty under certain restrictive assumptions that do not always hold for most countries' inventories. Consequently, the Department is conducting further analysis using available NGER scheme uncertainty data to improve accuracy of the uncertainty estimate for Australia across the *energy*, *industrial processes and product use*, and *waste* sectors.

1.7 General assessment of completeness

The Paris Agreement MPGs require that national inventories are assessed by inventory compilers to determine the level of completeness of reported sources. The sources of greenhouse gas emissions are many and diverse and, in general, are not directly observable without human and financial investment. Many emission sources are minor and resource intensive to estimate. Consequently, all national inventories have minor omissions which, for transparency, need to be identified. This section addresses the completeness of key activity datasets and the completeness of the coverage of emissions and removals sources for the Australian inventory.

1.7.1 Information on completeness

The inventory is largely complete with a few minor sources not estimated due to either a lack of available information or methodology in the IPCC 2006 Guidelines. Australia does, however, report a number of additional, voluntary emissions sources from the IPCC 2019 Refinement (IPCC 2019) and the IPCC 2013 Wetlands Supplement (IPCC 2013).

For the industrial sectors, the primary data source is NGER scheme data. The data collected under this scheme is not complete for a range of reasons, including reporting thresholds.

Table 1.2 summarises how completeness is achieved in those categories where NGER scheme data is not solely used to achieve completeness.

Table 1.2 Summary of data sources used to achieve completeness, where NGER scheme data is not the sole source, by IPCC category

Category	Source	
1.A.1.a	Electricity (gas)	Completeness is achieved through use of data from the Australian Energy Statistics (AES) published by the Department. As explained in Chapter 3, Section 3.2.4.2 Methodological issues – Activity Data of this Report, the energy use of the small power stations that do not meet the NGER scheme reporting thresholds are estimated as the difference between the total of reported data under the NGER scheme and AES for ANZSIC subdivision 26. This approach has been adopted throughout the time series. Therefore, the improved coverage of power stations under the NGER scheme does not alter the method for estimating total fuel consumption in this sector.
1.A.1.a	Electricity (liquid)	As above.
1.A.1.c	Oil and gas extraction	Completeness is achieved through the use of data from the AES published by the Department. Further detail is provided in Volume 1, Chapter 3, Section 3.3.2 of this Report.
1.A.2	Manufacturing	Completeness is achieved through use of energy balance data, by fuel type and subsector from the AES published by the Department. Further detail is provided in Volume 1, Chapter 3, Section 3.2.5 and Volume 2, Annex 5 of this Report.
1.A.3	Transport	Completeness is achieved through use of national transport fuel use data, by fuel type and subsector from the AES, published by the Department. Further detail is provided in Volume 1, Chapter 3, Section 3.2.6 and Volume 2, Annex 5 of this Report.
1.A.4	Other sectors	Completeness is achieved through use of energy balance data, by fuel type and subsector from the AES published by the Department. Further detail is provided in Volume 1, Chapter 3, Section 3.2.7 and Volume 2, Annex 5 of this Report.
1.A.5	Other	This category comprises military transport only. Completeness is achieved for this source using data obtained directly from Australia's Department of Defence. Further detail is provided in Volume 1, Chapter 3, Section 3.2.8 and Volume 2, Annex 5 of this Report.
1.B.2	Oil & Gas	NGER scheme data are complemented by a range of data sources to ensure completeness. Further detail is provided in Volume 1, Chapter 3, Section 3.3.2 and Volume 2, Annex 5 of this Report.
2	IPPU	Completeness is achieved through the use of consultancy reports in sectors and years where NGER data is not available.
3	Agriculture	Completeness is principally achieved through using Australian Bureau of Statistics agricultural census data. Further detail is provided in Volume 1, Chapter 5 and Volume 2, Annex 5 of this Report.
4	LULUCF	Completeness is principally achieved through the application of annual wall-to-wall spatial monitoring changes in woody vegetation cover. Completeness is achieved through use of energy balance data, for combusted harvested wood products, from the AES published by the Department. Further detail is provided in Volume 1, Chapter 6 and Volume 2, Annex 5 of this Report.
5.A	Solid waste	Completeness for solid waste disposal is discussed in Volume 1, Chapter 7, Section 7.2 of this Report. NGER scheme data covers about 70 per cent of total waste disposal in Australia. Solid waste disposal data are also provided by the Circular Economy Division of the Department, which collects disposal data from each State and Territory annually as part of the National Waste Reporting initiative. The residual disposal not covered by the NGER scheme is calculated as the total disposal reported for each state and territory minus the sum of NGER scheme disposal in each State and Territory. Figure 7.6 graphs the relationship between State and Territory reported disposal and disposal reported under the NGER scheme. Methane capture data obtained under the NGER scheme are considered complete as they are supplied by gas capture companies (as distinct from landfill operators) all of which trigger reporting thresholds of the NGER scheme.
5.B	Biological treatment of solid waste	Emissions estimates are based on an annual industry survey undertaken by the Recycled Organics Unit at the University of NSW. Further detail is provided in Volume 1, Chapter 7, Section 7.3 of this Report.

Category	Source	
5.C	Waste incineration	Data on the quantities of municipal solid waste incinerated are based upon published processing capacities of the three incineration plants prior to decommissioning in the mid-90s. Data on the quantities of clinical waste incinerated have been obtained from a per- capita waste generation rate derived from data reported under the NGER scheme, by O'Brien (2006b) and an estimate of State population reported by the Australian Bureau of Statistics. Further detail is provided in Volume 1, Chapter 7, Section 7.4 of this Report.
5.D.1	Domestic and commercial wastewater	Major wastewater treatment facilities report under the NGER scheme. NGER scheme reporting requirements include the population serviced by each treatment plant. Population data and per-capita wastewater organic matter and N generation rates are used to determine the residual. Further detail is provided in Volume 1, Chapter 7, Section 7.5 of this Report.
5.D.2	Industrial wastewater	Where appropriate, national commodity production statistics are used to ensure completeness of AD for industrial wastewater. Further detail is provided in Volume 1, Chapter 7, Section 7.5 of this Report.

As the land sectors are not covered by the NGER scheme, a range of quality data sources and verification activities are undertaken to ensure completeness of Australia's inventory. These are detailed in Volume 1, Chapters 5 and 6, and Volume 2, Annexes A5.5 and A5.6 of this Report.

1.7.2 Geographical coverage

The Australian inventory covers the six states (New South Wales, Victoria, Queensland, South Australia, Western Australia and Tasmania), the mainland territories (Northern Territory, Australian Capital Territory and Jervis Bay Territory) and the associated coastal islands.

The geographical coverage of the Australian inventory also includes emissions from the following external territories:

- Norfolk Island

  Norfolk Island is an external Australian territory in the Pacific Ocean about 1600 km northeast of Sydney. Norfolk Island is one of Australia's most isolated communities and one of its oldest territories. Norfolk Island has a diverse environment and notable historic sites, and during the most recent census recorded a population of 2,188 (ABS 2022) (DITRDCA 2024a).

- Christmas Island and Cocos (Keeling) Islands

  The Australian Government has responsibility for the external territories of Christmas Island and the Cocos (Keeling) Islands, collectively known as the Indian Ocean Territories (IOT). Christmas Island has an area of 137.4 square kilometres and includes the Christmas Island National Park (85 square kilometres). Christmas Island had a population of 1,692 in the most recent census (ABS 2022). The Cocos (Keeling) Islands consist of 27 coral islands in the group with a total land area of approximately 15.6 square kilometres. North Keeling Island was declared a National Park in 1995. During the most recent census, Cocos (Keeling) Islands recorded a population of 593 (ABS 2022) (DITRDCA 2024b).

- Heard and McDonald Islands

  Heard Island and McDonald Islands (HIMI) are a sub-Antarctic Island group. They are located in the Southern Ocean, about 4,000 km southwest of mainland Australia. The islands have a World Heritage protection and marine reserve status and are uninhabited (DCCEEW 2024a).

  Australia's Antarctic Program operations are also covered, which occur across four stations (Macquarie Island, Casie, Davis, and Mawson). Approximately 500 people inhabit these stations in summer, dropping to around 80 people in the winter (DCCEEW 2024b).

The following external territories are also covered and included in the state statistical territories by the ABS.

- Coral Sea Islands (Queensland)

  The Coral Sea Islands Territory is made up of the islands situated in an area of approximately 780,000 square kilometres of the Coral Sea extending from the outer edge of the Great Barrier Reef. The coral and sand islands are quite small with some grass and low vegetation cover. Only Willis Island is inhabited by Bureau of Meteorology staff. Unmanned weather stations, beacons and a lighthouse are located on several other islands and reefs. During the most recent census, Willis Island recorded a population of 78 (ABS 2022) (DITRDCA 2024c).

- Ashmore and Cartier Islands (Northern Territory)

  The Territory of Ashmore and Cartier Islands comprises West, Middle and East Islands of the Ashmore Reef, Cartier Island and the 12 nautical mile territorial sea generated by these islands. The islands are uninhabited and composed of coral and sand with some grass cover (DITRDCA 2024d).

  The coverage of emissions/removal categories for the external territories is as follows.

  - *fuel combustion, waste* and HFC emissions associated with refrigeration are estimated,
  - *fugitive emissions* and *industrial processes and product use* emissions are assumed to be not occurring, and
  - *agriculture* and *LULUCF* emissions and removals are not estimated but are likely to be negligible.

1.7.3 Total aggregate emissions considered insignificant (per MPG paragraph 32)

In accordance with paragraph 32 of the MPG, a Party may use the notation key “NE” (not estimated) for a source when the estimates would be insignificant. Insignificance is defined as having a likely emissions value below 0.05 per cent of the national greenhouse gas emission total (excluding LULUCF), does not exceed 500 kt CO_2-e, and that the aggregate of all “NE” sources remains below 0.1 per cent of the national greenhouse gas emission total (excluding LULUCF).

In 2021–22, Australia's total national aggregate of “NE” emissions for all gases and categories represent 0.052 per cent of Australia's total emissions (excluding LULUCF), which is below the 0.1 per cent significance threshold (Table 1.3). No individual sources exceed the 500 kt CO_2-e significance threshold.

Table 1.3 Emissions sources reported as "NE"

Source	Absolute Estimated Emissions (kt CO_2-e)	Relative Estimated Emissions (%)
Total national inventory (excluding LULUCF)	**520,995.1**	**100**
Total inventory significance threshold	521.0	0.1
Total omitted sources estimate	**271.8**	**0.052**
1.A.3.b.vi Urea-based catalysts [(a)]	154.5	0.03
1.A.3.c Railways – Solid Fuels	24.3	<0.01
2.D.2 Paraffin Wax Use	0.7	<0.001
3 Agriculture (external territories)	14.7	<0.01
3.D. 1.d Other organic fertilisers	0.6	<0.001
3.F Field burning of agricultural residues (cotton)	3.98	<0.001
4 Land use, land use change and forestry (external territories)	To be determined.	To be determined.
5. B.2 anaerobic digestion at biogas facilities	2.9	<0.001
5.C.1 Incineration of clinical waste	0.8	<0.001
5.C.2 Accidental fires at solid waste disposal sites	17.3	<0.01
5.C.1 Incineration of waste other than clinical waste and solvents	52.0	0.01

(a) This activity is sometimes identified as a part of the IPPU sector due to the process not being a fuel combustion activity.

1.7.4 Description of insignificant ("NE") categories

Australia's reported, omitted insignificant emissions sources are estimated using simple methods in line with paragraph 32 of the MPG.

The data and assumptions Australia has used to derive the likely emissions levels presented in Table 1.3 are described by category below.

1.A.3.b.vi Urea-based catalysts

The use of urea-based additives (diesel emissions fluid – DEF) in catalytic converters occurs in Australia. Including heavy duty trucks, medium trucks, light commercial vehicles and passenger cars (with much lower uptake of selective catalytic reduction – SCR – in reality; the most popular passenger cars in Australia are the Toyota Hilux and Ford Ranger that do not employ SCR), emissions are estimated at 154.5 kt CO_2 or 0.03 per cent of the national total. Even applying this extremely conservative scenario of significant SCR penetration in the Australian fleet, emissions are still well under the threshold for significance according to the MPG.

Australia has no immediate plans to report emissions from Urea-based catalysts category (1.A.3.b.vi) – there is a considerable data requirement to estimate the emissions considering fuel consumption rates and penetration of the technology in the fleet. Given the insignificance of the source, this is not considered to add materially to the completeness of the inventory.

1.A.3.c Railways – Solid Fuels

Australia has a number of tourist railways operating historic steam trains. It is estimated that around 10kt of black coal is consumed, resulting in around 24.3 Gg of CO_2 (less than 0.01% of the national total). This is considered insignificant and emissions are "not estimated".

2.D.2 Paraffin Wax Use

Australia derived a paraffin wax use factor weighted per-capita from all Annex-1 Parties reporting emissions from this source. This per capita factor was applied to Australia's population to estimate emissions for 2021–22, resulting in 0.7 kt CO_2-e of emissions (approximately 0.001 per cent of the national total excluding LULUCF). This is well below the significance threshold for reporting. Accordingly, this source is reported as Not Estimated ("NE").

3 Agriculture (external territories)

As described in Section 1.7.2, Australia's external territories are largely uninhabited, and include large areas of national terrestrial and marine parks. In 2020–21 during the most recent census, the population was approximately 5,000 people across all external territories. On this basis, any emissions are likely negligible.

Dividing total agriculture emissions by Australia's population in 2021–22 provides an estimated average agriculture emissions intensity of just under 3 t CO_2-e per person. Applying this intensity to the population of Australia's external territories provides a conservative overestimate of 14.7 kt CO_2-e.

3.D.1.d Other organic fertilisers

The organic fertilisers used in Australia are principally derived from animal wastes (3.D.1.d). Emissions from this organic N source are covered elsewhere. Data on the application of other organic N fertiliser is not available through either ABS or industry data collections, nor is a comprehensive list of organic fertiliser producers available. To assess the significance of the category, data was sourced from one of the largest commercial producers. They reported production of meat and fish meal containing 117.8 tonnes of Nitrogen. Applying the IPCC default EF of 1 per cent this equates to 0.6 kt CO_2-e of emissions. Even allowing for the complete estimate to be over 900 times greater, this category can be considered insignificant (<500 kt CO_2-e) and as such, emissions are "not estimated".

3.F Field burning of agricultural residues (cotton)

The smallest value for "fraction burned" for other crops determined during the 2014 expert review of Australia's submission that year was 6 per cent. Therefore, it is reasonable to assume that for cotton the fraction burned is 5 per cent or less. As a conservative maximum estimate, if it assumed that 5 per cent of the total emissions from residue burning (CH_4 and N_2O combined) it would result in 3.98 kt CO_2-e in 2020–21. This is well below the significance threshold for reporting. Accordingly, this source is reported as Not Estimated ("NE").

4 Land use, land use change and forestry (external territories)

As described in Section 1.7.2, Australia's external territories are largely uninhabited, and include large areas of national terrestrial and marine parks. In 2020–21 during the most recent census, the population was approximately 5,000 people across all external territories. On this basis, any LULUCF emissions from this source are likely negligible. Australia plans to estimate the likely emissions level for this source to improve completeness.

5.B.2 Anaerobic digestion of solid waste at biogas facilities

To date, no facilities have reported emissions associated with the anaerobic digestion of solid waste at biogas facilities under the NGER scheme. The Australian biogas industry is emerging. There are three known facilities in operation in Australia that could be classed as anaerobic digestion facilities for solid waste. The Richgro facility in Jandakot Western Australia became operational in 2015 and has the capacity to process up to 140 tonnes of food waste per day. Another facility known as Earthpower has been operating in Sydney since 2003 and can process up to 130 tonnes of organic waste per day. As with the Richgro facility, emissions of less than 1,000 tonnes of CO_2-e are estimated. A third facility in Wollert, to the north of Melbourne, has been operating since May 2017. The facility has the capacity to process around 90 tonnes of food waste per day.

When the IPCC default CH_4 EF of 0.8 g CH_4/kg wet waste treated is applied to the maximum quantity of waste that could be processed at these three facilities, it results in annual emissions of around 2.9 kt CO_2e. This is well below the significance threshold for reporting. Accordingly, this source is reported as Not Estimated (“NE”).

5.C.1 Incineration of clinical waste

For the incineration of clinical waste and solvents (5.C.1), the IPCC 2006 do not provide default CH_4 and N_2O emission factors. Furthermore, when the highest IPCC 2006 default EFs for CH_4 and N_2O listed for municipal solid and general industrial waste incineration are applied to the AD for clinical waste and solvents incineration, emissions estimates contribute less than 0.001 per cent (0.8 Kt CO_2-e) of total emissions from all sectors. Accordingly, emissions of CH_4 and N_2O from this source can be considered insignificant (<500 kt CO_2-e) and as such, emissions are “not estimated”.

5.C.2 Accidental fires at solid waste disposal sites

For unintentional (accidental) fires on solid waste disposal sites (5.C.2), Australia has estimated emissions of CO_2, CH_4 and N_2O to contribute around 17.3 kt CO_2-e or 0.004 per cent of total emissions from all sectors. Accordingly, emissions from this source are reported as “not estimated” on the grounds that they fall below the significance threshold.

5.C.1 Incineration of waste other than clinical waste and solvents

For the incineration of waste other than solvents, municipal and clinical waste (5.C.1), when the highest IPCC 2006 default EFs for CO_2 and N_2O listed for waste lubricant, hazardous waste and biosolids are used, emissions are estimated to contribute around 52.0 kt CO_2-e or less than 0.01 per cent of total emissions from all sectors. Accordingly, emissions from this source are reported as “not estimated” on the grounds that they fall below the significance threshold.

1.8 Metrics

Consistent with paragraph 37 of the MPG, this Report is prepared using 100-year time-horizon global warming potential (GWP) values from the IPCC Fifth Assessment Report (AR5).

While not a requirement under the MPG, Australia maintains a version of its inventory prepared on the basis of 100-year time-horizon GWP values from the IPCC Fourth Assessment Report (AR4). This information is made available to support users who seek to compare Australia’s inventory to those countries that are yet to transition to the updated GWPs of AR5. These data are published on the Australia’s National Greenhouse Accounts.

2. Trends in emissions

2.1 Description of emission and removal trends for aggregated GHG emissions and removals

2.1.1 Overview of emissions trends since 1990

Australia's total greenhouse gas emissions were 432.6 million tonnes (Mt) of carbon dioxide equivalent (CO_2-e) in 2021–22. Total net emissions, presented in Table 2.1, have decreased by 1.4 per cent (or 6.1 Mt CO_2-e) on 2020–21 levels, 29.0 per cent (or -176.8 Mt CO_2-e) on 2004–05 levels, and 29.7 per cent (or -182.8 Mt CO_2-e) on 1989–90 levels.

Decreases on the previous year were driven by:

- Ongoing reductions in the emissions intensity of electricity generation,
- Reduced travel as a result of the COVID-19 pandemic and ongoing mode of work changes,
- Decreased coal production due to damaged infrastructure from floods and storms as well as restrictions of imports to China (DCCEEW 2023), and
- A small reduction in fugitive emissions (down 1.1 per cent), where decreases in emissions from underground coal mining and flaring associated with gas extraction were largely offset by growth in venting emissions from oil and natural gas extraction.

These reductions were partially offset by increases in the agriculture sector caused by drought recovery, resulting in increasing livestock numbers and increased crop yields.

The LULUCF net sink remained relatively stable in 2021–22 as the increasing sink in croplands and grasslands due to high rainfall La Niña conditions were offset by increases in emissions in forest lands due to wildfires and increased rates of soil carbon decay also caused by wetter conditions. In addition to the inter-annual variations in climate drivers of emissions, the long-term trends towards reduction in native forest harvesting and land clearing rates have continued in 2021–22 (see section 6.1 for more information). Net forest cover increased by around 300,000 hectares in 2021–22, reflecting increases in native vegetation in previously cleared forest lands and grasslands exceeding clearing rates (see Chapter 6, Table 6.2.1, land transition matrix). These trends have also contributed to the net LULUCF sink in 2021–22. Significant updates to the FullCAM Tier 3 emissions model have been made in this submission as part of ongoing improvement programs for soil carbon and native forest harvesting. The recalculation in 2021 also includes the impact of new climate data reflecting wetter conditions due to the La Niña climate cycle.

Figure 2.1 Comparison of 2021-22 emissions with past emissions levels by sector, million tonnes of carbon dioxide equivalent (Mt CO_2-e) and percentage change (%)

		Change in 2021–22 emissions since:		
Emissions Sectors	**2021–22 emissions**	**1989–90**	**2004–05**	**2020–21**
Total emissions	433 Mt CO_2-e	-183 Mt CO_2-e -30%	-177 Mt CO_2-e -29%	-6 Mt CO_2-e -1%
1. Energy	397 Mt CO_2-e	+33% +99 Mt CO_2-e	-7 Mt CO_2-e -2%	-8 Mt CO_2-e -2%
2. Industrial Processes and Product Use	33 Mt CO_2-e	+31% +8 Mt CO_2-e	+9% +3 Mt CO_2-e	+0.3% +0.1 Mt CO_2-e
3. Agriculture	77 Mt CO_2-e	-14 Mt CO_2-e -15%	-7 Mt CO_2-e -9%	+1% +1 Mt CO_2-e
4. Land use, land use change and forestry	-88 Mt CO_2-e	-267 Mt CO_2-e -150%	-163 Mt CO_2-e -218%	+0.2% +0.2 Mt CO_2-e
5. Waste	14 Mt CO_2-e	-10 Mt CO_2-e -41%	-2 Mt CO_2-e -12%	+3% +0.4 Mt CO_2-e

Note: Icons in this figure are sourced from Freepik, and Uniconlabs on flaticon.com.

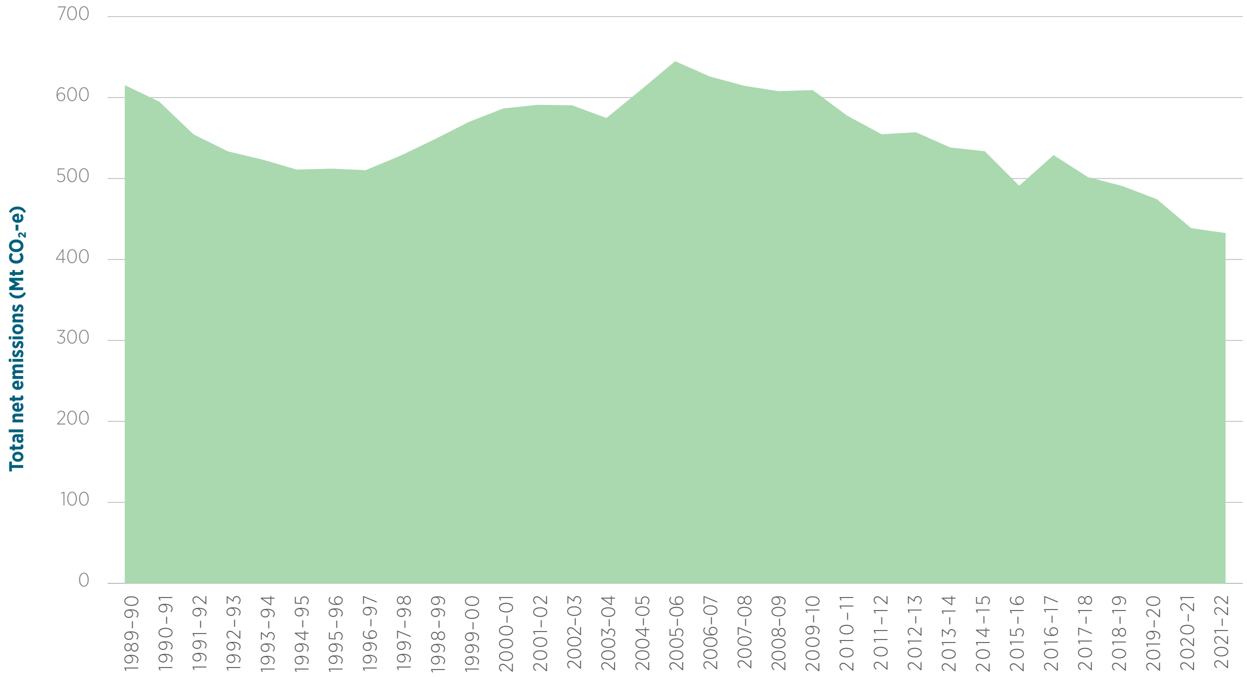
Table 2.1 Net greenhouse gas emissions by sector, Australia (Mt CO_2-e)

UNFCCC classification sector and subsector	Net emissions (Mt CO_2- e)							% change in emissions between 2021–22 and:		
	1989–90	2004–05	2009–10	2014–15	2019–20	2020–21	2021–22	1989–90	2004–05	2020–21
1 Energy (combustion + fugitive)	297.4	403.7	422.4	422.5	418.8	404.3	396.7	33.4	-1.7	-1.9
Stationary energy	195.7	278.9	288.2	278.7	271.7	265.6	258.9	32.3	-7.2	-2.5
Transport	61.4	82.0	88.6	95.2	93.2	90.1	89.8	46.3	9.4	-0.4
Fugitive emissions from fuel	40.3	42.8	45.5	48.6	53.9	48.6	48.1	19.3	12.3	-1.1
Carbon capture and storage	NO	NO	NO	NO	0.012	0.002	0.0003	NA	NA	-84.7
2 Industrial processes and product use	25.1	30.1	33.4	30.5	31.9	32.9	33.0	31.3	9.4	0.3
3 Agriculture	91.2	84.9	74.0	77.7	71.6	76.6	77.5	-15.0	-8.8	1.1
4 Land use, land use change and forestry	178.3	75.0	63.3	-9.7	-61.2	-88.5	-88.4	-149.6	-217.9	0.2
6 Waste	23.5	15.7	16.0	12.7	13.5	13.4	13.9	-40.9	-11.8	3.1
Total net emissions	**615.4**	**609.4**	**609.2**	**533.7**	**474.5**	**438.7**	**432.6**	**-29.7**	**-29.0**	**-1.4**
Memo: *Total net emissions without application of the natural disturbance provision*	615.4	577.9	584.9	516.9	1193.3	305.0	320.6	-47.9	-44.5	5.1

To ensure transparency, and consistent with Paris Agreement decision 18/CMA.1, Table 2.1 also presents total net emissions without the application of the natural disturbance provision. Australia's approach to addressing emissions and subsequent removals from natural disturbances is detailed in Chapter 6 of this Report and the full time series is provided in Table 4 of the CRT.

Australia's net emissions peaked in 2005-06 and have generally been on a long-term decline since that year (Figure 2.2).

Figure 2.2 Total net emissions per year, Australia, Mt CO_2-e



The decline from the 2005–06 peak is caused by a complex mixture of long-term and short-term factors. Long-term downward pressures on emissions include changes in the electricity generation mix (including strong growth in renewable sources), increased methane capture in the energy and waste sectors, technology innovations and the LULUCF sector changing from a net source to a net sink (including in response to reduced land clearing, increasing forest cover through plantations and natural regeneration). There are also several shorter-term drivers of emissions reduction since the 2005–06 peak, including general economic downturn during the Global Financial Crisis (2007 to 2009), temperature influences on electricity demand, the Australian Government's Carbon Pricing Mechanism (2012–15; CER 2015), broader climatic factors (including from the El Niño and La Niña cycle, which has the strongest impact on year-to-year climate variability in Australia – BoM 2021), multiple significant flooding events (2007, 2009 to 2015, 2020, 2021, and multiple events of widespread flooding in 2022; BoM 2022a, BoM 2022b, BoM 2024a), two significant drought events (the Millennium drought 1997 to 2009, and 2017 to 2019; BoM 2024b), and broadscale impacts resulting from the COVID-19 pandemic, including reductions in travel including as a result of international and state/territory border restrictions (2020 to 2022; JSCFADT 2020). Further detail on Australia's emissions trends by sector, are provided in Section 2.2.1 and sectoral Chapters 3-7 of this Report.

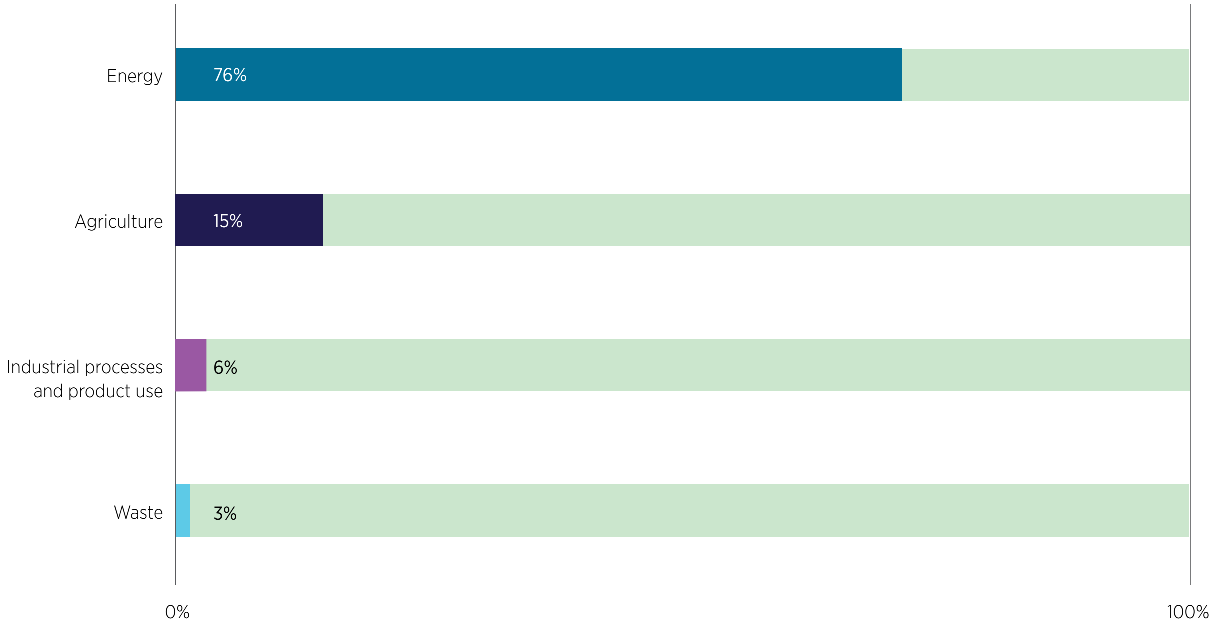
2.2 Description of emission and removal trends by sector and by gas

The following sections present Australia's emissions trends by sector, by greenhouse gas, and by ozone precursor and indirect gas. As the LULUCF sector is a net sink in 2021–22, emissions by sector are described with and without LULUCF in ES.2 and ES.3, and are largely described excluding LULUCF in Section 2.2.

2.2.1 Sectoral trends

Emissions by sector (excluding LULUCF, which is a net sink in 2021–22) are presented in Figure 2.3. The combined *energy* subsectors (including *stationary energy, transport* and *fugitive emissions*) were the largest source of greenhouse gas emissions in 2021–22, followed by the *agriculture* sector.

Figure 2.3 Share of national emissions (excluding LULUCF) on a CO_2-e basis by sector, 2021-22



Note: LULUCF emissions are a net sink in 2021–22 and have been excluded from this figure.

Sectors with increasing emissions over the reporting period included *stationary energy, transport, fugitive emissions from fossil fuels* and *industrial processes and product use*. Conversely, emissions decreased in the *waste, agriculture* and *LULUCF* sectors.

The contribution of each sector to total emissions by year is presented in Figure ES.01, with total and net total emissions by year presented in Figure ES.02. The principal drivers of these emissions trends are as follows:

- *Energy:* The largest sectoral increase in greenhouse gas emissions over the reporting period occurred in the stationary energy sector, driven in part by increasing population, household incomes and export increases from the resource sector. Emissions from the public electricity and heat production sub-sector have more recently decreased from the peak in 2008–09, despite continuing population and economic growth. This is primarily driven by a decrease in the share of generation from coal, along with an increase in the share of generation of renewable energy in the National Electricity Market, with the largest increases coming from wind and solar. The main drivers for the increase in transport emissions are continuing growth in the number of passenger vehicles, along with an increase in diesel consumption in heavy vehicles and an increase in air travel, other than where impacted by the COVID-19 pandemic. Fugitive emissions have increased over the period largely due to increased production from open cut coal mines and increased gas production. The most recent increase, since 2014–15, is associated with an expansion of LNG exports.

- *Industrial processes and product use:* The emissions in the industrial processes and product use sector have increased over time. The increase is primarily driven by the growth in the bank of hydrofluorocarbons (HFCs) used in refrigeration and air-conditioning equipment (which replaced ozone depleting chemicals phased out by the Montreal Protocol). Increased HFC emissions over the period from refrigeration and air conditioning were partly offset by declining emissions in other activities, in particular, in metals production. Declines in emissions from iron and steel production have been observed due to plant closures while declines in emissions from aluminium production are largely due to improvements in process control and plant upgrades and closures.
- *Agriculture:* Agricultural emissions have decreased since 1989–90. Climate (droughts, recovery from droughts, large seasonal differences, rainfall and floods) as well as economic forces (national and international markets and produce demand) directly impact emissions from the agricultural sector. The decline is primarily associated with a decline in sheep numbers as a result of the wool crisis and the collapse of the wool reserve price scheme. From 1994–95 to 1999–2000 emissions increased due to increased beef cattle numbers and crop production, which resulted most markedly in increased enteric fermentation emissions and increased emissions from agricultural soils. From 1999–2000 until 2009–10, prolonged and widespread drought conditions over southern and eastern Australia contributed to reductions in livestock populations, crop production, and fertiliser use. In turn, emissions declined over this period. As Australia saw relief from the Millennium Drought, emissions rose between 2010–11 and 2016–17, as farmers were able to increase herds and flocks and crop production. Drought conditions in more recent years have resulted in a lack of feed and elevated levels of turn-off of cattle and sheep and a contraction in the livestock population. In addition, crop production and fertiliser consumption has decreased. Decreases in emissions have followed. The higher rainfall from 2019–20 to 2021–22 was mostly reflected in improved growing conditions and water availability, although flooding did impact horticultural production regionally.
- *Waste:* Emissions from the waste sector have decreased over time, as increases in waste generation associated with growing populations and industrial production have been offset by increased methane recovery. The majority of emissions were from solid waste disposal, which has experienced a substantial improvement in methane recovery rates since 1989–90. The increase in emissions in 2021–22 was primarily driven by declines in methane recovery over the year.
- *LULUCF:* The decrease in emissions from LULUCF since 1989–90 has been mainly driven by the decline in emissions from land clearing (forest land converted to other land uses), forest cover expansion (including plantation establishment), and declines in the harvesting of native forests.

Trends in emissions from each sector are discussed further in Chapters 3–7.

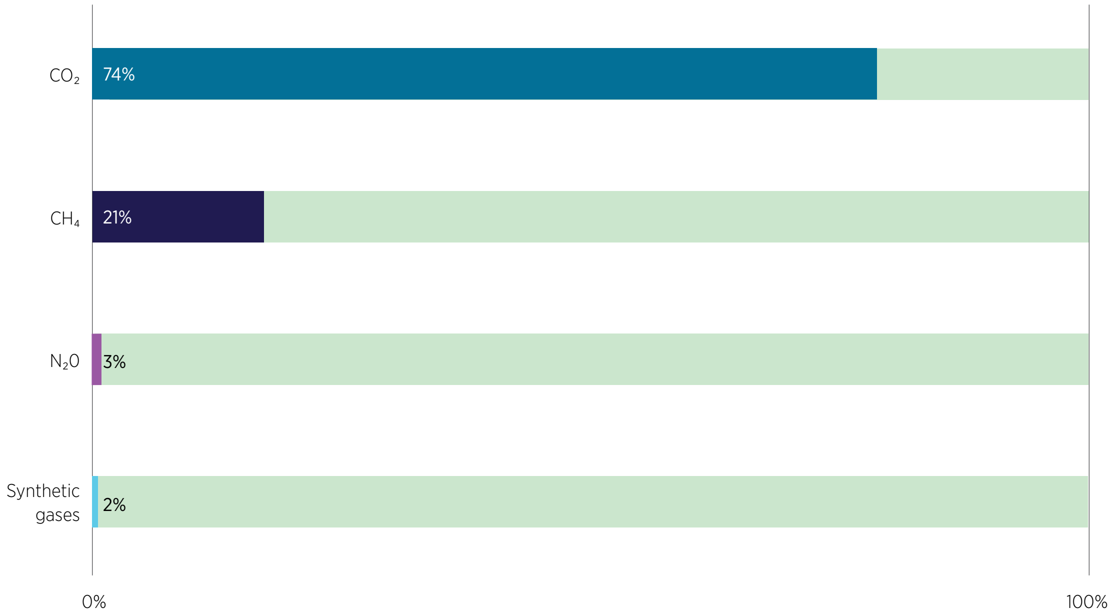
2.2.2 Trends by gas

Greenhouse gases

Greenhouse gases are those which absorb infrared radiation, heating the atmosphere. The greenhouse gases, and associated GWPs, included in this Report are set out in section 1.1.2. Greenhouse gases by sector are discussed in more detail at the start of Chapters 3-7 in this Report.

Australia's inventory by greenhouse gas for 2021–22 is presented in Figure 2.4. The LULUCF sector is excluded from this figure as it is a net sink in this year, however, this sector and its trends are explained in more detail in Volume 1, Chapter 6 of this Report.

Figure 2.4 Share of national emissions (excluding LULUCF) on a CO_2-e basis by gas, 2021–22



Note: Synthetic gases refers to SF_6, NF_3, HFCs, and PFCs.
LULUCF emissions are a net sink in 2021–22 and, therefore, they have been excluded from this figure.

Changes in emissions by greenhouse gas since 1989–90 and 2004–05 are presented in Table 2.2.

Table 2.2 National emissions totals (excluding LULUCF) by greenhouse gas, Australia, Gg CO_2-e

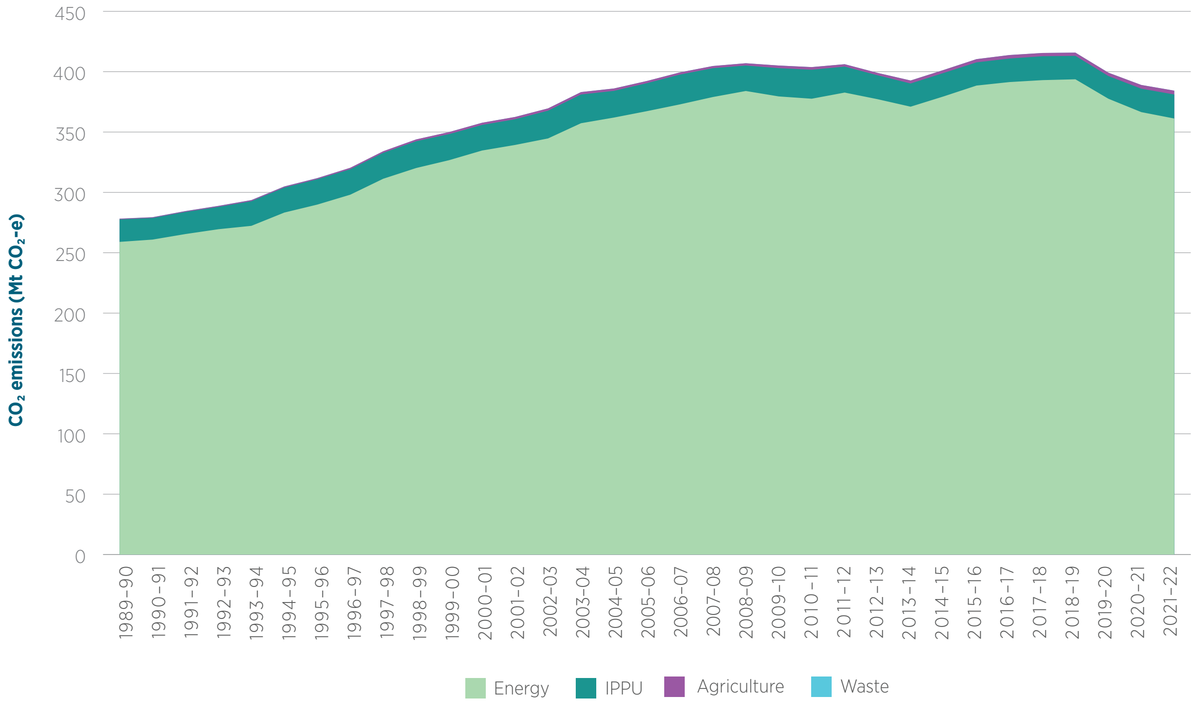
Greenhouse gas	1989-90	2004-05	2021-22	% change since 1989–90	% change since 2004–05
CO_2	278,160	386,176	384,362	38.2	-0.5
CH_4	140,144	125,747	108,473	-22.6	-13.7
N_2O	13,251	17,041	16,709	26.1	-1.9
HFCs	1,194	3,700	11,047	825.5	198.6
PFCs	4,144	1,611	247	-94.0	-84.7
SF_6	227	202	158	-30.7	-22.1
Total	**437,120**	**534,477**	**520,995**	**19.2**	**-2.5**

Note: LULUCF emissions are a net sink in 2021-22 and, therefore, they have been excluded from this table.

CO_2 represents the largest source of anthropogenic greenhouse gases globally and contributes 73.8% of Australia's emissions in 2021–22 (excluding LULUCF) (Figure 2.5). Most CO_2 emissions are produced through combustion of fossil fuels in the energy sector.

Excluding LULUCF, CO_2 increased by 38.2 per cent since 1989–90 and decreased by 0.5 per cent since 2004-05 (Figure 2.5). CO_2 emissions decreased 4.7 Mt (1.2 per cent) since 2020–21, largely driven by reductions in the energy sector (-5.3 Mt CO_2-e) which partially offset increases in the IPPU (+0.5 Mt CO_2-e, 2.7 per cent), agriculture (+0.1 Mt CO_2-e, 3.9 per cent), and waste (+0.0001 Mt CO_2-e, 0.4 per cent) sectors. Recent decreases in CO_2 in the energy sector have been largely driven by reduced travel and associated road transport and domestic aviation emissions as a result of the COVID-19 pandemic and the continuing decrease in emissions intensity of electricity generation due to fuel switching.

Figure 2.5 National CO_2 emissions (excluding LULUCF) by year, Australia, Mt CO_2-e



Note: LULUCF emissions are a net sink in 2021–22 and, therefore, they have been excluded from this figure.

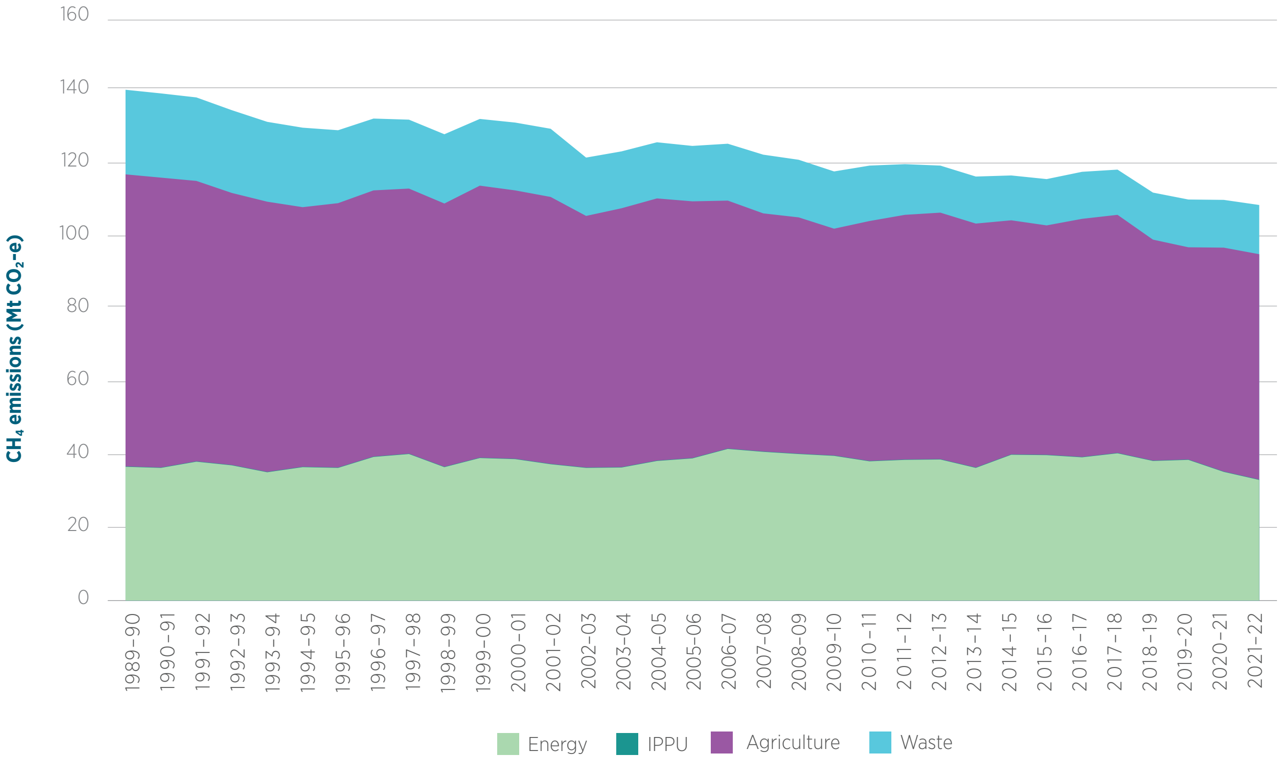
CH_4 emissions are the second largest source of greenhouse gases in Australia's inventory, representing 20.8 per cent of total emissions (excluding LULUCF) (Figure 2.4). The largest sources of CH_4 (Figure 2.6) are from the following sectors:

- agriculture (61.8 Mt CO_2-e), predominantly consisting of enteric fermentation by livestock,
- energy (33.1 Mt CO_2-e), predominantly consisting of fugitive emissions from coal, crude oil, and natural gas extraction, and
- waste (13.5 Mt CO_2-e), predominantly generated through the anaerobic decomposition of organic matter.

Excluding LULUCF, CH_4 emissions have decreased 31.7 Mt CO_2-e (22.6 per cent) since 1989–90 and 17.3 Mt CO_2-e (13.7 per cent) since 2004–05. CH_4 emissions decreased 1.4 Mt CO_2-e (1.2 per cent) when compared with the previous year (2020–21). Long-term decreases in CH_4 are driven by:

- CH_4 capture and flaring in the waste sector,
- fluctuations in absolute number and composition of livestock numbers which are, in turn, driven by Australia's complex climatic variations and market conditions,
- reductions in CH_4 venting in the oil and gas sub-sector, and
- decreased share of coal production in the gassiest southern coal field, flaring of pre-drainage gas, and adoption of technologies to recover and utilise coal mine waste gas for electricity generation.

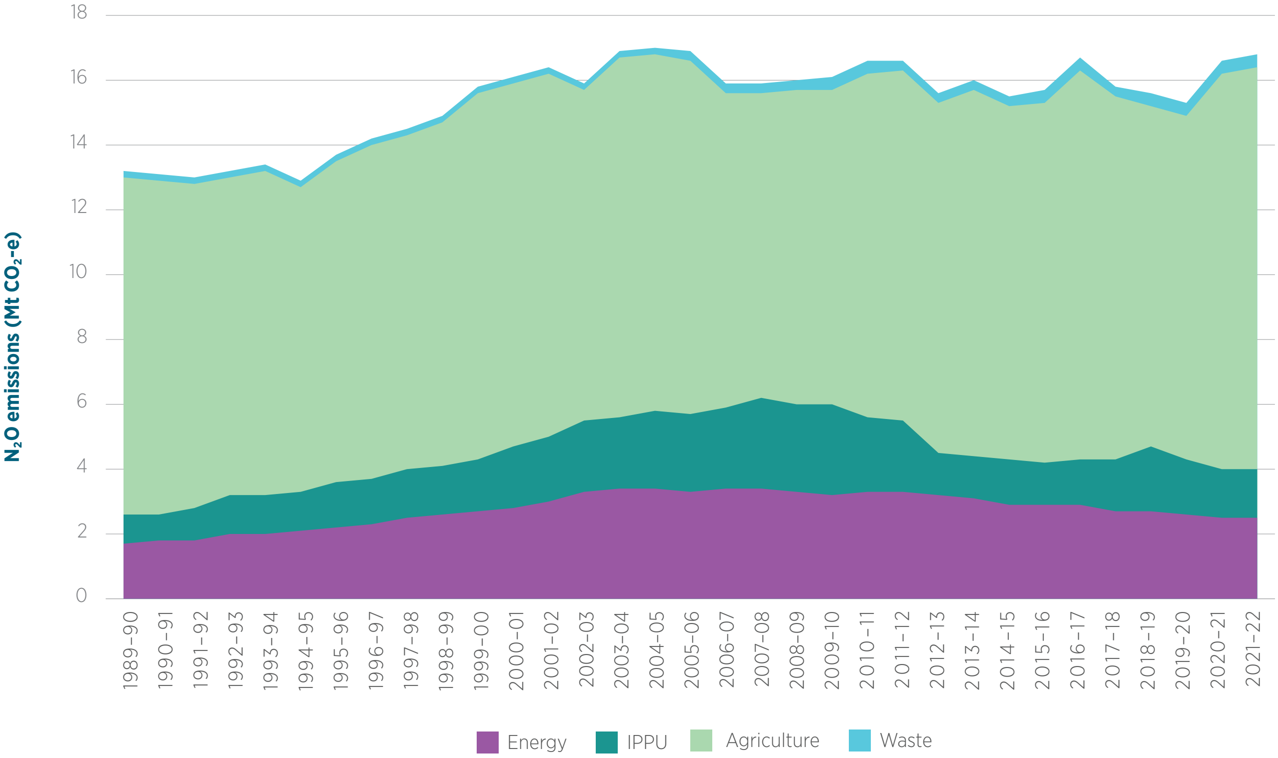
Figure 2.6 National CH_4 emissions (excluding LULUCF) by year, Australia, Mt CO_2-e



Note: LULUCF emissions are a net sink in 2021–22 and, therefore, they have been excluded from this figure.

N_2O emissions represent 3.2 per cent of Australia's greenhouse gas inventory (excluding LULUCF) (Figure 2.4). The majority of N_2O emissions (Figure 2.7) are sourced from the agriculture sector (74.2 per cent of the national total, excluding LULUCF), predominantly arising from microbial and chemical transformations that produce and consume nitrous oxide in agricultural soils. N_2O is also generated as a by-product of combustion in the energy sector and of nitric acid production in the IPPU sector. Excluding LULUCF, N_2O emissions have increased 3.5 Mt CO_2-e (26.1 per cent) since 1989–90 and have decreased 0.3 Mt CO_2-e (1.9 per cent) since 2004–05. N_2O emissions increased 0.2 Mt CO_2-e (1.2 per cent) when compared with the previous year (2020–21). IPPU sector N_2O emissions fluctuate in response to fluctuating nitric acid production at individual facilities. Plant-level N_2O emissions intensities have been declining since the 1990s, resulting from more recent introductions of continuous monitoring and associated improvements in management of process catalysts.

Figure 2.7 National N_2O emissions (excluding LULUCF) by year, Australia, Mt CO_2-e



Note: LULUCF emissions are a net sink in 2021–22 and, therefore, they have been excluded from this figure.

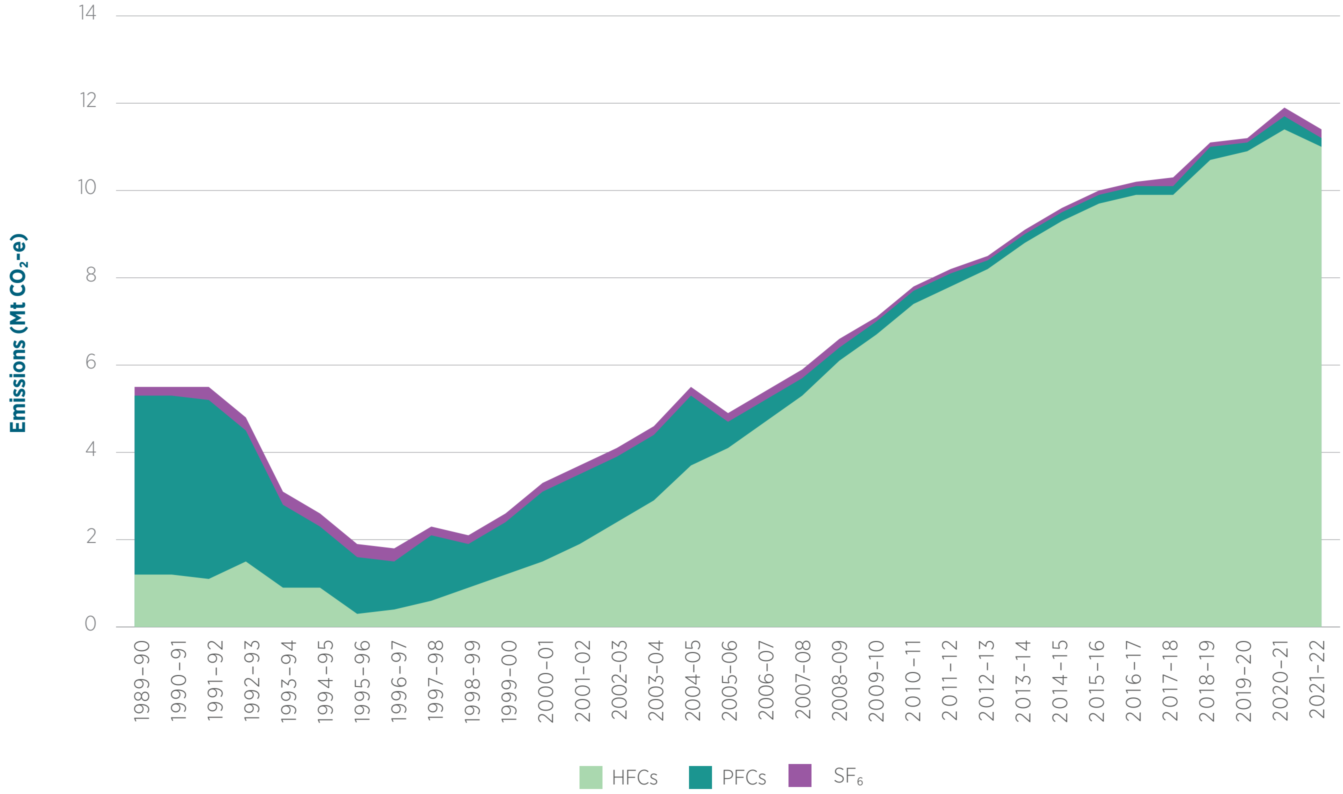
IPPU is the only sector that reports synthetic greenhouse gases, which include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). Nitrogen trifluoride (NF_3) is a reportable synthetic gas used in electronics manufacturing, however, Australia reports this source as not occurring (see Chapter 4.6 of this Report). Synthetic gases represent 2.2 per cent of the national total (excluding LULUCF) in 2021-22 (Figure 2.3). They have increased 5.9 Mt CO_2-e (105.8 per cent) since 1989-90, 5.9 Mt CO_2-e (107.7 per cent) since 2004–05, and decreased 0.5 Mt CO_2-e (3.9 per cent) since the previous year (2020–21) (Figure 2.8).

HFC gases, primarily used as refrigerants, have been increasing in use since the early 1990's to replace the Montreal Protocol's phasing out of ozone-depleting refrigerants. They currently dominate synthetic gas emissions, growing from a 21.5 per cent share in 1989–90 to a 96.5 per cent share in 2021–22, from 1.2 Mt CO_2-e to 11.0 Mt CO_2-e.

Conversely, PFCs emissions have been reducing significantly driven by lower emissions rates from aluminium production. Australia's PFC intensity in aluminium production has decreased approximately 95% since the year 1989–90, which mirrors the 90 per cent decline globally reported by the International Aluminium Institute (2020). Australia's PFC emissions have reduced from 4.1 Mt CO_2-e in 1989-90 to 0.2 Mt CO_2-e in 2021–22.

SF_6 is predominantly used in electrical equipment. Emissions from consumption of SF_6 have decreased 0.1 Mt CO_2-e (30.7 per cent) since 1989-90 and 0.04 Mt CO_2-e (22.1 per cent) since 2004-05, and have decreased 0.04 Mt CO_2-e (18.2 per cent) on the previous year (2020–21). These estimates have been calibrated to changes in atmospheric concentrations measured at the Cape Grim monitoring station in Tasmania (CSIRO 2021), which is possible because there are no sinks of SF_6 and therefore changes in atmospheric concentrations reflect changes in emissions.

Figure 2.8 Synthetic gas emissions by year, Australia, Mt CO_2-e

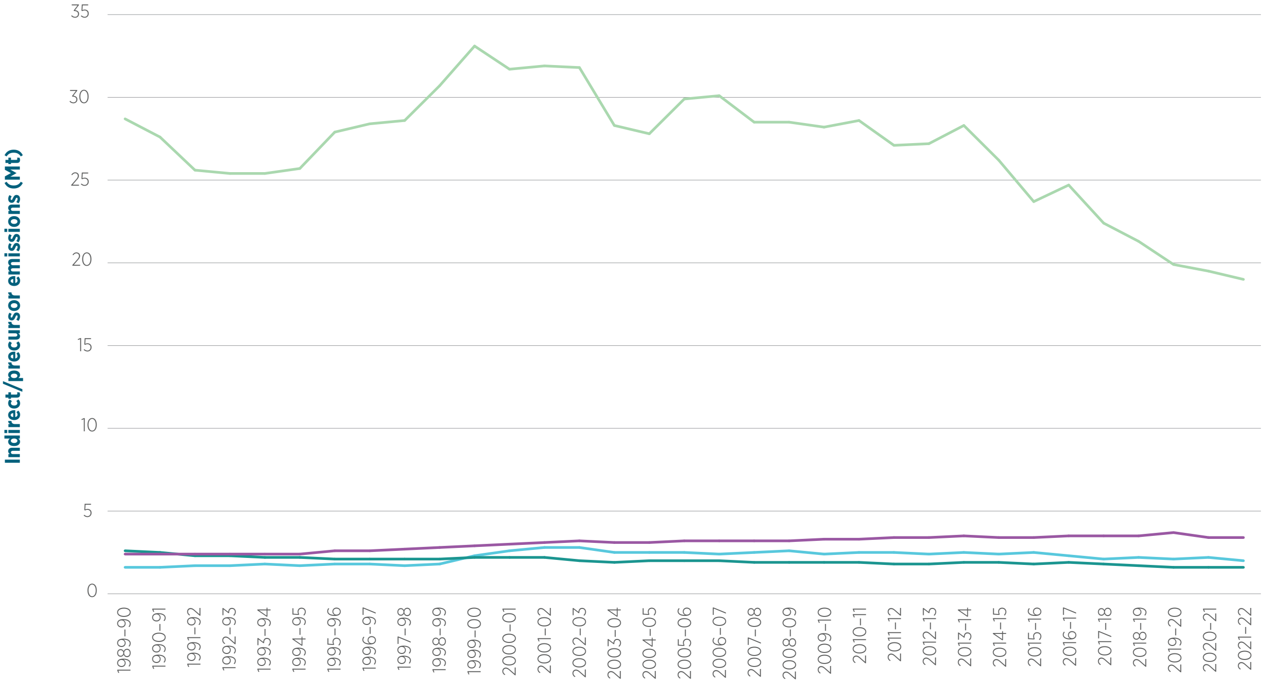


Ozone precursors and indirect emissions

In line with IPCC 2006 Guidelines (Volume 1, Chapter 7), Australia reports emissions estimates of the precursors of ozone (O_3 – a greenhouse gas) and indirect emissions. These include carbon monoxide (CO), oxides of nitrogen (NO_x), and non-methane volatile organic compounds (NMVOCs), and sulphur dioxide (SO_2). These gases are not greenhouse gases themselves and are not included in the national emissions totals, however, they chemically alter the atmosphere leading to an increase in the greenhouse gases known as tropospheric (ground-level) ozone and aerosols.

Precursor emissions by gas by year are presented in Figure 2.9.

Figure 2.9 Precursor and indirect emissions by year, Australia, million tonnes of gas



CO represents the largest precursor greenhouse gas by mass in Australia, representing 73.2 per cent (19.0 Mt) of these emissions in 2021–22. It is predominantly emitted by biomass burning in the LULUCF sector, and is also emitted by the energy, IPPU, and agriculture sectors. CO emissions have decreased 33.7 per cent (9.7 Mt) since 1989–90, 31.6 per cent (8.8 Mt) since 2004–05, and 2.5 per cent (0.5 Mt) since the previous year (2020–21).

NO_x represents 13.1 per cent (3.4 Mt) of the precursor greenhouse gases by mass in Australia. They are emitted by the agriculture, IPPU, and LULUCF sectors and are dominated by the energy sector. Most energy-related NO_x emissions result from fuel combustion, formed by the conversion of chemically bound nitrogen of the fuel. NO_x emissions have increased 40.1 per cent (1.0 Mt) since 1989–90, 10.3 per cent (0.3 Mt) since 2004-05, and have decreased 1.1 per cent (0.04 Mt) since the previous year (2020–21). Whilst most energy-related NO_x has been increasing through time reflecting increasing combustion, NO_x from transport has been decreasing since its peak in 1995–96 despite increasing activity attributable to increasing uptake of emissions-control technologies in road transport vehicles.

NMVOCs represent 6.1 per cent (1.6 Mt) of the precursor greenhouse gases by mass in Australia. They are predominantly emitted by biomass burning in the LULUCF sector, gasoline consumption in road transport, and gasoline and wood consumption in the residential energy sectors. NMVOC emissions have decreased 39.2 per cent (1.0 Mt) since 1989–90, 20.0 per cent (0.4 Mt) since 2004–05, and 2.2 per cent (0.04 Mt) since the previous year (2020–21). This long-term reduction trend has largely been driven by reductions in biomass burning.

SO_2 represents 7.5 per cent (2.0 Mt) of the precursor greenhouse gases by mass in Australia. It is emitted by the energy and IPPU sectors. Emissions have increased 23.4 per cent (0.4 Mt) since 1989–90 but have decreased 22.4 per cent (0.6 Mt) since 2004–05 and 12.1 per cent (0.3 Mt) since 2020-21.

Australia's metal ores are predominantly sulphide ores, leading to the generation of SO_2 as a by-product of metal production. IPPU is the predominant source for SO_2 in Australia, all emitted from the metal industry – particularly from copper and zinc production under 2.C.7 *Other*. Variations and levels of SO_2 reflect variations and level of production of these metals.

SO_2 in the energy sector is largely emitted from coal-generated electricity, and has been decreasing since peaking in 2007–08. This trend is driven by black coal consumption decreasing, substituted by gas and renewable energy sources, and one third of brown coal generating capacity being decommissioned since 2013–14 (GA 2022).

Black carbon

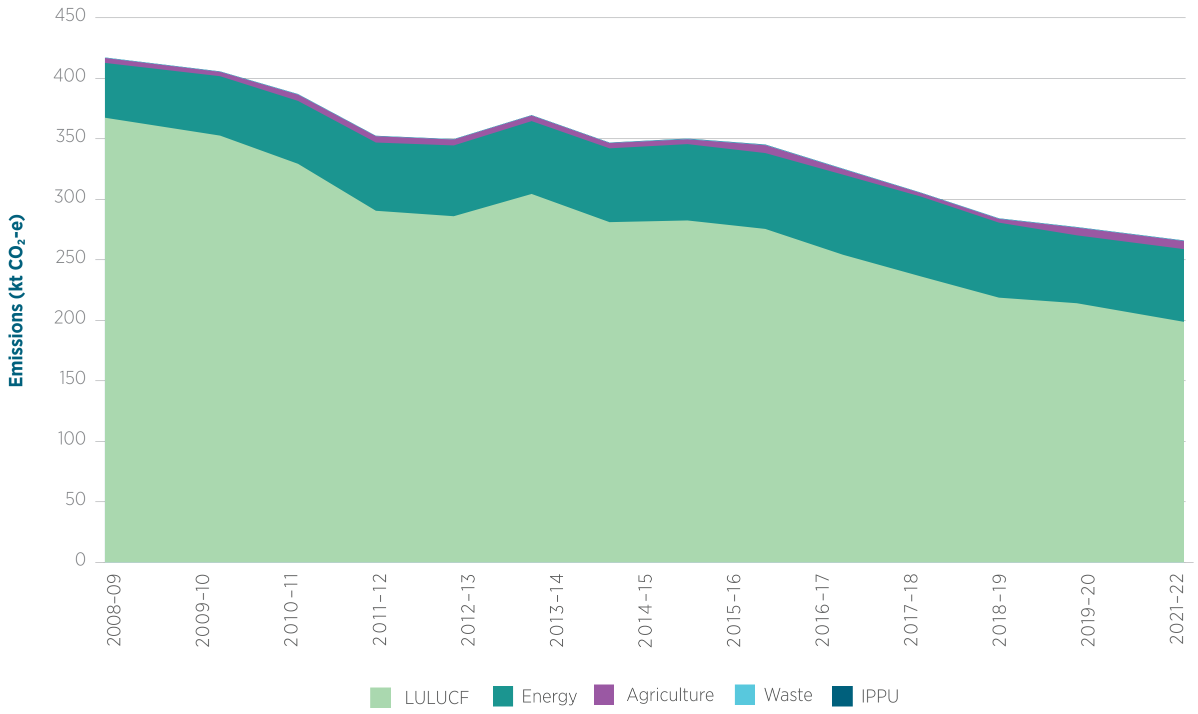
Black carbon is a fine particulate formed by the incomplete combustion of fossil fuels and biomass. On a 100-year AR5 basis, it's global warming potential is estimated to be approximately 1,600 times more potent than CO_2 (Chapter 8, Section 8.5.2.1.3, IPCC 2013). Black carbon is particulate matter that is short-lived in the atmosphere lasting days or weeks at most, compared with gaseous CO_2 which may remain in the atmosphere for hundreds or thousands of years (Columbia University, 2016).

Australia voluntarily reports black carbon emissions using Tier 2 and Tier 3 methods based on data collected under its National Pollutant Inventory (NPI). It is mandatory for Australian facilities that exceed defined thresholds for 93 specified substances to report estimates of these substances to the NPI, which includes emissions of black carbon. The NPI covers particulates of 10 microns in diameter or less (PM10) and of fine particulates of 2.5 microns in diameter or less (PM2.5), to which fractions of black carbon content are applied. More details on reporting requirements, thresholds, estimation methods, and searching the NPI dataset are available online (published by DCCEEW).

Biomass burning in the LULUCF sector is the largest source of black carbon in Australia, contributing 74.7 per cent (198.7 kt) of emissions in 2021–22. This is followed by the energy sector (22.6 per cent, 60.1 kt), and agriculture (2.5 per cent, 6.7 kt). The IPPU and waste sectors contribute 0.2 per cent (0.5 kt), combined.

Estimates are available from 2008–09 onwards. Since 2008-09 black carbon emissions have generally decreased, reducing 36.2 per cent (151.2 kt) by 2021–22 (Figure 2.10). This is largely driven by decreasing biomass burning.

Figure 2.10 Black carbon emissions by year, Australia, kilotonnes



Black carbon emissions from the transport sector increased 57.6 per cent (19.2 kt) between 2008–09 and 2017–18, before reducing 18.9 per cent (9.9 kt) between 2017–18 and 2020–21 and increasing 8.2 per cent (3.5 kt) between 2020-21 and 2021-22. Long-term increases are driven by increasing fuel use in the transport sector, and recent decreases in fuel use are driven by the impacts of travel restrictions and border closures during the COVID-19 pandemic. The increase in 2021–22 is a result of transport rebounding following the end of COVID-19 pandemic travel restrictions.

Further detail on the methods and definitions used by Australia to estimate black carbon emissions is provided in Volume 2, Annex 5.7 of this Report. This Annex also provides data tables and graphs of black carbon by year and by sector.

2.3 Description of emissions trends by emissions intensity

2.3.1 Kaya Identity analysis

Background

The Kaya Identity expresses total national CO_2 emissions in relation to four factors: population, gross domestic product (GDP), energy intensity, and carbon intensity. This allows for identifying and measuring high-level change in various measures of carbon intensity across the country.

The following equation (Equation 2.1) based on the Kaya identity expresses CO_2 emissions from fuel combustion and industrial processes and product use (IPPU) as the product of four factors: population; GDP per capita; the energy intensity of the economy and the emissions intensity of energy.

Equation 2.1: CO_2 from fuel combustion and IPPU $= P \times \frac{GDP}{P} \times \frac{Energy}{GDP} \times \frac{CO_2}{Energy}$

Where P = Population

GDP = Gross domestic product (Chain volume measures, $ millions)

Energy = Total net energy consumption (PJ)

CO_2 = Mt CO_2-e emissions from fuel combustion and IPPU

Trends in these factors provide insight into how Australia's national circumstances have impacted on CO_2 emissions since 1990. However, it should be noted that each factor is not necessarily independent of each other (i.e. increases in GDP per capita may change the energy intensity of the economy) and an increase in a single factor will not automatically result in a corresponding change in CO_2 emissions (i.e. an increase in population does not automatically result in an equivalent increase in CO_2 emissions).

Results

Between 1989–90 and 2021–22, CO_2 emissions from fuel combustion and IPPU increased by 35 per cent (Figure 2.11). Underlying growth factors were a 52 per cent increase in population and a 65 per cent increase in GDP per capita. Declining factors were a 42 per cent decline in the energy intensity of the economy and an 8 per cent decline in the emissions intensity of energy consumption. Over the time series, Australia's CO_2 emissions from fuel combustion and IPPU trended upwards to a peak in 2008–09 before largely declining to 2021–22 as the impacts of improved energy intensity of the economy and emissions intensity of energy supply more than offset increases in population and GDP per capita.

Figure 2.11 Growth in CO_2 emissions from fuel combustion and IPPU and underlying drivers, Australia, 1989–90 to 2021–22

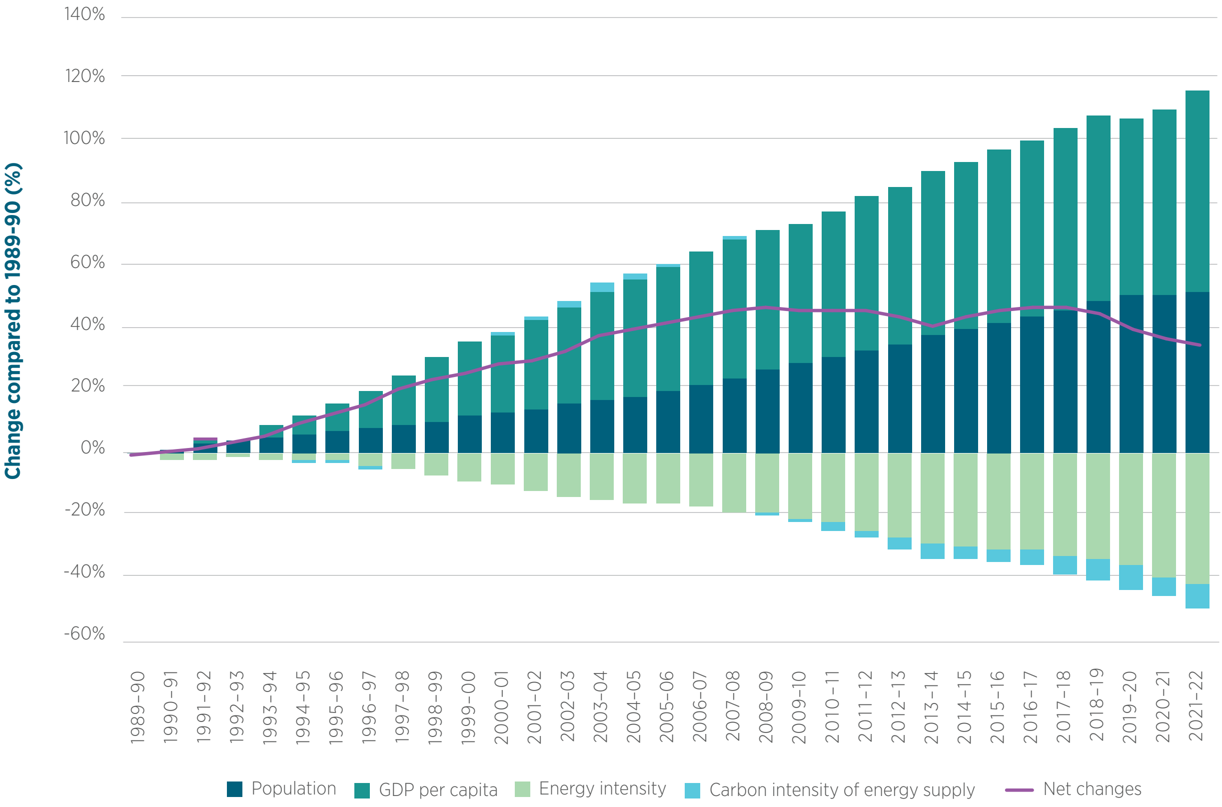


Figure 2.12 attributes annual emissions changes to the four underlying factors. The combined impact of increases in population and GDP per capita have contributed to increasing emissions since 1989–90.

A combination of factors, outlined below, contributed to reductions in CO_2 emissions from energy and IPPU of 1.8 per cent in 2021–22 when compared with the previous year.

Like many other regions, Australia's economic activity was impacted by COVID-19 from 2020. GDP per capita fell by 1.7 per cent in 2019–20 (the only other falls in GDP per capita were 1.7 per cent in 1990–91 and 0.3 per cent in 2008–09). GDP per capita grew in 2021-22, increasing 3.5 per cent on the previous year. When compared with the pre-COVID-19 year 2018-19, GDP per capita increased 3.5 per cent, which is well above the average GDP per capita rate of +1.6 per cent per year since 1990–91.

The rate of population growth grew from +0.4 per cent in 2020–21 to +0.8 per cent in 2021–22. The low growth in 2020–21 is the lowest in the time series since 1990-91, and can be attributed to the Australian Government closure of the international border from 20 March 2020 in response to the COVID-19 pandemic. The border was not fully re-opened until 21 February 2022, and in 2020–21 it contributed to a net population loss of around 85,000 people as more people migrated out of the country than into it (the second lowest annual net migration since 1861) ((ABS 2022); Australian Government 2022)[6].

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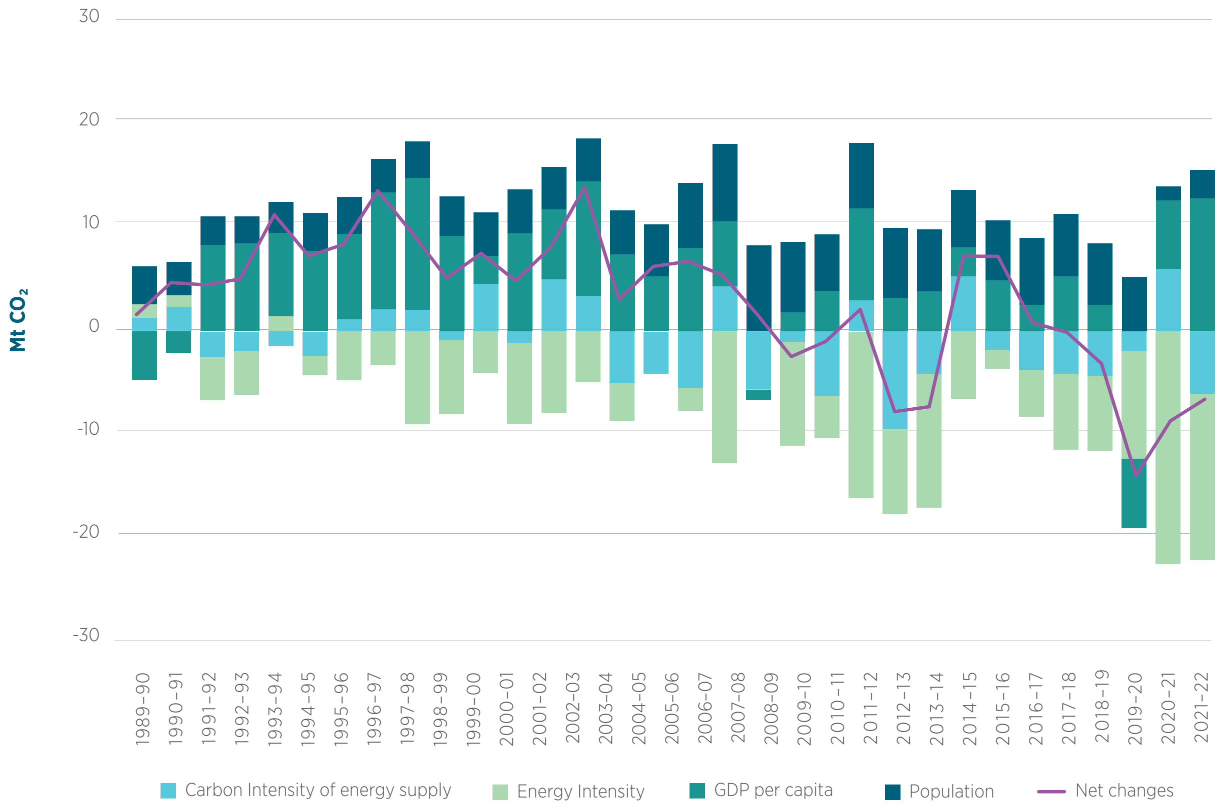
[6] Historically, more people migrate to Australia than migrate away each year, meaning overseas migration has been a significant source of population gain for Australia rather than loss. In 2020-21, approximately 145,900 people migrated into Australia whereas approximately 230,900 people migrated out of Australia. (ABS 2022).

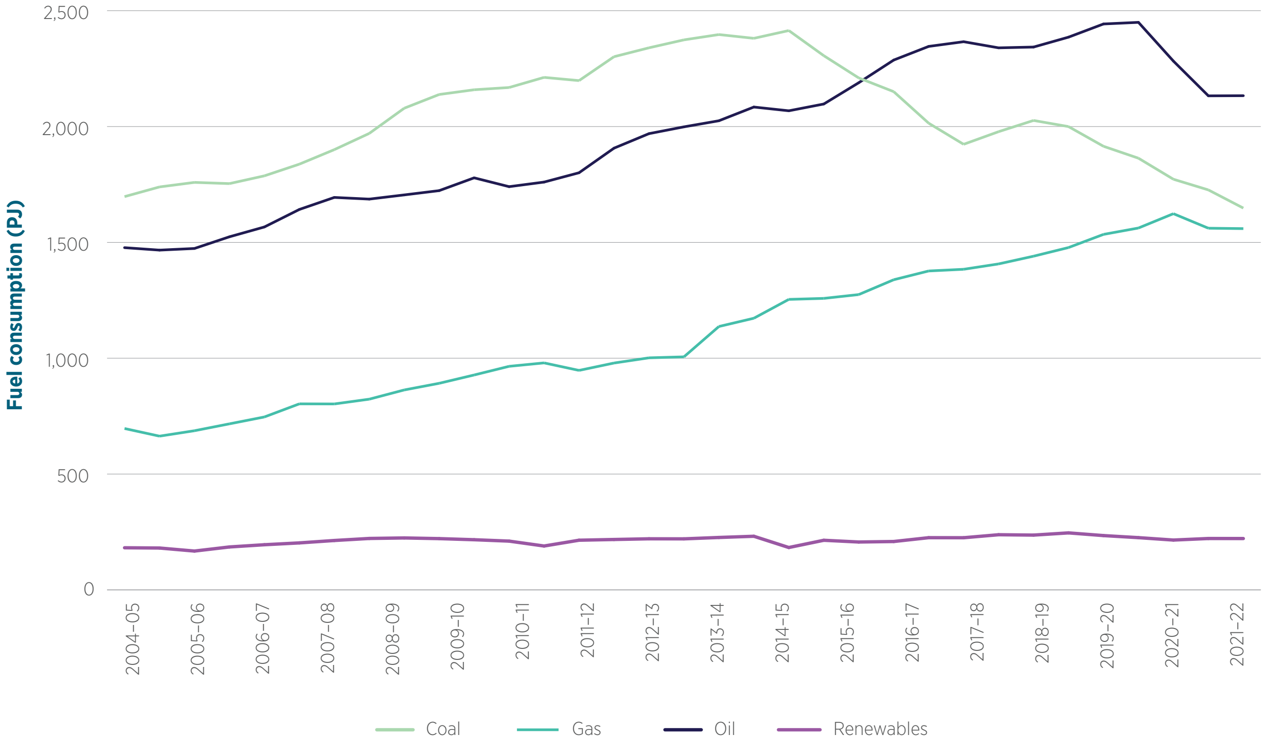
The energy intensity of the economy decreased in 30 of the 33 years at varying annual rates reflecting energy efficiency improvements and structural change in the economy towards less energy intensive service sectors. The emissions (carbon) intensity of energy supply has fluctuated over the time series however there has been a declining trend since 2004–05 as the proportion of electricity generation from coal has declined (see Figure 3.11 for more details).

Figure 2.12 Annual change in CO_2 emissions from fuel combustion and IPPU from underlying drivers, Australia, 1990–91 to 2021–22, Mt CO_2



This trend is reflected in the fuel switching evident in the observed choice of fuel for energy consumption (Figure 2.13). Over the period 1989–90 to 2008–09, consumption of coal, oil and natural gas (for fuel combustion) increased. From 2008–09, oil and gas consumption continued to grow, driven by the transport and electricity sectors. In contrast, coal consumption has largely continued to decline since 2008–09. In 2021–22, coal consumption was 31.7 per cent below its 2008–09 peak level of 2,414 PJ. Oil consumption in 2021–22 fell 12.9 per cent by 2021–22 when compared to its peak in 2018–19, largely driven by reduced use in the transport sector during the COVID-19 pandemic.

Figure 2.13 Energy consumption by fuel type, Australia, PJ, 1989-90 to 2021-22



Source: (DCCEEW 2023): Australian Energy Statistics Table D

The Kaya analysis considers a subset of Australia's total emissions. At the national level, increases in CO_2 emissions from fuel combustion and IPPU have been offset by declines in other emissions sources. Figure 2.14 expands the decomposition to include other emissions sources as a fifth driver of total emissions (equation 2.2). This analysis does not attempt to break down other emissions into underlying drivers such as energy consumption, population or GDP growth which have less of an effect on these types of emissions.

Total CO_2 emissions from fuel combustion and IPPU fell by 1.8 per cent in 2021–22 compared to 2020–21, or by 2.5 per cent on a per capita basis. Similarly, carbon intensity improved by 1.6 per cent.

Changes in other emissions sources generally have a downward impact on total emissions; however, annual changes are subject to considerable variation.

Equation 2.2: $$\text{Total emissions} = P \times \frac{GDP}{P} \times \frac{Energy}{GDP} \times \frac{CO_2}{Energy} + \text{other emissions sources}$$

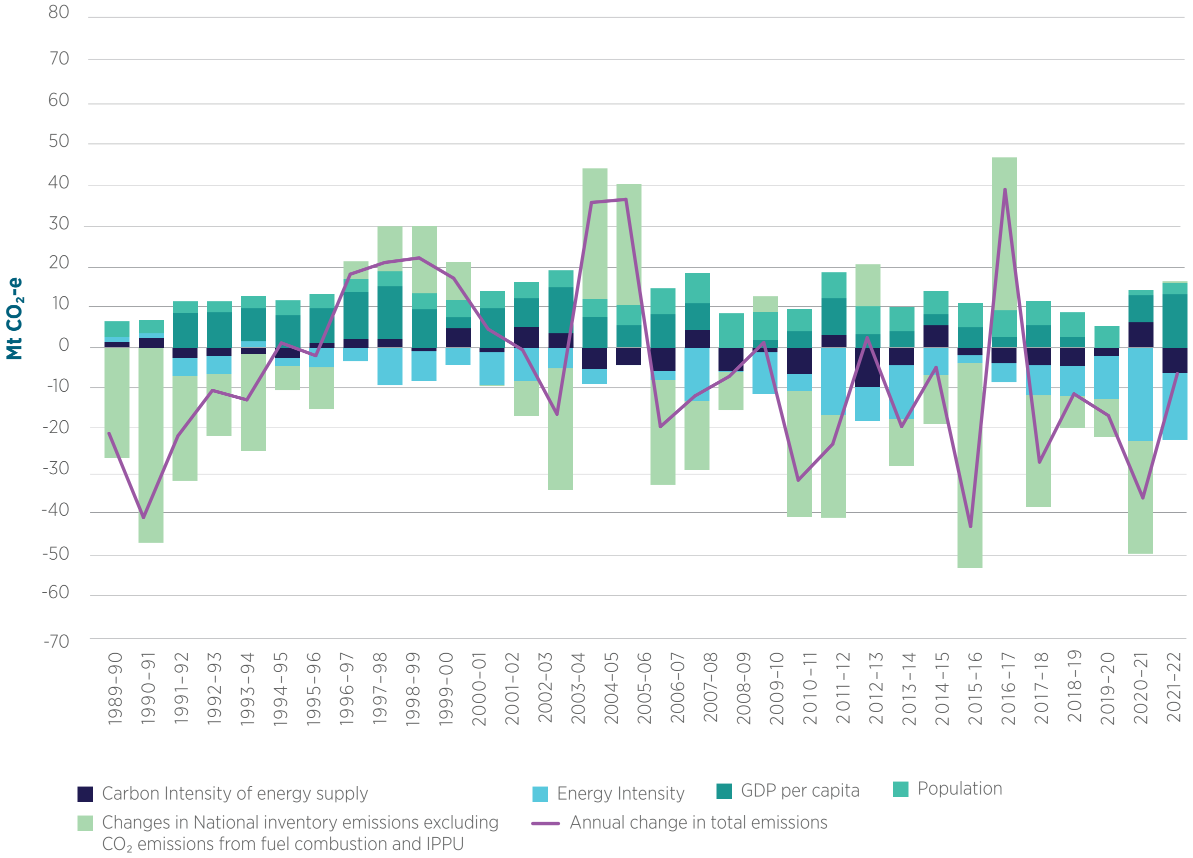
Where P = Population

GDP = Gross domestic product (Chain volume measures, $ millions)

Energy = Total net energy consumption (PJ)

CO_2 = Mt CO_2-e emissions from fuel combustion and IPPU

Figure 2.14 Annual change in total emissions from underlying drivers, Australia, 1989–90 to 2021–22, Mt CO_2-e



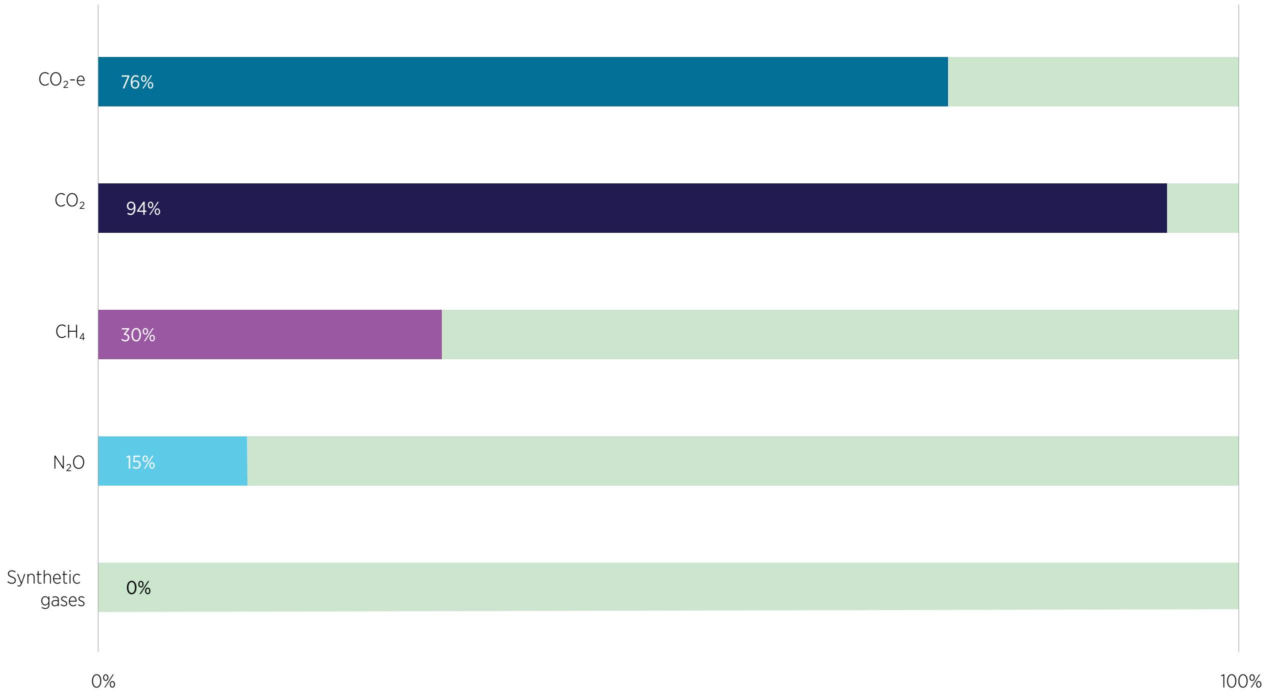
(a) Note that "changes in agriculture, LULUCF and waste emissions" in this graph refers to changes in the sum of non-CO_2 emissions from fuel combustion and IPPU, and total emissions from the fugitive emissions, agriculture, LULUCF, and waste sectors. That is, the national inventory total with the CO_2 emissions from fuel combustion and IPPU excluded.

3. Energy

3.1 Overview

The *energy* sector is Australia's largest source of emissions, largely emitted as CO_2 from fuel combustion activities such as electricity generation and transportation. This sector is the second largest source of methane emissions, with the majority comprised of fugitive emissions from coal, oil, and gas extraction and processing. The energy sector as a portion of total emissions (excluding LULUCF) is presented in Figure 3.1.

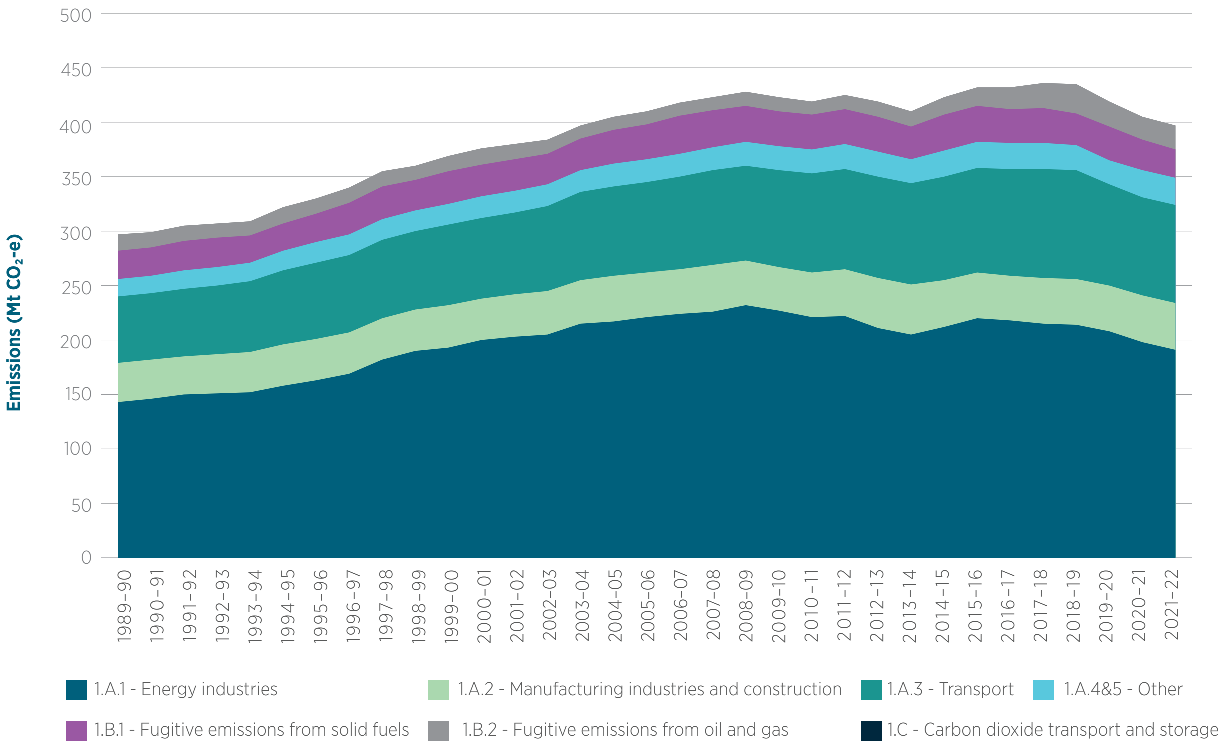
Figure 3.1 Share of national emissions (excluding LULUCF) for the energy sector by gas, 2021–22



Note: Synthetic gases refers to SF_6, NF_3, HFCs, and PFCs.

The full time series of energy emissions by subsector are presented in Figure 3.2. Energy industries (which includes electricity generation) is the largest contributor to total energy emissions, followed by transport, and fugitive emissions from fuels.

Figure 3.2 Energy emissions by subsector, 1989–90 to 2021–22



Changes in emissions by energy subsector in 2021–22 since 1989–90, 2004–05, and 2020–21 are shown in Figure 3.3. Tables of energy emissions by subsector and by gas are presented in NIR Volume 2, Annex 5.8. Decreases in the most recent years have been largely driven by ongoing COVID-19 pandemic impacts and the continuing decrease in the emissions intensity of electricity generation.

Figure 3.3 Comparison of 2021–22 emissions with past emissions levels from key energy subsectors, million tonnes of carbon dioxide equivalent (Mt CO_2–e) and percentage change (%)

		Change in 2021–22 emissions since:		
Energy Subsectors	**2021–22 emissions**	**1989–90**	**2004–05**	**2020–21**
1.A.1 Energy industries (including electricity)	**191 Mt**	▲ +34% +48 Mt CO_2-e	-25 Mt CO_2-e ▼ -12%	-7 Mt CO_2-e ▼ -3%
1.A.2 Manufacturing Industries and Construction	**43 Mt**	▲ +19% +7 Mt CO_2-e	▲ +4% +2 Mt CO_2-e	-0.1 Mt CO_2-e ▼ -0.1%
1.A.3 Transport	**90 Mt**	▲ +46% +28 Mt CO_2-e	▲ +9% +8 Mt CO_2-e	-0.3 Mt CO_2-e ▼ -0%
1.A.4&5 Other	**25 Mt**	▲ +50% +8 Mt CO_2-e	▲ +18% +4 Mt CO_2-e	-0.1 Mt CO_2-e ▼ -0%
1.B Fugitive emissions from coal, oil, and gas	**48 Mt**	▲ +19% +8 Mt CO_2-e	▲ +12% +5 Mt CO_2-e	-1 Mt CO_2-e ▼ -1%
1.C Carbon dioxide transport and storage	**<0.1 Mt**	–	–	<-0.01 Mt CO_2-e ▼ -85%

Note: Icons in this figure are sourced from Geotata, adi_sena, Freepik, and Creatype on flaticon.com.

3.2 Fuel Combustion (CRT category 1.A)

The Fuel Combustion category is comprised of the combustion of fossil fuels and biomass to produce thermal energy for stationary and mobile sources. Emissions from the combustion of solid, liquid, and gaseous fuels for energy use have been identified as key sources in Australia's inventory and, along with biomass, are presented in Figure 3.4.

Figure 3.4 Energy emissions by fuel type, 1989–90 to 2021–22

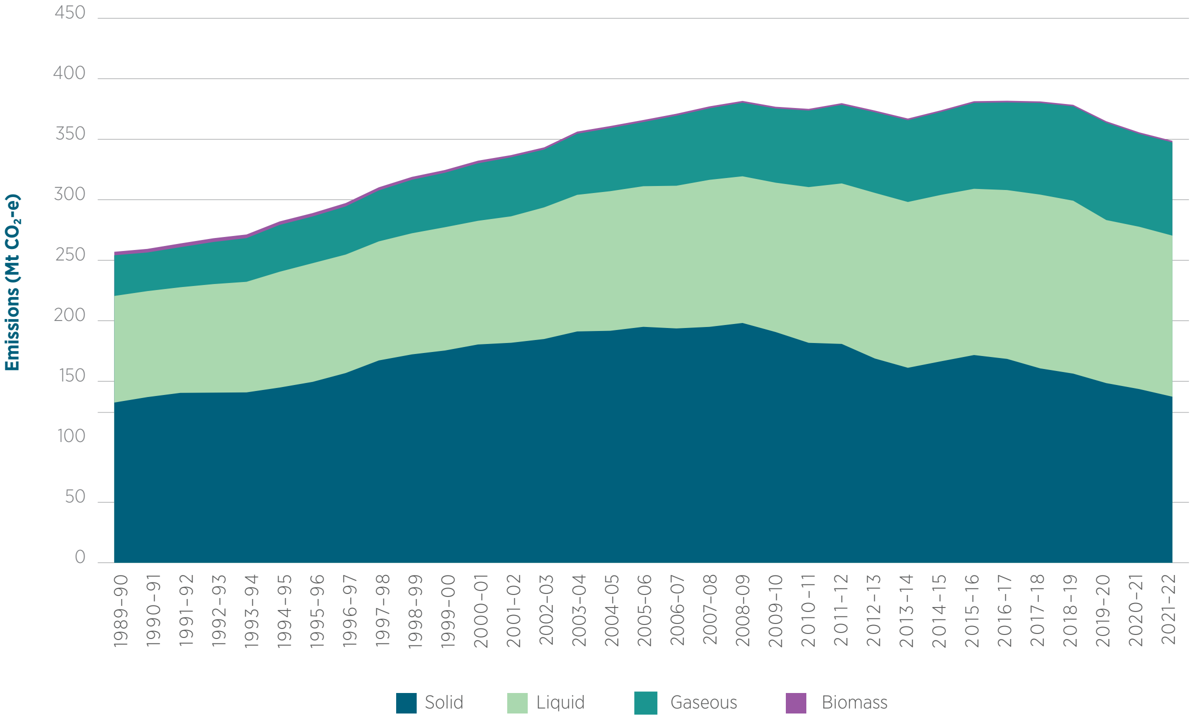
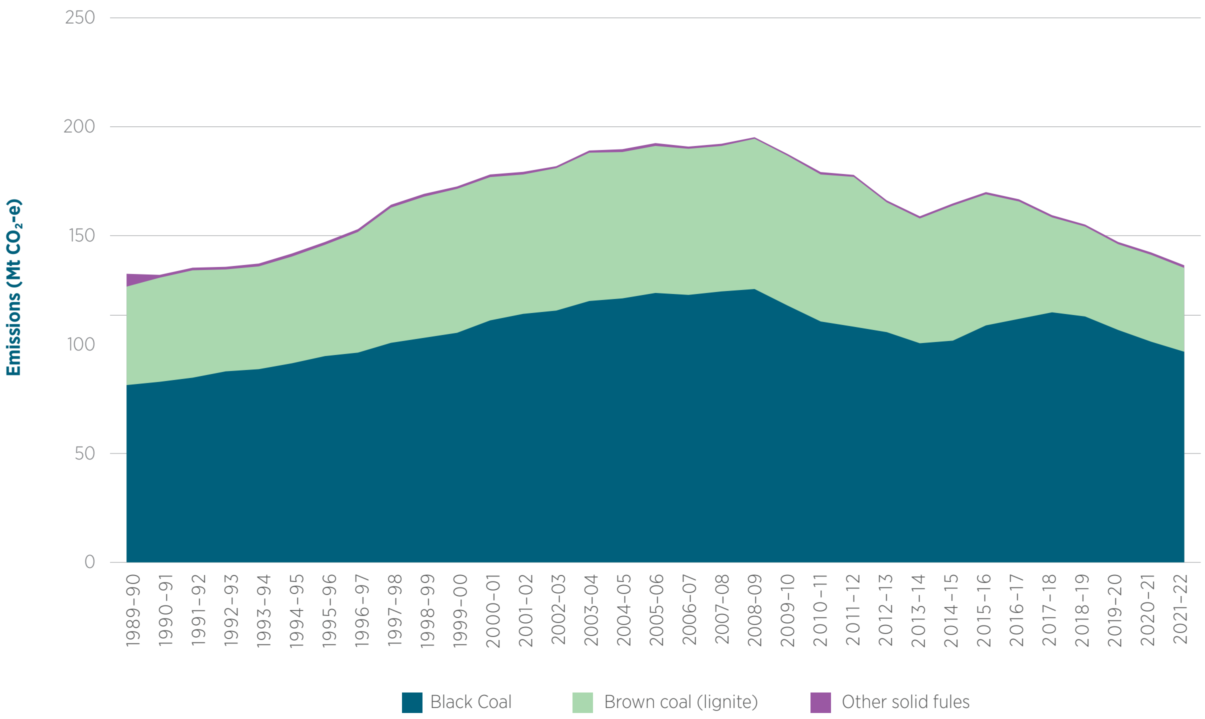


Figure 3.5 presents emissions from solid fuel use over time for black coal, brown coal, and other solid fuels. Emissions from black coal consumption have decreased since 2008–09 as this fuel is substituted for gas and renewable energy sources such as wind, solar and hydro. One third of brown coal generating capacity has been decommissioned since 2013–14 (GA 2022).

Figure 3.5 Emissions from solid fuel combustion, 1989–90 to 2021–22

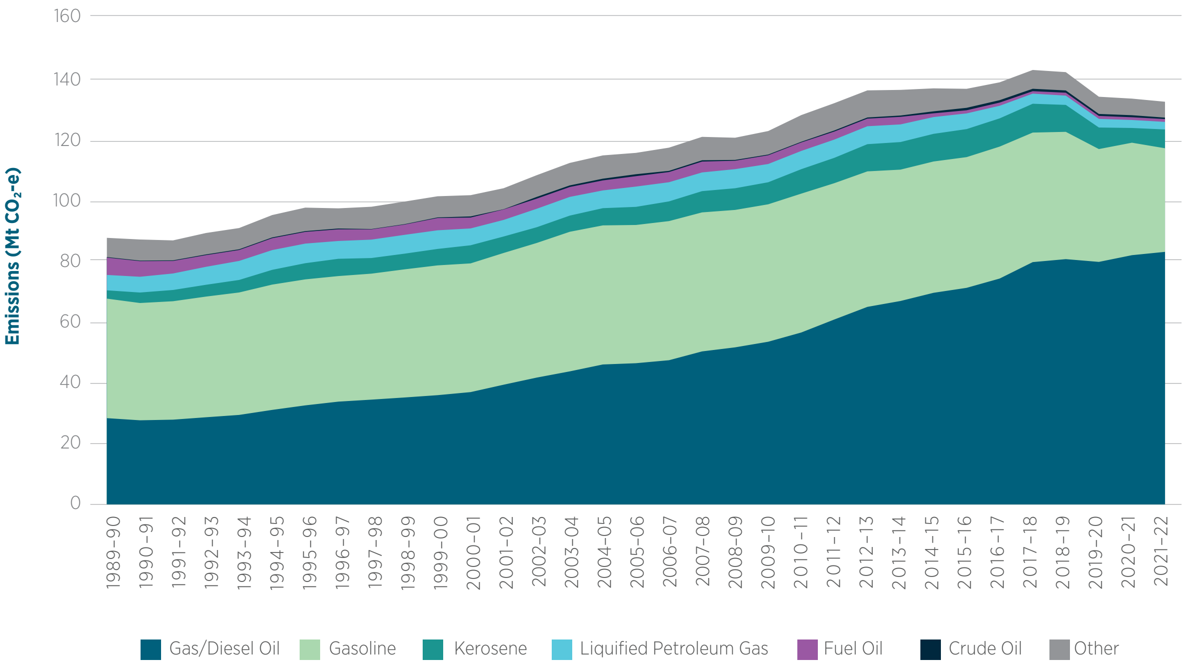


Note: 'Other solid fuels' includes coking coal, black coal by-products, brown coal briquettes, coke oven coke, and recycled materials.

The transport sector is the main source of emissions from liquid fuels. Trends in liquid fuels emissions follow consumption patterns in the transport sector.

The growth in emissions from the combustion of liquid fuels is comprised of an increase in diesel consumption (Figure 3.6). The underlying reasons for this growth include the population and economically driven increase in the road transport fleet, a shift in the vehicle fleet away from petrol towards diesel fuelled vehicles and the demand for diesel in the resources sector.

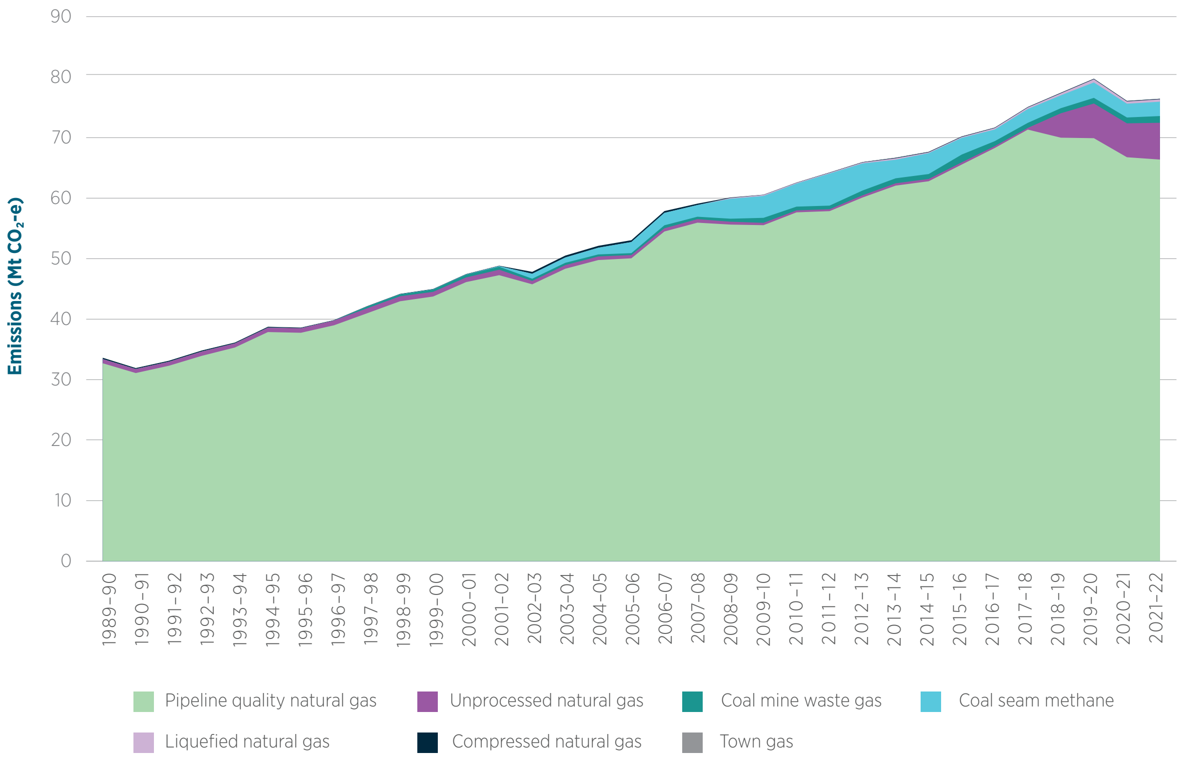
Figure 3.6 Emissions from liquid fuel combustion, 1989–90 to 2021–22



In Australia, the majority of gaseous fuels are consumed within the electricity generation and oil and gas extraction sectors, with more recent growth attributed to the liquified natural gas export industry.

Pipeline-distributed natural gas was the most significant gaseous fuel combusted throughout the time-series. There has been an increasing amount of coal seam methane and unprocessed natural gas consumed predominantly in the oil and gas extraction and electricity generation sectors with a corresponding reduction in pipeline natural gas (Figure 3.7). The decrease in emissions in 2021–22 corresponds to a 10 per cent decrease in natural gas fired generation, reaching its lowest level in the time series, largely due to a rapid increase in renewable electricity generation.

Figure 3.7 Emissions from gaseous fuel combustion, 1989–90 to 2021–22



The methodologies for estimating emissions from fossil fuel combustion are described in this chapter.

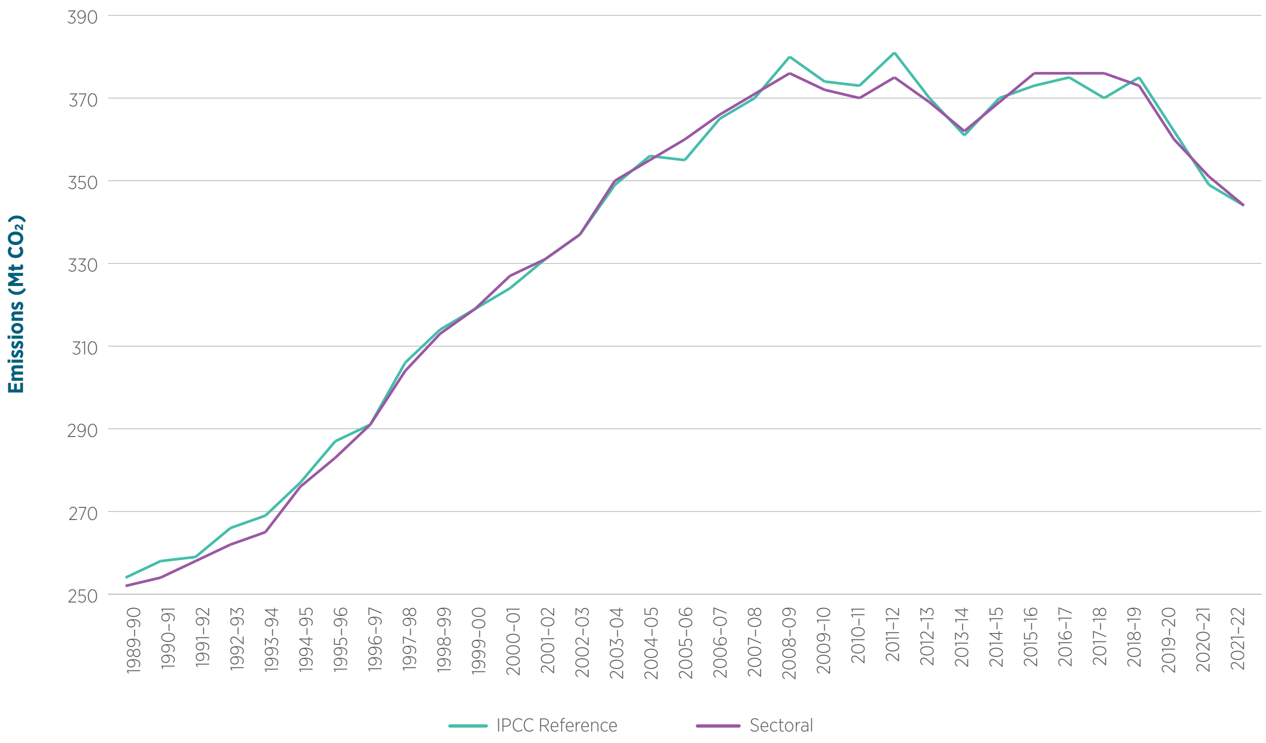
The primary data sources for fuel combustion emissions and activity data are the Australian Energy Statistics (AES) (DCCEEW 2023) and data collected under the mandatory National Greenhouse and Energy Reporting scheme, which are described in more detail in NIR Volume 2, Annexes 5.1 and 5.2.

3.2.1 Comparison of the sectoral approach with the reference approach (CRT categories 1.AA and 1.AB)

In accordance with the 2006 IPCC Guidelines (volume 2, chapter 6) (IPCC 2006), Australia estimates its CO_2 emissions from fuel combustion using a top-down reference approach independent of the sectoral approach used in CRT category 1.AA. Whilst these two approaches are not expected to match each other, significant differences between the reference and sectoral approaches may indicate problems in inventory data.

AES and APS (Australian Petroleum Statistics) datasets are used to estimate Australia's energy balance for production, imports, exports, and stock changes (DCCEEW 2022, 2023). The difference between the reference approach and the sectoral approach at the total level is within 2 per cent for all years. However, the differences between the reference approach and the sectoral approach for specific fuel types does exceed 2 per cent for some years. The main reason for the differences in petroleum fuels relates to the sensitivity of final apparent consumption and emissions to the average density and energy content values used to convert production, exports, imports, and stock changes from volume/mass units into energy units. Other minor differences can be attributed to the derived implied emission factors used by the reference approach and the different reporting techniques and categories used by the publications used for activity data.

Figure 3.8 Fuel combustion emissions under the sectoral and reference approaches, 1989–90 to 2021–22



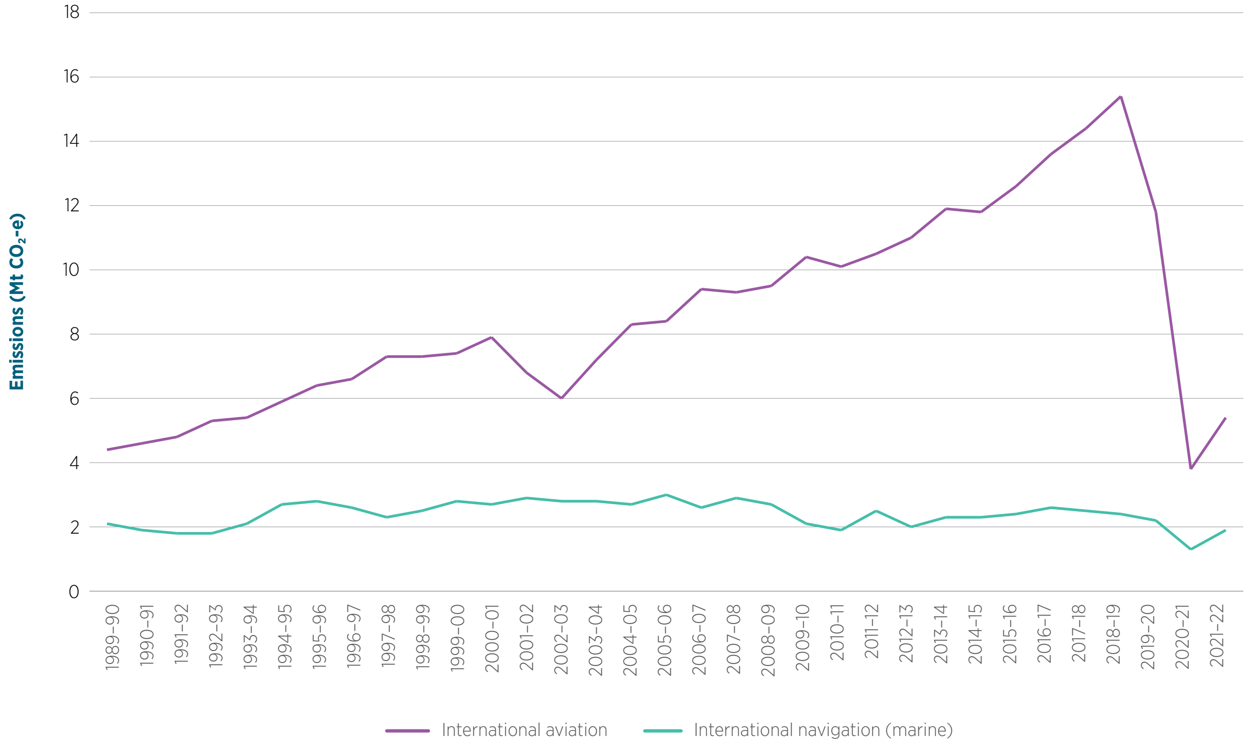
3.2.2 International Bunker Fuels (CRT category 1.D.1)

The 2006 IPCC Guidelines require emissions from international aviation and marine bunkers to be reported separately to the national total emissions from the energy sector (IPCC 2006). They are instead reported as memo items (CRT table 1.D.1) and are used in the carbon balance and in the reference approach (CRT Table 1.A(b)) as a quality control tool.

Activity data for both international marine and aviation bunkers are estimated using the annual Australian Energy Statistics (DCCEEW 2023). Differentiation between international and domestic fuel consumption is made according to fuel sales data collected according to deliveries to domestic and international airport terminals and the tax treatment of marine bunker fuels.

Emissions from international aviation increased by 40 per cent in 2021–22 when compared with the previous year as activity increased after the lifting of border lockdowns and restrictions on movement in place during the COVID-19 pandemic (Figure 3.9). Despite this large year-on-year increase, emissions from international aviation remain well below the long-term trend. The Australian Government closed the borders to most international travel to and from Australia between March 2020 and February 2022, which significantly reduced international aviation activity and emissions from 2019–20 to 2021–22.

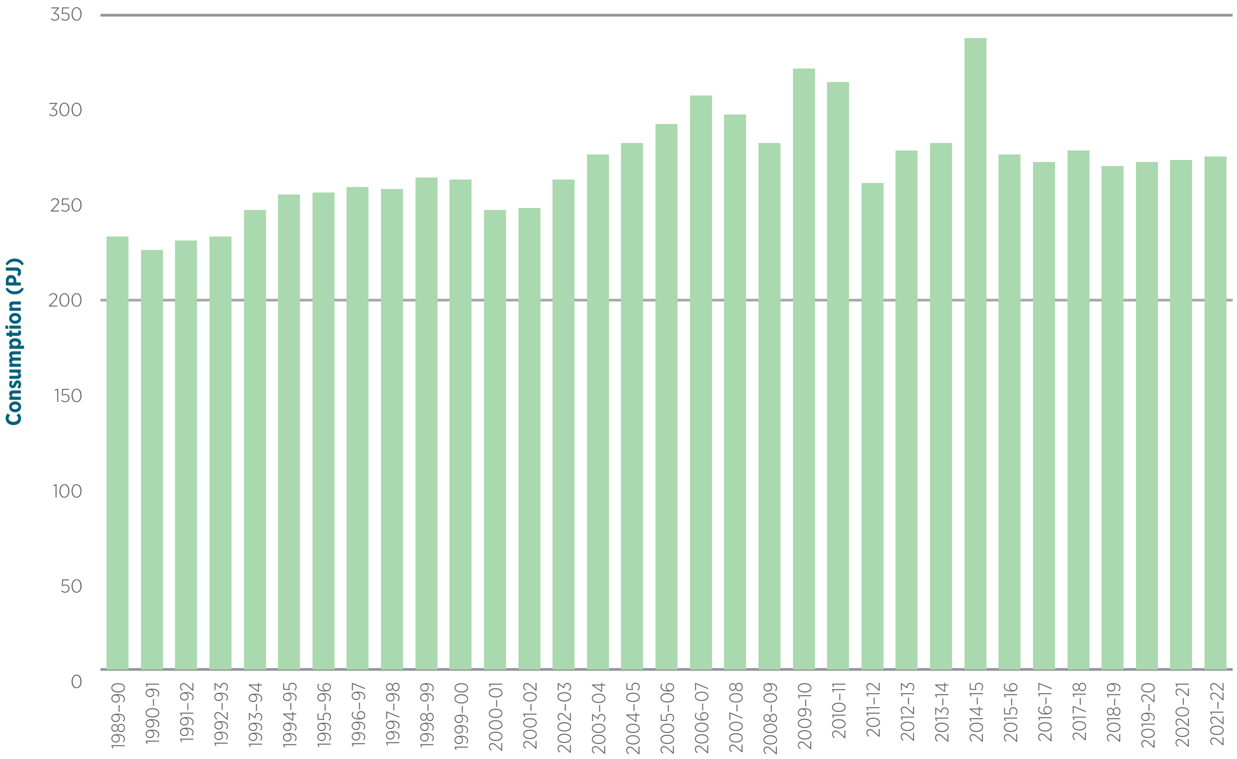
Figure 3.9 Emissions associated with international bunker fuels, 1989–90 to 2021–22



3.2.3 Feedstocks and non-energy use of fuels (CRT category 1.AD)

This category includes excluded carbon, which includes both stored carbon and carbon used and emitted as CO_2 in other sectors. The total consumption of these fuels per year is presented in Figure 3.10.

Figure 3.10 Consumption of non-energy uses of energy products, petajoules, 1989–90 to 2021–22



Source: *Australian Energy Statistics 2023*, DCCEEW

Activity data and emissions associated with the non-energy use of fuels are not reported within the fuel combustion subsector. In accordance with the 2006 IPCC Guidelines, they are reported under the *industrial processes and product use* sector and *fugitive emissions from fuels* subsector as follows (IPCC 2006):

Reported in industrial processes and product use

- Coke and natural gas where used as a reductant in the integrated coke/iron and steel production – reported in 2.C.1 Iron and Steel Production;
- Pulverised black coal where used as a reductant in the integrated coke/iron and steel production – reported in Iron and Steel Production;
- Black coal where used as a reductant in synthetic rutile production – reported in 2.B.6 Chemical Industry Titanium Dioxide Production;
- Black coal, coke, petroleum coke and fuel oil where used as a reductant in base metal production – reported in Ferroalloys Production and 2.C.7 Other;
- Petroleum coke where used as a reductant in titanium dioxide production – reported in 2.B.6 Chemical Industry – Titanium Dioxide Production;
- Petroleum coke, coal tar and coke used for anodes in aluminium production – reported in 2.C.3 Aluminium Production;
- Natural gas used as a feedstock in Ammonia production – reported in 2.B.1 Ammonia Production;
- Coke where used as a reductant in soda ash production – reported with other emissions from soda ash production in 2.B.7 Soda Ash Production; and
- Lubricants and grease consumption where used for non-energy purposes – reported in 2.D.1 Lubricant use

Reported in fugitive emissions from fuels

- Oil refinery flaring – reported in 1.B.2.a. Oil Refining/Storage; and
- Natural gas leakage – reported in 1.B.2.b Natural Gas Distribution.

3.2.4 Energy industries (CRT category 1.A.1)

3.2.4.1 Category Description

This category includes emissions from fuel combustion within electricity generation, petroleum refining and other energy manufacturing industries such as coke ovens, briquette production, coal mining, oil and gas extraction, and natural gas production and distribution.

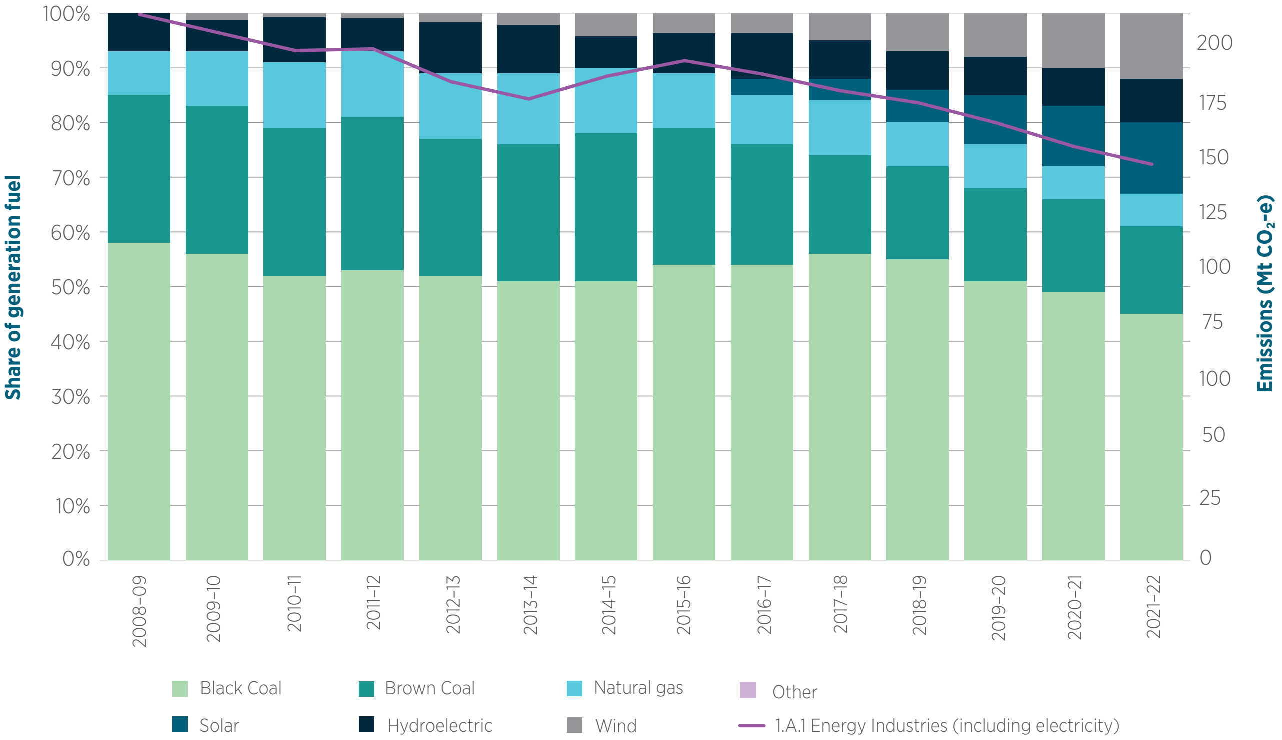
Public electricity and heat production (CRT category 1.A.1.a)

This is a key category for CO_2 emissions from solid, gaseous, and liquid fuel combustion.

Emissions from public electricity generation have increased from 1989–90 to a peak in 2008–09. Since this peak, emissions from this category have decreased despite continuing population and economic growth.

Coal remains the most-used fuel source for electricity generation in Australia. A significant scale up of renewable generation sources and system-wide energy efficiency improvements has been reducing electricity generation emissions since 2008–09. This can be observed in data from the National Electricity Market (NEM), which connects six of Australia's eastern and southern states and territories and consists of the majority of Australia's electricity consumption (DISR 2023) (Figure 3.11).

Figure 3.11 Emissions from electricity generation and shares of generation fuel since 2008–09



Source: Generation by fuel from Australia's National Electricity Market (NEM) queried using NEMReview v6

Petroleum refining (CRT category 1.A.1.b)

This is a key category for CO_2 emissions from gaseous and liquid fuel combustion. Australia uses facility-level emission factors and activity data to estimate emissions from this category.

This category is defined by the 2006 IPCC Guidelines as including all combustion activities supporting the refining of petroleum products (IPCC 2006). It does not include evaporative emissions occurring at refineries, which are reported under fugitive emissions from crude oil refining/storage (1.B.2.a.4) and flaring (1.B.2.c.2.i).

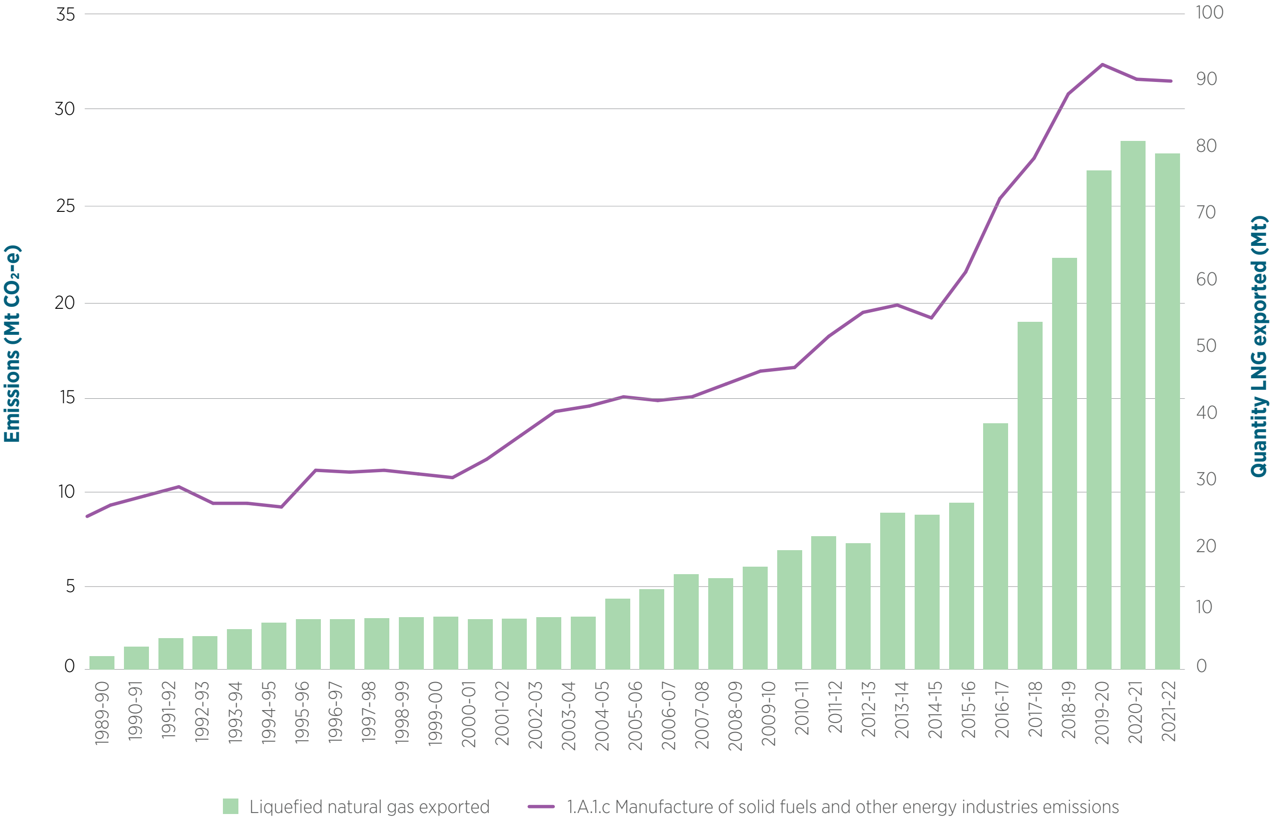
The number of refineries in operation has experienced a steep decline in recent years. Imports, largely from the Asian region, make up the difference between capacity and demand (GA 2022).

Manufacture of solid fuels and other energy industries (CRT category 1.A.1.c)

This is a key category for CO_2 emissions from solid, gaseous, and liquid fuel combustion. Australia uses country-specific emissions factors or models and a combination of facility-level and AES activity data to estimate emissions from this category.

The 2006 IPCC Guidelines describe this category as comprising combustion emissions of fuels used during the manufacture of secondary and tertiary products (IPCC 2006). Trends in this category have been dominated in recent years by the consumption of energy associated with gas extraction for the expansion of Australia's liquefied natural gas (LNG) export industry.

Figure 3.12 Emissions from the manufacture of solid fuels and other energy industries, and liquefied natural gas (LNG) exports, 1989–90 to 2021–22



Source: Exports data from Table N of the Australian Energy Statistics (DCCEEW,2023)

Manufacture of solid fuels (CRT category 1.A.1.c.i)

This category includes emissions arising from fuel combustion to produce coke, brown coal briquettes, and patent fuel.

In Australia, the production of coke in the iron and steel industry is the most significant source of emissions from this category. Brown coal briquetting has ceased production.

Other energy industries (CRT category 1.A.1.c.ii)

This category includes combustion emissions from energy industries other than the above-mentioned categories. In Australia, this is comprised of fuels combusted for coal mining and gas production and distribution.

3.2.4.2 Methodological issues

The Australian Energy Statistics report energy consumption by functional activity and classifies these to industries associated with them as a primary activity using the Australian and New Zealand Standard Industrial Classification (ANZSIC) (ABS 2006). These activities can be mapped to IPCC classifications (Table 3.1).

Table 3.1 Relationship between IPCC source categories and ANZSIC classifications: Energy Industries

	ANZSIC Subdivision		
IPCC Source Category	**Division**	**Subdivision**	**Description**
a Electricity and heat production [(a)]	D Electricity, Gas and Waste Services	26	Electricity supply
b Petroleum refining	C Manufacturing	17	Petroleum refining [(b)]
c Solid fuel transformation and other energy industries	B Mining	06	Coal mining (incl. briquette production)
	B Mining	07	Oil and gas extraction
	C Manufacturing	21	Coke ovens associated with Basic iron and steel manufacturing
	D Electricity, Gas and Waste Services	27	Gas supply

Notes:

(a) There is no public generation of distributed heat in Australia.

(b) Coal briquette manufacturing, which no longer occurs in Australia, has in historical data been reallocated to solid fuel transformation and other energy industries.

Electricity generation (CRT category 1.A.1.a)

The 2006 IPCC Guidelines define this category as converting the chemical energy stored in fuels to electrical power (IPCC 2006). Public heat production from a central point to consumers via a pipeline grid is also described, however, this activity does not occur in Australia.

Electricity generation includes both power for supply to the main electricity grids of each state or territory and all off-grid generation.

The methods and data used to estimate emissions from this source category are presented in Table 3.2.

Table 3.2 Summary of methods and emission factors: Public Electricity and Heat Production

	CO_2		CH_4		N_2O	
1.A.1.a Public Electricity and Heat Production	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**
Liquid Fuels	T2	CS	T2	CS	T2	CS
Solid Fuels	T2	PS,CS	T2	CS	T2	CS
Gaseous Fuels	T2	PS,CS	T2	CS	T2	CS
Biomass	T2	CS	T2	CS	T2	CS

T1 = tier 1, T2 = tier 2, CS = country specific, PS = plant specific, NO = not occurring, NA = not applicable, 🟪 = key category

Choice of emission factors

A tier 2 approach is used for the key category of electricity generation in which EFs for fuels such as coal vary by source and over time.

Data is collected from power stations through the National Greenhouse and Energy Reporting (NGER) scheme. Under this scheme, facilities over certain thresholds are required to submit annual data on fuel consumption, fuel energy content, fuel EFs (incorporating oxidation factors), emission estimates and the amount of electricity generated and sent out to the Clean Energy Regulator. Power stations must sample and analyse their primary solid and gaseous fuels in accordance with the requirements and standards listed in the *National Greenhouse and Energy Reporting (Measurement) Determination 2008* (Cwlth) (the Determination). The adoption of these methods and standards ensures accuracy and comparability in the facility specific information reported. This data provides facility specific energy content and EFs for the solid and gaseous fuels consumed in each power station.

Prior to the establishment of the NGER scheme, methods for estimation were provided by the Generator Efficiency Standards program – as detailed in the *Generator Efficiency Standards Technical Guidelines* (AGO 2006). The adoption of consistent methods in the NGER scheme and the Generator Efficiency Standards program ensured time series consistency in the emission estimates in the national inventory.

Country-specific EFs are utilised for minor (mainly liquid) fuels.

Activity data

NGER scheme data are received from all large and medium sized power stations in Australia. These data are currently available for around 140 fossil-fuel-based power stations in Australia. The energy use of small power stations that do not meet the NGER scheme reporting thresholds are estimated as the difference between the total of reported values under the NGER scheme and Australian Energy Statistics for ANZSIC subdivision 26. This approach has been adopted throughout the time series. Therefore, the improved coverage of power stations under the NGER scheme does not alter the method for estimating total fuel consumption in this sector. The coverage of individual coal power station NGER scheme data is comprehensive and has displaced the necessity to use AES data to inform coal activity data.

Oxidation factors and the emission factors are linked in that coal power station operators report CO_2 emission factors including the effects of oxidation based on analysis of ash contents in accordance with the NGER scheme. In such cases applying an additional oxidation factor would double-count the effect of incomplete combustion, so an oxidation factor of 100 per cent is used. The NGER scheme requires emission factors reported by generators to use a default oxidation factor of 100 per cent unless measurements are undertaken to support an alternative value.

Emissions from landfill gas captured for combustion for electricity generation are reported in this subsector. CH_4 and N_2O are included in the energy industries aggregates, while CO_2 emissions are included in the memo item on CO_2 emissions from biomass (CRT category 1.D.3) in accordance with IPCC Guidelines on the treatment of CO_2 emissions from biogenic fuels.

Petroleum refining (CRT table 1.A.1.b)

The 2006 IPCC Guidelines (Volume 2) describe that, in a petroleum refinery, crude oil is converted into a broad range of products (IPCC 2006). Part of the energy content of the products obtained from transformation of crude oil is used at the refinery, complicating the derivation of activity data from energy statistics. As such, it is considered good practice to obtain fuel consumption from the refinery industry to verify the appropriate values reported by energy statistics.

The main fuels used by petroleum refineries are refinery gas/liquids and natural gas, with minor use of other liquids fuels. The combustion of refinery coke is also included under Petroleum Refining 1.A.1.b. The Australian Energy Statistics (AES) reports refinery feedstocks as energy outputs, comprising crude oil combined with other undefined petroleum products (DCCEEW 2023). The various market petroleum products are also shown as energy outputs. The total energy content of the products produced by the sector is less than the energy content of the petroleum input, with the difference being energy consumed by the refining processes (such as distillation, catalytic cracking, etc.). The fuel from which petroleum refining energy consumption is derived is obtained from the crude oil input (referred to in the AES as refinery fuel).

The methods and data used to estimate emissions from this source category are presented in Table 3.3.

Table 3.3 Summary of methods and emission factors: Petroleum Refining

	CO_2		CH_4		N_2O	
1.A.1.b Petroleum Refining	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**
Liquid Fuels	T2	PS	T2	CS	T2	CS
Gaseous Fuels	T2	PS	T2	CS	T2	CS
Other Fossil Fuels	T2	PS	T2	CS	T2	CS

T1 = tier 1, T2 = tier 2, CS = country specific, PS = plant specific, NO= not occurring, NA = not applicable, ■ = key category

Choice of emission factors

Facility-specific emission factors for refinery gas and liquids, refinery coke, and natural gas are sourced from NGER scheme data for all currently operating petroleum refineries.

In line with the relevant decision tree (2006 IPCC Guidelines, Volume 1, Figure 1.2), PS EFs are used for all refineries (IPCC 2006). It is recognised that refinery EFs for these fuel types are strongly linked with the specific technology types and process configurations inherent in individual refineries.

Activity data

The refinery fuel balance contained in the AES is analysed using a model that examines the expected refinery plant efficiency in the conversion of crude oil to final products, considering factors such as the change to low sulphur diesel. The model is used to derive refinery fuel consumption for the years 1999–00 to 2007–08. This is in response to QC analysis demonstrating that the AES petroleum refining data does not provide representative activity data using an input/output balance method for that period.

The 2006 IPCC Guidelines are ambiguous as to where emissions from refinery coke should be reported (IPCC 2006). Detailed fuel consumption data was made available via the NGER scheme for all Australian oil refineries from 2008–09 onwards. Refineries captured under the NGER scheme use methodologies involving measurement of flue flow rates, flue gas composition, and reference to the *Fluid Catalytic Cracking* handbook used by the industry. These data report the combustion of refinery gas/liquids and the burning of refinery coke to restore the activity of the catalyst during the refining process separately. Given this level of disaggregation was unavailable in data covering 1989–90 to 2007–08, refinery fuel use of gas/liquids and refinery coke continue to be reported together for 2008–09 onwards to maintain time series consistency.

Consistent with the 2006 IPCC Guidelines, flaring at refineries is reported under 1.B.2.c.2.i flaring of oil (IPCC 2006).

Implied Emission Factor

NGER scheme plant specific data shows that the total gaseous fuel IEF for petroleum refining fluctuates through the time series. These fluctuations are caused by reported fuel categories and related plant specific emission factors and plant closures.

"Other gaseous fuels" reported under the NGER scheme are included under the "other fossil fuel" IPCC category to allow a comparable natural gas IEF to be estimated. Manufacture of Solid Fuels and Other Energy industries (CRT category 1.A.1.c)

Manufacturing industries involve converting raw materials into products. This comprises the following subsectors:

- Coke Oven Operation,
- Briquetting,
- Coal Mining,
- Oil and Gas Extraction,
- Other Transport Services and Storage, assumed to be gas pipeline transport, and
- Gas Supply.

Emissions are estimated according to the general methods provided in Annex 5.3.1 and is presented in Table 3.4.

Table 3.4 Summary of methods and emission factors: Manufacture of Solid Fuels and Other Energy Industries

	CO_2		CH_4		N_2O	
1.A.1.c Manufacture of Solid Fuels and Other Energy Industries	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**
Liquid Fuels	T2	CS	T2	CS	T2	CS
Solid Fuels	T2	CS	T2	CS	T2	CS
Gaseous Fuels	T2	CS	T2	CS	T2	CS
Biomass	T2	CS	T2	CS	T2	CS

T1 = tier 1, T2 = tier 2, CS = country specific, PS = plant specific, NO= not occurring, NA = not applicable, ■ = key category

The *Coke Oven Operation* subsector is effectively a subsidiary activity of the iron and steel industry but is classified by the IPCC as an energy transformation industry and hence is reported separately. This subsector is both a consumer of black coal and coal by-products and a producer of coke and coal by-products. Consequently, fuel combustion is calculated by deducting derived fuels produced by the sector from energy inputs. Additional information is provided to improve the transparency of activity data for the black coal/coke oven gas fuel mix consumed in 1.A.1.c Manufacture of Solid Fuels and Other Energy Industries sector. The percentage of black coal/coke oven gas fuel mix is presented in Table A5.3.2.25.

The *Gas Production and Distribution* sector is also one of the energy transformation industries, manufacturing town gas up until 2011–12 from both natural gas and LPG. Fuel consumption consists of:

- natural gas and LPG used to make town gas; and
- other gas (including both natural gas and town gas) used by the industry for its own purposes.

The quantity of town gas produced is shown as an energy output of the sector in the Australian Energy Statistics (DCCEEW 2023).

It is assumed that all LPG is converted to town gas, and none is combusted in the conversion process. LPG consumption was therefore offset in full against an equal quantity (in terms of energy content) of town gas produced. The remaining town gas production was subtracted from total natural gas consumption.

Methane emission factors in the *oil and gas extraction* category for four-stroke rich burn/lean burn engines were taken from US EPA (AP-42) and weighted in the proportions observed by Zimmerle, et al. (2020) in the US industry to derive a single methane emission factor for reciprocating engines of 404.61 t CH_4/PJ for use in the Australian inventory.

In accordance with the 2006 IPCC Guidelines, fugitive emissions associated with gathering and boosting stations are reported under 1.B.2.b.2 (IPCC 2006).

3.2.4.3 Uncertainty assessment and time-series consistency

The tier 1 uncertainty analysis in Annex II provides estimates of uncertainty according to IPCC source category and gas.

Time series variability of implied emissions factors are influenced by changes in the fuel mix within categories, and changes of facility specific fuel emissions factors. Notable examples of where such variations occur in CO_2 implied emissions factors for energy industries (1.A.1) are set out below:

Public electricity (CRT category 1.A.1.a)

Liquid fuels: variations occur in the implied emission factor over the time series due to changes in the proportions of Fuel Oil and Diesel Oil in the liquid fuel mix. These fuels have consumption variability year on year as they are generally used for unscheduled and off-grid electricity generation.

Biomass: combustion for electricity consists of a growing proportion of biogas from landfill. Biogas has a relatively low CO_2 emission factor compared to other biomass fuel, hence Australia's CO_2 biomass implied emission factor is relatively low.

Petroleum refining (CRT category 1.A.1.b)

Liquid fuels: variations in the implied emission factor of around 2 per cent are evident since 2007–08. Facility-specific emission factors obtained from the NGER scheme are used, noting that Australia has a small number of refineries. The implied emission factors vary depending on the liquid fuel mix used and the refinery processes undertaken in the year.

Manufacture of solid fuels and other energy industries (CRT category 1.A.1.c)

Solid fuels: the implied emission factor declines by 10 per cent between 1989–90 and 2000–01. This results from fuel switching from black coal (90 Gg/PJ) to the lower emissions intensive coke oven gas (37 Gg/PJ).

3.2.4.4 Category-specific QA/QC and verification

Results for the reference approach for the *energy* sector, reported in Chapter 3.2.1, and the carbon reconciliation reported in Annex 4.8, provide quality control checks for this sector.

Fuel and generation data for 1.A.1.a *public electricity* are compiled by the Department from NGER scheme data and from Australian Energy Statistics energy data. Activity and emission input data is fully reconciled against the emission outputs to ensure the accurate reporting in this sector.

Fuel and generation data are also checked and reconciled against alternative data sources compiled by the Energy Supply Association of Australia (ESAA) and the Australian Energy Market Operator (AEMO) (ESAA 2005–2015). These comparisons confirm the consistency of the estimates to a high level of accuracy and show that all energy/carbon has been accounted for.

3.2.4.5 Category-specific recalculations

The recalculations reported in the current submission are shown in Table 3.5, and include:

A. **Updates to the Australian Energy Statistics**

   Australia's official statistics on energy production and use receives periodic updates to support improved understanding of Australia's energy systems, including for time series consistency. These updates are reflected in the inventory.

B. **Landfill gas emission factor change**

   Minor recalculations to CH_4 and N_2O emissions from the combustion of Landfill biogas in energy industries have been made due to facility level corrections to emission factors for a small number of facilities.

Table 3.5 Energy Industries: recalculation of total CO_2–e emissions, 1989–90 to 2020–21

	2023 Submission	2024 submission	Change		Reasons for recalculation (Gg CO_2–e)	
Year	**Gg CO_2–e**	**Gg CO_2 -e**	**Gg CO_2 -e**	**%**	**A**	**B**
1989–90	143,172.8	143,172.8	0.0	0.0%	-	-
1994–95	158,140.2	158,140.2	0.0	0.0%	-	-
1999–00	192,519.7	192,519.7	0.0	0.0%	-	-
2004–05	216,528.1	216,528.1	0.0	0.0%	-	-
2005–06	221,026.7	221,026.7	0.0	0.0%	-	-
2006–07	224,088.0	224,088.0	0.0	0.0%	-	-
2007–08	225,886.9	225,886.9	0.0	0.0%	-	-
2008–09	232,820.8	232,466.0	-354.8	-0.2%	-354.8	-
2009–10	226,959.0	226,604.4	-354.6	-0.2%	-354.6	-
2010–11	221,003.0	220,628.4	-374.6	-0.2%	-374.6	-
2011–12	222,772.0	222,400.8	-371.2	-0.2%	-371.2	-
2012–13	211,608.4	211,400.1	-208.3	-0.1%	-208.3	-
2013–14	205,575.0	205,423.4	-151.7	-0.1%	-151.7	-
2014–15	212,312.5	212,201.7	-110.9	-0.1%	-110.9	-
2015–16	219,696.6	219,584.8	-111.8	-0.1%	-111.8	-
2016–17	218,631.0	218,445.5	-185.5	-0.1%	-179.20	-6.3
2017–18	214,859.2	214,642.1	-217.1	-0.1%	-218.95	1.9
2018–19	213,954.3	213,713.9	-240.4	-0.1%	-242.38	2.0
2019–20	207,918.8	207,669.1	-249.7	-0.1%	-260.05	10.4
2020–21	198,077.8	197,854.0	-223.8	-0.1%	-233.95	10.1

3.2.4.6 Category-specific planned improvements

Emission estimation methods are kept under review as part of Australia's commitment to continuous improvement of its national greenhouse gas inventory.

The incorporation of NGER scheme data into the Inventory is an ongoing improvement, as it is gradually included at the sub-category level to replace AES aggregated data with facility-specific activity data and emission factors.

3.2.5 Manufacturing Industries and Construction (CRT category 1.A.2)

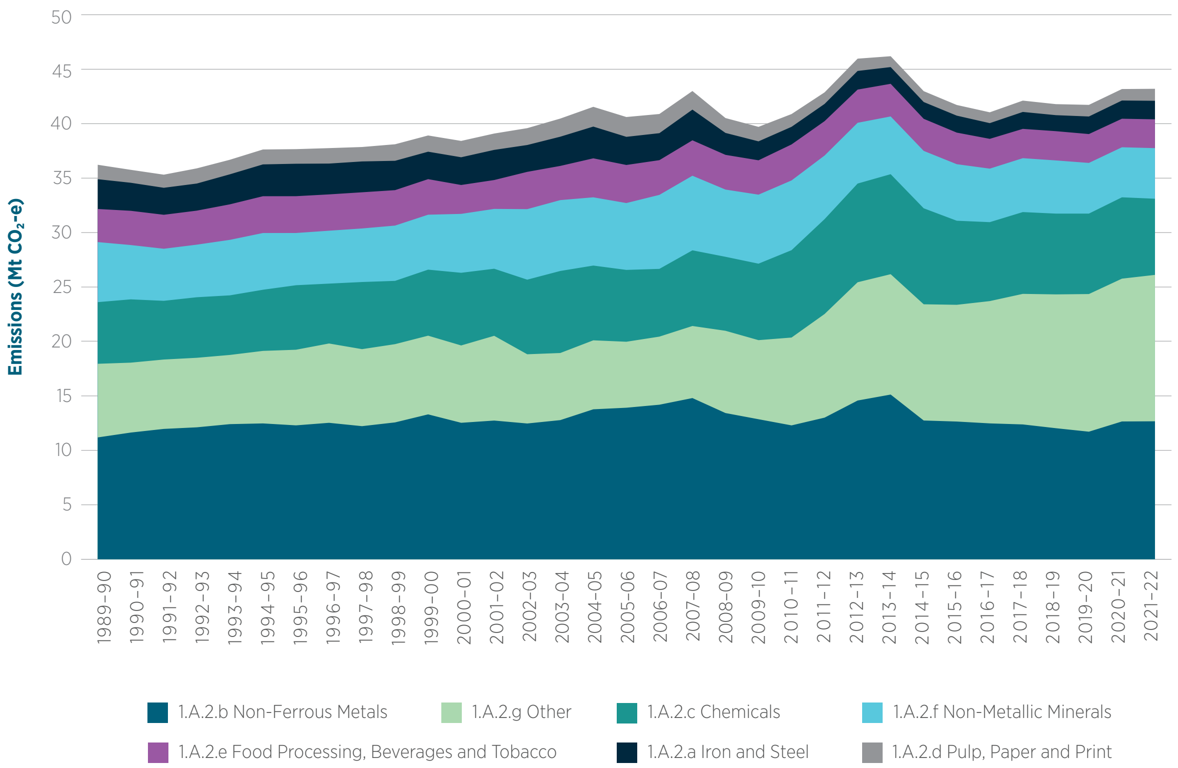
3.2.5.1 Category description

This source category includes emissions from combustion of fuels in the manufacturing and construction industries. In accordance with the 2006 IPCC Guidelines, emissions from fuel combustion in coke ovens in the iron and steel industry are reported under 1.A.1.c (IPCC 2006).

This sector includes emissions from both stationary equipment (such as cranes) and mobile equipment (such as earth moving and mining equipment).

The full time series of energy emissions by subsector are presented in Figure 3.13. Non-ferrous metals is the largest contributor to emissions from this category, followed by other (including construction, manufacturing of machinery, textiles, pulp, paper and print, mining (excluding fuels) and quarrying) and basic chemical manufacturing.

Figure 3.13 Emissions from the manufacturing and construction industries by subsector, 1989–90 to 2021–22



3.2.5.2 Methodological issues

Emissions for *manufacturing industries and construction* are estimated using tier 2 approaches with country-specific emission factors. Key categories and the further application of plant-specific emission factors are identified in Table 3.6. Emissions estimated from activity data are based on the energy consumption by industry sector and fuel type. CO_2 EFs are country-specific and direct industry advice on the use of CO_2 emissions factors has been adopted for the use of coal by-products within *1.A.2.C chemicals,* black coal within *1.A.2.a iron and steel,* and natural gas in general. Non-CO_2 EFs have been calculated using a sectoral equipment-weighted average approach and are reported in Annex 5.3.2, Table A5.3.2.1. Additional stratification is provided for the metal and chemicals industries.

Table 3.6 Summary of methods and emission factors: Manufacturing and Construction

		CO_2		CH_4		N_2O	
Category		**Method applied**	**Emission factor**	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**
1.A.2.a	Iron and Steel	T2	CS	T2	CS	T2	CS
1.A.2.b	Non-Ferrous Metals	T2	CS	T2	CS	T2	CS
1.A.2.c	Chemicals	T2	CS	T2	CS	T2	CS
1.A.2.d	Pulp, Paper and Print	T2	CS	T2	CS	T2	CS
1.A.2.e	Food Processing, Beverages and Tobacco	T2	CS	T2	CS	T2	CS
1.A.2.f	Non-metallic minerals	T2	CS	T2	CS	T2	CS
1.A.2.g	Other	T2	CS	T2	CS	T2	CS

CO_2 Emission Factors		Liquid fuels	Solid fuels	Gaseous fuels	Biomass
1.A.2.a	Iron and Steel	CS	CS	CS	NO
1.A.2.b	Non-Ferrous Metals	CS	CS	CS	CS
1.A.2.c	Chemicals	CS	CS	CS	CS
1.A.2.d	Pulp, Paper and Print	CS	CS	CS	CS
1.A.2.e	Food Processing, Beverages and Tobacco	CS	CS	CS	CS
1.A.2.f	Non-metallic minerals	CS	CS	CS	CS
1.A.2.g	Other	CS	CS	CS	CS

Notes: T1 = tier 1, T2 = tier 2, T3 = tier 3, CS = country specific, D= IPCC default, 🟪 = key category

The Australian Energy Statistics report energy consumption by functional activity and classifies these to industries associated with them as a primary activity using the Australian and New Zealand Standard Industrial Classification (ANZSIC). These activities can be mapped to IPCC classifications (Table 3.7).

Table 3.7 Relationship between IPCC source categories and ANZSIC classifications: Manufacturing and Construction

	ANZSIC Subdivision/Group/Class			
IPCC Source Category	**Division**	**Subdivision**	**Group/ Class**	**Description**
a Iron and Steel	C Manufacturing	21	211–212	Iron and steel manufacturing (excl. Coke ovens)
b Non-Ferrous Metals	C Manufacturing	21	213–214	Basic non-ferrous metal manufacturing
c Chemicals	C Manufacturing	17	1709	Other petroleum and coal product manufacturing
		18–19		Basic chemical and chemical, polymer and rubber
d Pulp, Paper and Print	C Manufacturing	14		Wood and paper products
		15–16		Pulp, paper and printing
e Food Processing, Beverages and Tobacco	C Manufacturing	11–12		Food, beverages, tobacco
f Non-metallic minerals	C Manufacturing	20		Non-metallic mineral product manufacturing
g Other (Mining (excluding fuels) and quarrying)	B Mining	8–10		Other mining
g Other (Textile and leather)	C Manufacturing	13		Textiles, clothing, footwear, and leather
g Other (All other manuf.)	C Manufacturing	22		Fabricated metal products
		25		Furniture and other manufacturing
g Other (Manufacturing of Machinery)	C Manufacturing	23–24		Machinery and equipment
g Construction	E Construction			Construction

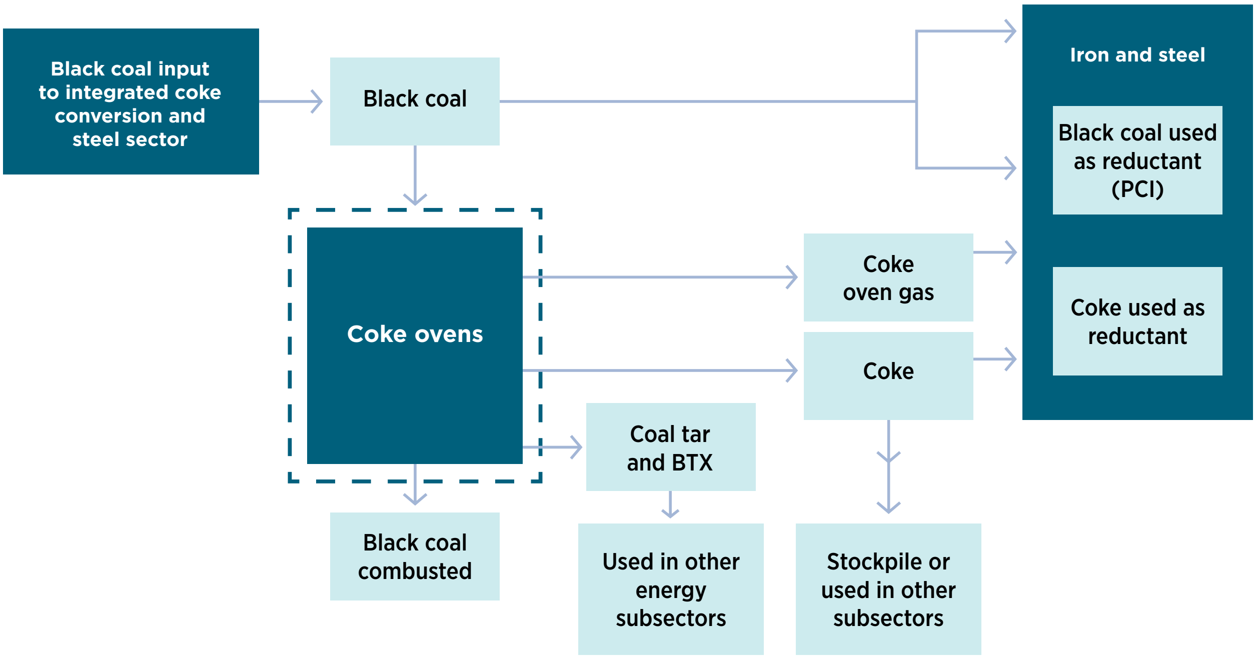
Iron and Steel (1.A.2.a)

The methodology in the *iron and steel* subsector is somewhat more complex than many other sections of the inventory. This complexity arises from several factors:

- The operation of Coke Ovens is considered to be an energy transformation industry, and hence must be reported separately to the rest of the iron and steel emissions;
- The production of coke yields a variety of by-products, including coke oven gas, coal and tar;
- Liquefied aromatic hydrocarbons and naphthalene each have quite different calorific values and EFs. Coke oven gas is used as fuel in coke ovens and adjacent steelworks, while the other products are in general not combusted, but are used as feedstock in the chemical industry;
- Overall, the Coke Ovens sector is a producer of coke, most of which is consumed in the Iron and Steel sector and some of which is exported to other sectors (and other countries);
- The operation of blast furnaces to produce pig iron also produces yet another coal by-product, blast furnace gas, which is a low calorific value fuel consisting mainly of CO (and atmospheric nitrogen), used elsewhere in the steelworks. For the purpose of calculating CO_2 emissions, the production and subsequent combustion of blast furnace gas is ignored, and it is assumed that all coal and coke used in the iron and steel industry undergoes complete oxidation to CO_2, apart from a small adjustment for carbon sequestered in steel;
- The use of coke, as well as natural gas in hot briquetted iron production is regarded primarily as a chemical process rather than fuel combustion under IPCC reporting guidelines. Consumption and emissions are therefore reported under the *industrial processes and product use* sector 2.C.3 rather than the *energy* sector;
- Pulverised black coal has been used as a reductant in the production of iron since 2002–03. Therefore, the consumption and emissions are reported under the *industrial processes and product use* sector in *2.C.1 metal production* rather than the *energy* sector;
- Although Coke Ovens are in operation in the iron and steel industry, they are considered an energy transformation industry under the IPCC methodology. Therefore, Coke Ovens must be separated from the other parts of the iron and steel industry, so that it can be reported under IPCC category 1.A.1.c;
- The statistics show that production of both coke and coal by-products exceed consumption within the sectors, i.e. the iron and steel industry as a whole is a net producer of coke and coal by-products. Only the estimate of consumption is used to estimate emissions from the Iron and Steel sector. Some of the remaining production may appear elsewhere in the national inventory if it is consumed as fuel by other industries in Australia, in which case the emissions are allocated to the consuming industry; and
- Production consumed elsewhere includes some coke (though in most years the majority of surplus coke produced by the industry is exported from Australia), and surplus coal by-products, most of which are consumed by the Coal and Petroleum Products sector.

A schematic chart showing energy flows within the integrated coke oven/Iron and Steel subsectors is shown in Figure 3.14. Energy and carbon flows are balanced between input and outputs when compiling the inventory as part of the inventory quality controls. A discrete carbon balance is undertaken around the coke ovens input/output, as defined by dashed lines in Figure 3.14, to determine the carbon content of coke produced as a balancing item. The coke emission factor determined from this balance is shown for all years in Table A5.3.2.21.

Figure 3.14 Coke Oven and Iron and Steel energy flow chart



Note: The dashed lines define the discrete carbon balance undertaken for the coke oven inputs/outputs to determine the carbon content of the coke produced.

Non-Ferrous Metals (1.A.2.b)

The consumption of petroleum products NEC (unspecified petroleum products 'not elsewhere classified', meaning other) in this sector includes petroleum coke and coal tar used to make carbon anodes for aluminium production. CO_2 emitted from oxidation of carbon anodes in aluminium smelters is accounted in IPCC category 2.C.3. The quantity of petroleum coke and coal tar consumed in this sector, as advised by industry each year, is therefore subtracted from energy consumption of petroleum products NEC and coal by-products, to eliminate double counting. It is assumed that the remaining energy consumption of Petroleum Products NEC consists of naphtha. Some use of black coal in the production of synthetic rutile as well as black coal, coke, petroleum coke and fuel oil for base metal smelting occurs for reductant purposes. Therefore, these fuel quantities are also deducted from the *energy* sector fuel consumption and reported under the *industrial processes and product use* sector.

Chemicals (1.A.2.c)

The Chemicals sector is a major energy user. Most of the energy is used by the Petroleum Refining and Basic Chemical Manufacturing sub-categories. Energy use in these two sub-categories is separately reported at the national level.

Non-energy use of natural gas in the production of ammonia is regarded as an industrial process and is therefore reported under the *industrial processes and product use* sector rather than the *energy* sector, to prevent double counting. Likewise, the non-energy use of petroleum coke for titanium dioxide production and coke oven coke used in soda ash production are also reported within the *industrial processes and product use* sector.

The calculation of emissions in the Chemicals sector must identify and allow for carbon stored in products. Sequestration takes place in the Other petroleum and coal product manufacturing and the Basic chemical and chemical, polymer and rubber sub-categories, where fossil fuels are used as feedstock. Data are also obtained directly from chemical companies to estimate the quantity of carbon sequestered in products from feedstocks, with emissions estimates adjusted accordingly.

Coal by-products constitute the largest fuel input into the Other petroleum and coal product manufacturing sector. It is assumed that these consist of coal tar and liquefied aromatic hydrocarbons and that, in the absence of specific information about this industry sector in Australia, 75 per cent of this fuel is sequestered in long lived coal products, following the default assumption of the IPCC methodology.

The basic chemical and chemical, polymer and rubber sub-category includes the major bulk chemical manufacturing enterprises producing fertilisers, other nitrogenous chemicals, polymer resins (plastics) and carbon black. The fossil fuel feedstocks used include natural gas (CH_4), ethane, propane, butane, propylene, and naphtha. Ethane, propane, and butane may be either 'naturally occurring', i.e. sourced directly from oil and gas fields or derived from crude oil as by-products of refining. In Australia, all ethane is derived from naturally occurring source, while both naturally occurring and ex-refinery propane and butane are used. Propylene and naphtha are refinery products. The Australian Energy Statistics include ethane within the reported total natural gas consumption, after appropriately adjusting for the different energy content of ethane (DCCEEW 2023). The Australian Energy Statistics also groups propane and butane together as LPG and group propylene and naphtha as petroleum products NEC.

The important outputs of this sector can be classified into two components:

- synthetic resins (polymers), and
- nitrogenous fertilisers and other nitrogenous products.

A third component, carbon black manufacture, uses significant quantities of fossil fuel feedstock as a source of carbon, however relatively little is combusted. A fourth, methanol, has been manufactured in Australia since 1993–94.

Synthetic Resins

The balance between combustion and storage in products varies greatly between chemical plants, depending on the production processes involved and the configuration of the particular plant. Therefore, the quantity of feedstock supplied to chemical plants is not a useful indication of the quantity of stored carbon. The only reliable guidance comes from the quantities of chemical products produced. The major products in which fossil carbon is sequestered include polyethylene, polypropylene, synthetic rubber, and styrene. Other bulk plastics are made in Australia from imported monomers, e.g. PVC made from imported vinyl chloride monomer. These imported monomers contain large quantities of fossil carbon, but since this has not been derived from primary fossil fuels (crude oil, petroleum products and natural gas) produced in or imported to Australia, this carbon is not estimated.

The IPCC Methodology assumes that default fractions of specified fossil fuel products, e.g. ethane, naphtha, are sequestered (IPCC 2006, 2019). The national inventory utilises the actual production figures provided by the companies making the products concerned. The analysis is nevertheless relatively complex because most products are derived from several different feedstocks. The carbon contents of the various feedstocks and basic chemical products used in estimating the carbon sequestration are reported in Table 3.8 and Table 3.9.

The quantities of feedstocks used in the Chemical subsector, and the associated amounts of carbon stored in products, are detailed in CRT table 1.A(d) – Feedstocks and non-energy use of Fuels. The majority of emissions of ethane and naphtha combusted as fuels are reported in the national inventory under *1.A.2.c Chemicals.*

Carbon Black

Carbon black is produced in Australia by partial oxidation of petroleum feedstocks and used in a variety of long-lived products, including tyres.

Table 3.8 Feedstock assumptions in basic chemicals

Feedstock	Carbon Faction	Calorific Value (GCV)
Ethane	0.80	(a)
Propylene	0.86	52.2
Naphtha (Benzene)	0.84	48.1
Gas Oil (ADO)	0.85	45.6
Carbon Black Feedstock	(a)	(a)

Source: Energy Strategies 2007 Analysis. (a) Data is provided in a confidential manner annually from the relevant companies and hence is not reported here. Note that GCV stands for gross calorific value.

Table 3.9 Product assumptions in basic chemicals

Product	Carbon Faction
Polyethylene	0.86
Polypropylene	0.86
Butadiene Rubber / Styrene-Butadiene Rubber	0.86
Styrene	0.92
Carbon black	1.00

Pulp, Paper and Print (1.A.2.d)

The manufacture of pulp, paper, and print materials use a range of machinery to process and produce wood. The majority of fuel consumed in this sector is used for the generation and distribution of steam using boilers. Paper and paperboard production has been increasing, with notable increases during the COVID-19 pandemic lockdown periods in 2020 to 2021. Emissions intensity and fuel use have been reducing as the industry continues to make systemic changes to improve sustainability. As a result, the implied emission factors for solid and gaseous fuels have been reducing through time.

Emissions in this category are estimated based on fuel combustion reported in the AES (DCCEEW 2023).

Food Processing, Beverages and Tobacco (1.A.2.e)

Emissions in this category are estimated based on fuel combustion reported in the AES (DCCEEW 2023).

Non-metallic Minerals (1.A.2.f)

Emissions in this category are estimated based on fuel combustion reported in the AES (DCCEEW 2023).

Other (1.A.2.g)

Emissions in this category are estimated based on fuel combustion reported in the AES (DCCEEW 2023).

3.2.5.3 Uncertainties and time series consistency

The tier 1 uncertainty analysis in Annex II provides estimates of uncertainty according to IPCC source category and gas.

Time series variability of implied emission factors are likely to be influenced by changes in fuel mix within categories. Notable examples of where such variations occur in Category 1.A.2 are set out below.

1.A.2.a iron and steel: CO_2

Solid fuels

The use of coke in iron and steel is reported in industrial processes and product use sector in accordance with the 2006 IPCC Guidelines (IPCC 2006). Of the two remaining solid fuels: coal and coke oven gas, the coke oven gas has a relatively low CO_2 EF of 37 Gg/PJ compared to 91.8 Gg/PJ for coal. This tends to lower the overall CO_2 IEF for solid fuels.

Australia has allocated black coal used for pulverised coal injection (consumed as a reductant) to the industrial processes and product use sector. This has resulted in a reallocation of black coal from *1.A.2.a iron and steel* to *2.C.1 metal production* from 2002–03 onwards, when pulverised coal injection was first used in Australia. However, there is some minor use of black coal for combustion purposes remaining in the Energy sector under *1.A.2.a iron and steel.* This coal is driving the solid IEF to be higher than that of coke oven gas alone, as well as influencing the annual fluctuations observed in the solid IEF from 2002–03 onwards. Table 3.10 shows the percentage of black coal/coke oven gas fuel mix within solid fuels.

Table 3.10 Percentage of black coal and coke oven gas fuel mix in 1.A.2.a

Years	% cent of coal	% of coke oven gas
1989–90	10	90
1999–00	9	91
2004–05	23	77
2009–10	36	64
2014–15	4	96
2015–16	1	99
2016–17	16	84
2017–18	2	98
2018–19	1	99
2019–20	2	98
2020–21	2	98
2021–22	2	98

Liquid fuels

The liquid fuel CO_2 IEF is relatively low, driven by the dominant use of LPG (CO_2 EF of 60.2 Gg/PJ) compared to other liquid fuels with higher EFs. However, a sharp increase in the IEF in 2000–01 was the result of an increase in the use of diesel and fuel oil relative to the consumption of LPG. As LPG has a relatively lower CO_2 EF, the change in fuel mix resulted in an increase in the overall liquid CO_2 IEF.

1.A.2.c Chemicals:

Emissions and IEFs for *chemicals* are influenced by the mix of end products which sequester carbon. The production mix of the Australian chemicals industry changes over time, resulting in a variable trend.

3.2.5.4 Category-specific QA/QC and verification

This source category is covered by the general QA/QC of the greenhouse gas inventory described in Annex IV.

3.2.5.5 Category-specific recalculations

The recalculations reported in the current submission are shown in Table 3.11, and include:

A. Updates to the Australian Energy Statistics

Australia's official statistics on energy production and use receives periodic updates to support improved understanding of Australia's energy systems, including for time series consistency. These updates are reflected in the inventory.

B. Activity data adjustments

Historic activity data has been updated to align with the Australian Energy Statistics in the Chemicals and Non-ferrous metals categories. An energy conversion error has been rectified for 2020–21 within Mining (excluding fuels) and quarrying for natural gas consumption.

Table 3.11 Manufacturing and Construction: recalculation of total CO_2–e emissions, 1989–90 to 2020–21

	2023 Submission	2024 submission	Change		Reasons for recalculation (Gg CO_2–e)	
Year	Gg CO_2–e	Gg CO_2 -e	Gg CO_2 -e	%	A	B
1989–90	36,224.9	36,224.9	-	-	-	-
1994–95	37,628.9	37,628.9	-	-	-	-
1999–00	38,916.0	38,916.0	-	-	-	-
2004–05	41,546.8	41,546.8	-	-	-	-
2005–06	40,610.6	40,610.6	-	-	-	-
2006–07	40,888.5	40,888.5	-	-	-	-
2007–08	42,997.8	42,997.8	-	-	-	-
2008–09	40,516.0	40,516.0	-	-	-	-
2009–10	39,707.4	39,707.4	-	-	-	-
2010–11	40,883.5	40,883.5	-	-	-	-
2011–12	42,875.2	42,875.2	-	-	-	-
2012–13	45,969.2	45,969.2	-	-	-	-
2013–14	46,341.2	46,193.3	-147.9	-0.3	-	-147.9
2014–15	42,743.9	42,985.8	241.8	0.6	-	241.8
2015–16	41,457.6	41,716.4	258.8	0.6	-	258.7
2016–17	40,684.9	41,042.7	357.8	0.9	-	357.8
2017–18	41,667.8	42,117.1	449.3	1.1	84.9	364.4
2018–19	41,604.5	41,792.7	188.2	0.5	-50.5	238.7
2019–20	41,705.5	41,725.5	20.1	0.0	20.1	-
2020–21	42,413.0	43,179.5	766.5	1.8	-301.9	1,068.4

3.2.5.6 Category-specific planned improvements

The Department will continue to look at applying revisions to the earlier part of the time series in response to future Australian Energy Statistics releases.

In response to a recommendation from a previous review report, a study was commissioned by the Department to investigate the appropriateness of the fuel characteristics for liquid fuel types. As a result, further analysis of Australian liquid fuel characteristics will be undertaken in the future to consider whether any changes are necessary.

A new emission factor for the combustion for energy of non-biomass waste tyres was introduced for reporting in the NGER scheme for the 2022–23 reporting period. This data will be included in the next NIR and will allow for enhanced accuracy and transparency of this fuel.

3.2.6 Transport

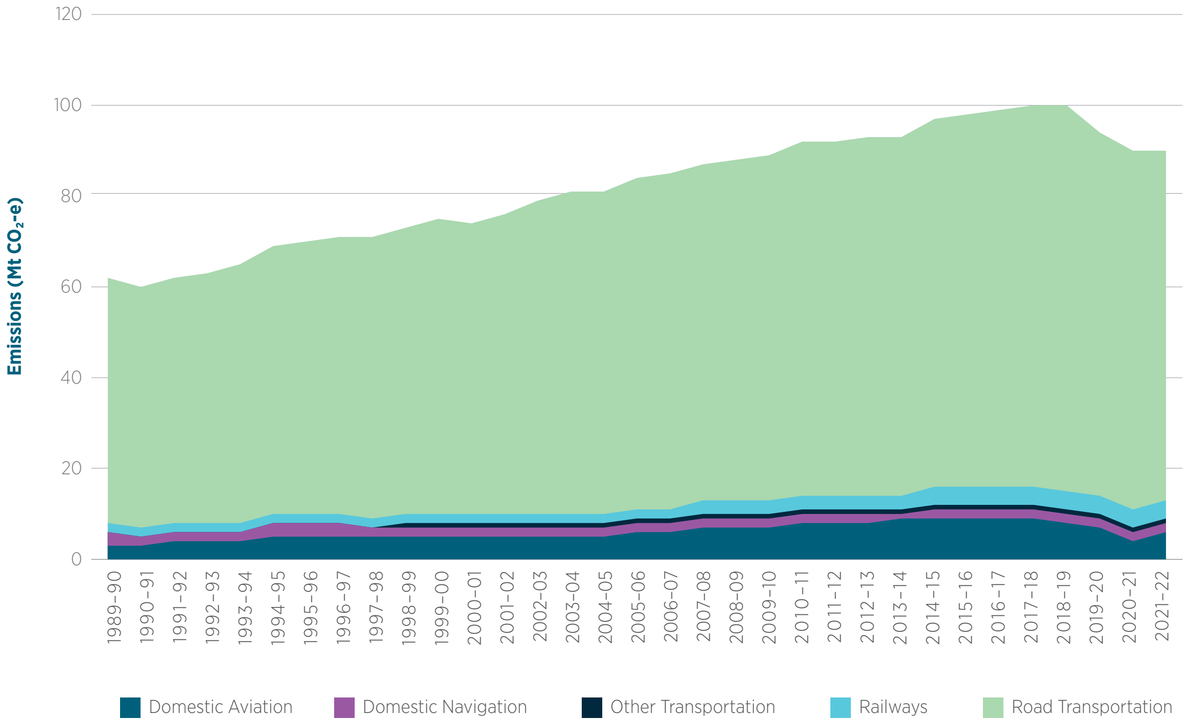
3.2.6.1 Category description

This source category includes emissions from the *transport* sector, comprising the domestic civil aviation, road transportation, marine navigation, railways and 'other' categories.

Road transportation accounts for the vast majority of *transport* emissions in Australia. This outcome is principally driven by the importance of motor vehicles as modes of transportation for passengers and freight in Australia.

Fuel used in *international transport (international aviation* and *marine 'bunkers')* is by international agreement reported separately from the national total net emissions. More information is available in Chapter 3.2.2.

Figure 3.15 Transport emissions by subsector, 1989–90 to 2021–22



Transport emissions are one of the strongest drivers of Australia's emissions. Except for observed decreases caused by the recent COVID-19 pandemic, emissions associated with transport have trended consistently upward over time (Figure 3.15). This is largely attributable to population and economic growth but is partially offset by improved efficiency in the modes of transport.

Increases in emissions from pipeline transport are due to increased throughput associated with the expansion of gas production, especially offshore production.

3.2.6.2 Methodological issues

Like other energy subsectors, the methodology for 1.A.3 is based on the application of 'bottom up' approaches to the estimation of emissions. The estimation of non-CO_2 emissions from road transport (besides motorcycles) utilises a Tier 3 approach that depends on data on vehicle kilometres travelled, vehicle fleet characteristics and vehicle operating modes. Non-CO_2 emissions from domestic civil aviation using aviation turbine fuel are estimated using a Tier 2 approach (with a Tier 1 approach applied to estimates of non-CO_2 emissions from domestic aviation using aviation gasoline), which takes account of fuel consumed, landing and take-off cycles and Australian fleet characteristics.

Table 3.12 Summary of methods and emission factors: Transport

	CO_2		CH_4		N_2O	
Source Category	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**
1.A.3.a Domestic Aviation						
Aviation Gasoline	T2	CS	T1	D	T1	D
Jet Kerosene	T2	CS	T2	CS	T2	CS
1.A.3.b Road Transportation – Cars, Trucks and Buses						
Liquid Fuels	T2	CS	T3	CS	T3	CS
Gaseous Fuels	T2	CS	T3	CS	T3	CS
Biomass	T2	CS	T3	CS	T3	CS
1.A.3.b Road Transportation – Motorcycles						
Liquid Fuels	T2	CS	T2	CS	T2	CS
Other Fossil Fuels (Lubricants)	T1	D	NE	NA	NE	NA
1.A.3.c Railways						
Liquid Fuels	T2	CS	T1	D	T1	D
Solid Fuels	NE	NA	NE	NA	NE	NA
Gaseous Fuels	NO	NO	NO	NO	NO	NO
1.A.3.d Domestic Navigation						
Liquid Fuels	T2	CS	T2	CS	T2	CS
Gaseous Fuels	T2	CS	T2	CS	T2	CS
Biomass	T2	CS	T2	CS	T2	CS
Other Fossil Fuels (Coal)	T2	CS	T2	CS	T2	CS
Other Fossil Fuels (Lubricants)	T1	D	NE	NA	NE	NA
1.A.3.e Other Transport – Pipeline Transport						
Gaseous Fuels	T2	CS	T1	D	T1	D

	CO_2		CH_4		N_2O	
Source Category	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**
1.A.3.e Other Transport – Off-road vehicles						
Liquid Fuels	T2	CS	T1	D	T1	D
Biomass	T2	CS	T1	D	T1	D
Other Fossil Fuels (Lubricants)	T1	D	NE	NA	NE	NA

Notes: T1 = Tier 1, T2 = Tier 2, T3 = Tier 3, CS = country specific, D = IPCC default, NE = not estimated, NA = not applicable, NO = not occurring, 🟪 = key category

General methodology

The emission estimate of a greenhouse gas from fuel combustion in the engines of a mobile source, using a specified fuel type, is calculated by:

$$E_{(l)ijk} = Au_{ijk} \times F_{(l)}u_{ijk}$$

Where $E_{(l)ijk}$ is the emission of greenhouse gas l in gigagrams (Gg) from a mobile vehicle and age class i and technology j using fuel type k

Au_{ijk} is the activity level, where u refers to either energy consumption in petajoules (PJ) or to distance travelled in kilometres (km)

$F_{(l)}u_{ijk}$ is the EF, in units of grams of gas l emitted per megajoule of energy use (g/MJ) for CO_2 and SO_2, and grams of gas l emitted per kilometre travelled (g/km) for other non-CO_2 gases

Fuel consumption data for the *transport* sector are taken from the Australian Energy Statistics (see Annex 5.2) (DCCEEW 2023). Special allocations are made for military transport based on information provided by the Australian Department of Defence since 2007–08. Allocations for prior years are linearly extrapolated between reported data points in 1993–94 and 2007–08.

Domestic aviation (1.A.3.a)

The estimation of CO_2 emissions from civil aviation is undertaken using a Tier 2 methodology and EFs given in Annex 5.3.1, Table A5.3.1.1.

Non-CO_2 emissions from domestic civil aviation are estimated using both a Tier 1 and a Tier 2 methodology. Small aircraft operating on aviation gasoline make up a small portion of aviation emissions and are estimated using a Tier 1 approach and IPCC default EFs.

For larger aircraft operating on aviation turbine fuel, emissions are calculated as a function of both the landing/take-off cycles (LTOs) and of cruise emissions for both domestic and international aircraft. The Tier 2 estimation of emissions from landing and take-off cycles of larger aircraft operating on aviation turbine fuel requires data on the number of LTO cycles at Australian airports; data on the profile of the Australian aviation capital stock or fleet; and EFs by type of aircraft. The data required for the total yearly LTO for the domestic and international aircraft are available from the Bureau of Infrastructure, Transport and Regional Economics (BITRE 2022) within the Department of Infrastructure, Transport, Regional Development, Communications and the Arts.

The Australian aviation fleet profile is developed using the Australian Aircraft Register which is available from the Civil Aviation Safety Authority (CASA 2022) (Table 3.13). EFs for each aircraft type are taken from the 2006 IPCC Guidelines (IPCC 2006) and are used to estimate weighted average LTO cycle EFs for the domestic/interstate and international aviation fleets (Table 3.14). These EFs most accurately reflect the technology and aircraft types currently in the Australian aircraft fleet. In a couple of instances EFs are not available for a certain aircraft type. These aircraft are allocated to the aircraft type, for which an EF exists, that most closely reflects the aircraft's engine characteristics.

The estimation of cruise emissions is a function of fuel use, after deduction of fuel consumption required for the LTO cycles, and cruise EFs. Data on the yearly fuel consumption for domestic and international activity are available from the Australian Energy Statistics (DCCEEW 2023). Cruise EFs are taken from the 2006 IPCC Guidelines (IPCC 2006) (Table 3.15), with N_2O being a weighted average EF for the Australian domestic aircraft fleet.

The methodology is applied to each of the eight Australian states and territories (except for the Australian Capital Territory, which, due to the unavailability of disaggregated fuel consumption data, is included in estimates for the state of New South Wales). Differences in emission estimates across the States principally reflect differences in fuel consumption and both the number of LTO cycles and the relative importance of major interstate movements relative to regional LTO cycles, which impacts on the aircraft type that use State airports. National emissions are estimated as the sum of the State and Territory emissions.

For small piston engine aircraft operating on aviation gasoline fuel, non-CO_2 emissions are estimated using a Tier 1 approach. This method applies default EFs (IPCC 2006) for all fuels and aircraft types to all aviation gasoline fuel consumed by state (Table 3.16).

Emissions from international aviation are also estimated, but are reported as a Memo item only, by international agreement. Activity data for international bunkers is estimated as part of the Australian Energy Statistics.

Table 3.13 The Australian aircraft fleet, 2021–22, and emission factors by type of aircraft

		LTO Emission Factors				
Type of aircraft	Number	CH_4 kg/LTO	N_2O kg/LTO	NO_x kg/LTO	CO kg/LTO	NMVOC kg/LTO
Domestic						
DHC-8-100	12	0.00	0.02	1.51	2.24	0.00
DHC-8-200	10	0.00	0.02	1.51	2.24	0.00
A320	80	0.06	0.10	9.01	6.19	0.51
A330-200/300	29	0.13	0.20	35.57	16.20	1.15
BAE 146	12	0.14	0.00	4.07	11.18	1.27
B717	20	0.01	0.10	10.96	6.78	0.05
B727-200	1	0.81	0.10	11.97	27.16	7.32
B737-300/400/500	8	0.08	0.10	7.19	13.03	0.75
B737-700	7	0.09	0.10	9.12	8.00	0.78
B737-800	160	0.07	0.10	12.30	7.07	0.65
B767-200	0	0.33	0.10	23.76	14.80	2.99
B767-300	3	0.10	0.20	28.19	14.47	1.07
SAAB 340	18	0.00	0.02	1.51	2.24	0.00
SA227	45	0.00	0.02	1.51	2.24	0.00
SA226	10	0.00	0.02	1.51	2.24	0.00
Gulfstream IV	62	0.14	0.10	5.63	8.88	1.23
EMB 110	6	0.06	0.01	0.30	2.97	0.58
EMB 120	14	0.00	0.02	1.51	2.24	0.00
Cessna 525	25	0.33	0.03	0.74	34.07	3.01

Type of aircraft	Number	LTO Emission Factors				
		CH$_4$ kg/LTO	N$_2$O kg/LTO	NO$_x$ kg/LTO	CO kg/LTO	NMVOC kg/LTO
Beech (King Air) 200	134	0.06	0.01	0.30	2.97	0.58
F27	139	0.03	0.02	1.82	2.33	0.26
International						
777	2	0.07	0.30	52.81	12.76	0.59
A380	12	0.40	0.30	69.31	28.40	2.02
787	22	0.17	0.18	34.65	15.27	1.08

Source: Australian Civil Aircraft Register (CASA 2022), ICAO Aircraft Engine Emissions Databank (EASA 2023). Note that LTO stands for landing and take-off cycle.

Table 3.14 Weighted average emissions factors per landing and take-off cycle (LTO)

Fleet	CH$_4$ (kg)	N$_2$O(kg)	NO$_x$(kg)	CO (kg)	NMVOC (kg)
Domestic Fleet	0.1	0.1	6.3	6.3	0.6
International Fleet	0.2	0.2	47.2	19.5	1.4

Source: DCCEEW estimates.

Table 3.15 Aviation cruise emission factors (grams per tonne of fuel consumed)

Fleet	CH$_4$ (g/t) (a)	N$_2$O (g/t) (a)	NO$_x$(g/t) (b)	CO (g/t) (b)	NMVOC (g/t) (b)
Domestic Fleet	0	0.01	11	7	0.7
International Fleet	0	0.01	17	5	2.7

Source:
(a) IPCC (2006) weighted average.
(b) IPCC (1997)

Table 3.16 Aviation Tier 1 Non-CO$_2$ Emission Factors

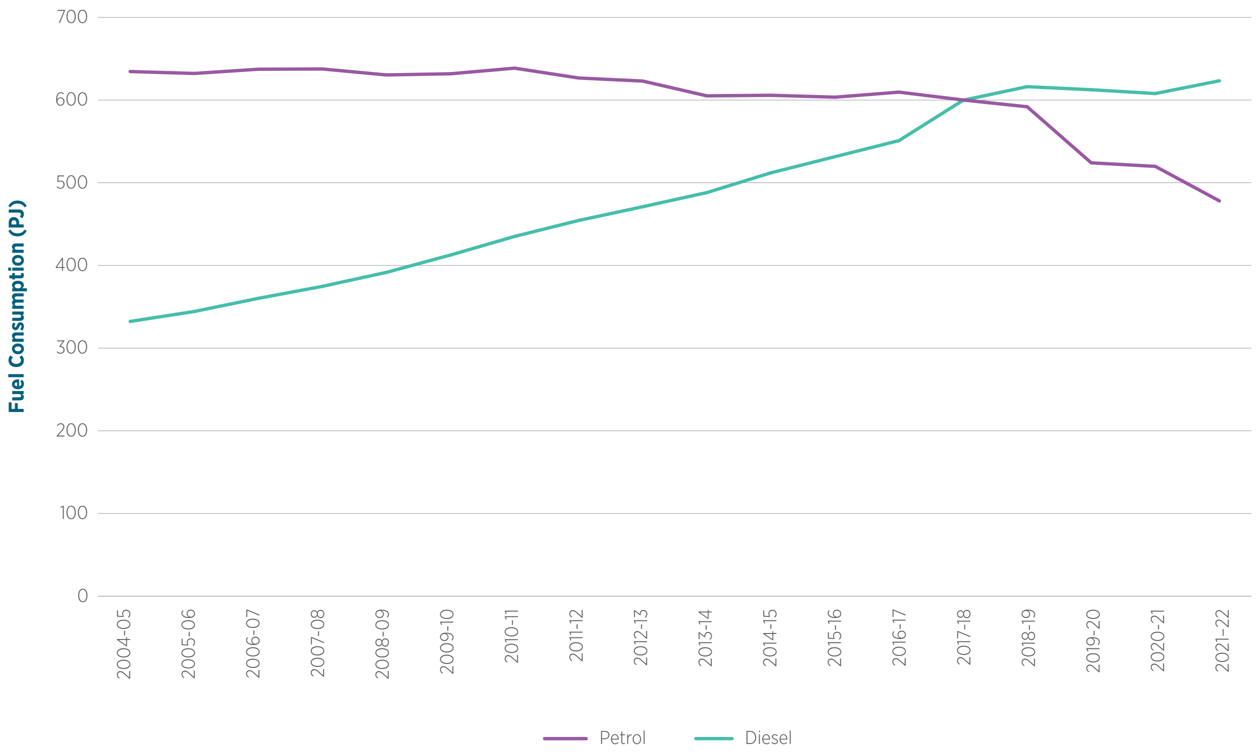
Fuel	CH$_4$ (kg/TJ)	N$_2$O (kg/TJ)	NO$_x$(kg/TJ)	CO (kg/TJ)	NMVOC (kg/TJ)
Aviation gasoline	0.5	2	250	0.024	0.00054

Source: IPCC (1997), IPCC (2006).

Road transportation (1.A.3.b)

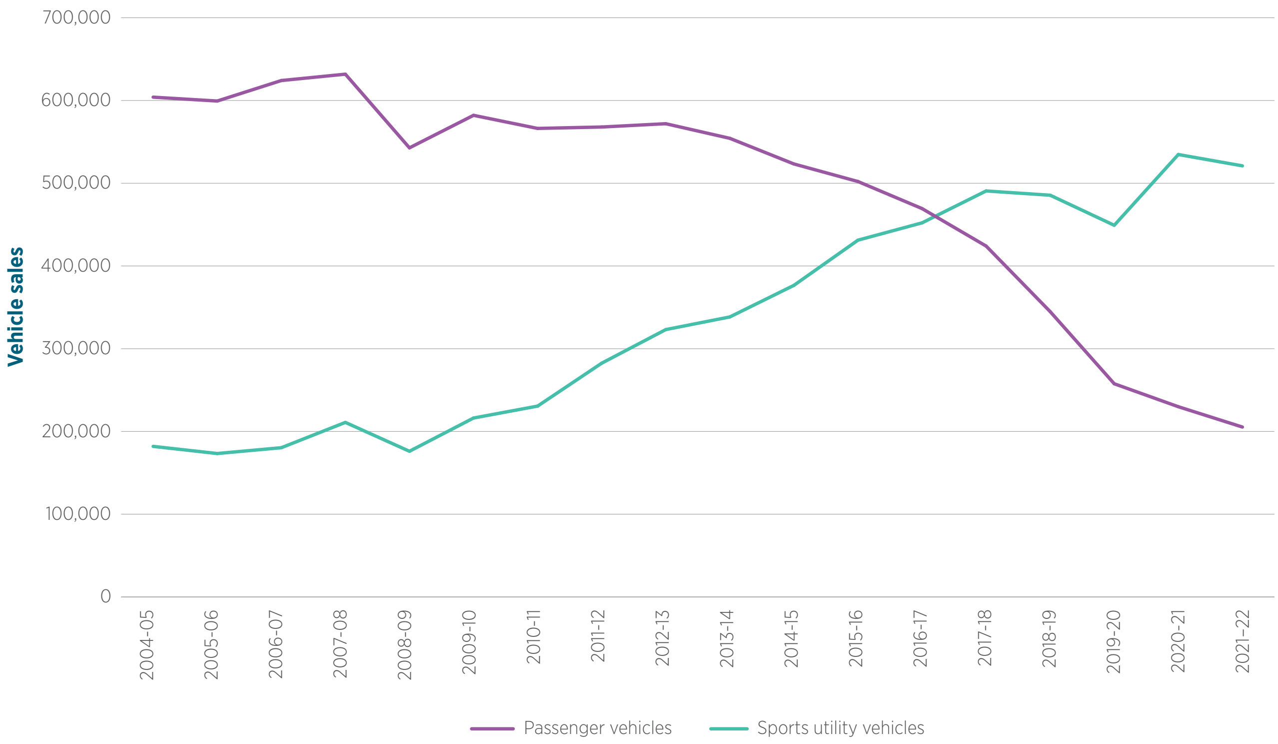
Australian Energy Statistics data shows that diesel consumption in total road transport has grown over time, while petrol consumption has slowly declined (Figure 3.16). This correlates with the increasing popularity of diesel vehicle options for passenger vehicles in Australia, including the Sports Utility Vehicle (SUV) (Figure 3.17), as well as the increasing demands for freight which is dominated by diesel-powered light commercial and heavy vehicles. As petrol-powered vehicles are more commonly used for private household purposes, the petrol consumption profile has been more significantly impacted by the net effect of various COVID-19 border and lockdown policies, as well as ongoing mode of work changes with greater working from home levels resulting in fewer car journeys to workplaces.

Figure 3.16 Energy consumption in road transport by fuel type, 2004–05 to 2021–22



Source: *Australian Energy Statistics 2023 (DCCEEW 2023)*

Figure 3.17 Sport utility vehicle (SUV) and passenger vehicles sales trend in Australia, 2004–05 to 2021–22

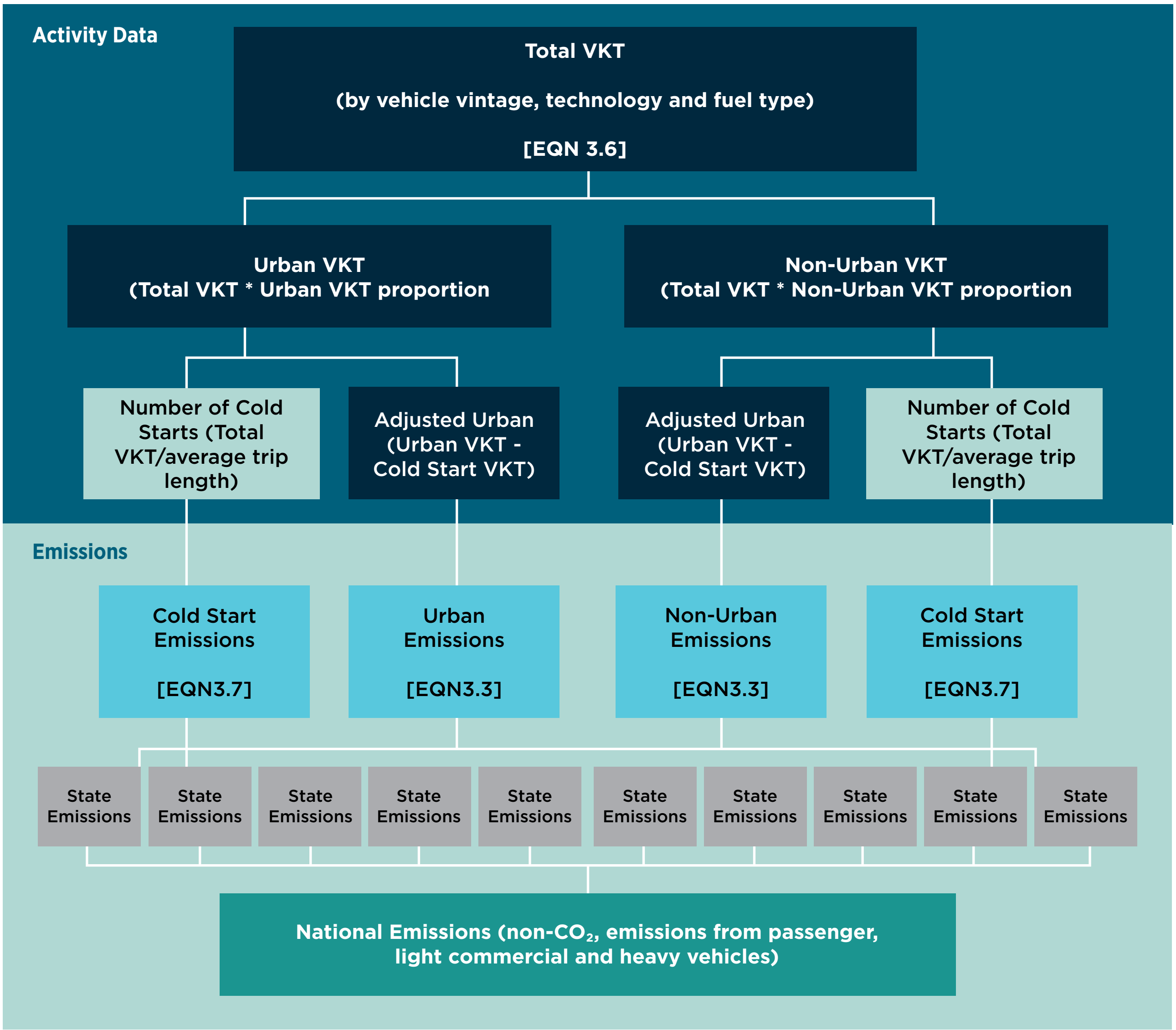


Source: ABS (2017), Federal Chamber of Automotive Industries (2018–2022).

Emissions from off-road vehicles are allocated to the subsector to which their function is relevant. For example, large trucks used in iron ore mining operations are allocated to 1.A.2.g, and tractors used in farming are allocated to 1.A.4.c. This is consistent with how fuel use is allocated to the industry most closely related to the functional activity in the Australian Energy Statistics, and the purpose of these vehicles is not transport. Regardless, the emissions associated with off-road vehicles are still estimated using the methods outlined in this chapter.

Like the aviation sector, the estimation of CO_2 emissions from the road transport sector is based on a Tier 2 method with EFs given in Annex 5.3.1, Table A5.3.1.1. The estimation of non-CO_2 emissions is based on a Tier 3 method, with the emission estimates dependent on the type of vehicle, the age of the vehicle capital stock, technology, operating mode (cold versus hot) and road type (urban versus non-urban). Activity data is expressed in terms of vehicle kilometres travelled and EFs are expressed in g/km. The methodology is applied to each of the eight Australian States and Territories. Differences in emission estimates across the States and Territories principally reflect differences in fuel consumption and the impacts on non-CO_2 emission estimates of differentials in the age distribution of each State and Territory's vehicle fleet. National emissions are estimated as the sum of the State and Territory emissions (see Figure 3.18).

Figure 3.18 Methodology for the estimation of non-CO_2 emissions from passenger, light commercial, heavy vehicles and buses



Passenger and light commercial vehicles, heavy vehicles and buses (1.A.3.b i-iii)

CO_2 emissions from all vehicle fuel sources have been estimated based on the quantity of fuel consumed multiplied by the CO_2 EF specific to that fuel and the proportion of that fuel which is completely oxidised.

$$E_{ijk} = A^{u=1}_{ijk} \times (F_{(l)k} \times P_k) \quad (3.2)$$

Where $F_{(l)k}$ is the CO_2 EF applicable to complete oxidation of fuel carbon content for fuel type k

P_k is the proportion of fuel that is completely oxidised upon combustion

Au_{ijk} is the activity data for vehicle type i with emission control technology j and fuel type k (and where $^{u=1}$ for fuel consumption in each Australian State or Territory)

The CO_2 EFs and oxidation factors for each fuel are summarised in Annex 5.3.1, Table A5.3.1.1. For all vehicles (besides motorcycles) consuming automotive gasoline, ethanol, diesel and LPG, non-CO_2 emissions for each age class are estimated based on vehicle kilometres travelled (VKT) in each State or Territory; the profile and age of the vehicle capital stock in each jurisdiction; the penetration of catalytic control technology; mode of operation and road type; and vehicle and fuel specific EFs.

It is assumed that all light duty vehicles go through a cold start phase for each trip which is associated with higher emissions due to engine and catalyst temperatures that are below optimum. The number of cold starts is derived from total VKT, and an average trip length sourced from Pekol Traffic and Transport (2022). Average trip length by State and Territory and by vehicle type is estimated for each year throughout the time series. This data replaced static average trip length of 10km that was previously applied across States and Territories and vehicle types. A cold-start duration of 3km (IPCC 2006) is used to determine the total cold start VKT. This is subtracted from total VKT to derive an adjusted total VKT value.

EFs vary by road type (urban versus non-urban) to reflect the different driving conditions and engine operating profiles. Distance travelled is disaggregated into urban and non-urban VKT in each State and Territory and by vehicle type (Pekol Traffic and Transport 2022).

Vehicles using automotive gasoline, ethanol, diesel and LPG are further classified by age of vehicle using data contained in (BITRE 2023). The divisions in the vehicle fleet enable differences in emissions control technology and differences in fuel efficiency across age classes to be factored into the emissions estimation. Passenger vehicles and light commercial vehicles manufactured and sold in Australia before 1976 are assumed to have no emissions control equipment. The 1975–76 to 1984–85 group uses a variety of non-catalytic control (such as exhaust gas recirculation) and all groups after 1984–85 use catalytic control.

In general, non-CO_2 exhaust emissions from vehicles have been calculated by the following form of equations:

$$E_{(l)ijk} = A^{u=2}_{ijk} \times EF_{(l)ijk} \quad (3.3)$$

Where $A^{u=2}_{ijk}$ is the distance travelled for vehicle type i and age class j, using fuel type k;

$EF_{(l)ijk}$ is the exhaust EF for gas l from vehicle type i and age class j using fuel type k

This is conducted for urban and rural operation in each state or territory and where vehicle distances travelled during the hot-engine phase of operation are related to energy consumption levels.

$$A^{u=2}_{ijk} = A^{u=1}_{ijk} / R_{ik} \times D_k \quad (3.4)$$

Where $A^{u=2}_{ijk}$ is the distance travelled for vehicle type i and age class j, using fuel type k

$A^{u=1}_{ijk}$ is the fuel consumption for vehicle type i with emission control technology j and fuel type k

R_{ijk} is the average rate of fuel consumption (in L/km) for vehicle type i and age class j, using fuel type k

D_k is the energy density of fuel type k (in MJ/L)

$$EF_{(l)ijk} = (ZKL_{ijk} + DR_{ijk} \times C_umVKT_{ijk}) \qquad (3.5)$$

Where $EF_{(l)ijk}$ is the EF for gas l from each vehicle type i and age class j, using fuel type k
ZKL_{ijk} is the zero-kilometre level emissions of a gas l from vehicle type i and age class j
DR_{ijk} is the deterioration rate for vehicle type i, age class j and fuel type k
C_umVKT_{ijk} is the cumulative VKT for vehicle type i and age class j, and fuel type k, in each state or territory

$$C_umVKT_{ijk} = \Sigma_{\,t=1-n}\, A^{u=2}{}_{ijk} \qquad (3.6)$$

Where $A^{u=2}{}_{ijk}$ is the average distance travelled (in km) by vehicle type i and age class j, using fuel type k=automotive gasoline, diesel, and LPG in each State or Territory summed over time

Cold start emissions are derived using equation 3.7:

$$Ecs_{ijk} = CS_{ijk} \times EF_cs_{ijk} \qquad (3.7)$$

Where Ecs_{ijk} are the cold start emissions for vehicle type i and age class j, using fuel type k
CS_{ijk} is the number of cold starts for vehicle type i and age class j, using fuel type k
EF_cs_{ijk} is the cold start EF (g/start) for vehicle type i and age class j, using fuel type k

Data on fuel consumption for individual vehicle types is derived from the Australian Energy Statistics (DCCEEW 2023) and Survey of Motor Vehicle Use Australia (ABS 2020). The data on fuel consumption rates are taken from Survey of Motor Vehicle Use Australia (ABS 2020). The profile and age of the passenger vehicle stock in each State and Territory required for equation 3.5 is taken from Motor Vehicles Australia (BITRE 2023). The vehicle stock from each historical year varies largely due to vehicle sales from each particular year, which in turn is largely driven by the prevailing economic conditions. For example, the vehicle stock in 1990–91 is lower than surrounding years as a result of lower vehicle sales impacted by an economic recession affecting Australia at the time.

Emissions of CH_4 from motor-vehicles are a function of the emission and combustion control technologies present as well as vehicle operating conditions. EFs chosen for passenger and light commercial vehicles were obtained from Australian sources where these were available and applicable to the vehicle fleet and its various modes of operation and fuel types. A major empirical study *(Second National In-service Emissions Study)* of emissions from the operation of light duty petrol vehicles was undertaken in 2009. The results of this study were analysed for the national inventory (Orbital Australia 2010). The study directly measured emissions from 347 petrol passenger vehicles and light commercial vehicles manufactured from 1994–2009. The 347 vehicles represented four ADR (Australian Design Rule, DIRD 1969–1988) age groupings.

A petrol Composite Urban Emissions Drive Cycle (CUEDC) was developed as a means of better representing driving under Australian conditions. All vehicles undertook a hot start CUEDC while a subset of the vehicles also undertook a cold start. Emission measurements were allocated to hot urban, non-urban and cold driving conditions. Total hydrocarbon, CO, NO_x, CO_2 and CH_4 emissions were measured from bag samples. EFs and deterioration rates were derived for ADR groupings for each gas and each driving condition.

Using the EFs and deterioration rates a zero-kilometre EF was derived. Results were assessed by cross-referencing the generated results to the zero-kilometre capability of the vehicle fleet. This reference point is based on the assumption that at zero kilometres the vehicles were generally in compliance with emission standards of the day and that in general the deterioration over the ADR specified period is indicated to be in line with automotive engineering expectations. Orbital Australia (2010) details these checks.

Another report by Orbital Australia (2011) was used to extend the direct measurement approach outlined above to older vehicles by utilising measurements taken for other studies including the pilot phase of the *Second National In-service Emissions Study* and the *First National In-service Emissions Study.* The outcomes from this report provided updated EFs and deterioration rates for petrol passenger vehicles and light commercial vehicles manufactured between 1986 and 1993. The use of disaggregated, country-specific EFs expressed in terms of emissions per kilometre travelled is consistent with the IPCC Tier 3 methodologies (IPCC 2006, 2019). For vehicles not covered by the studies outlined above the choice of US versus European default factors has been dictated by the exhaust emission standards in the Australian Design Rules (ADR) applicable to each particular vehicle vintage. Australian Design Rules have been harmonised with European Standards since 1996 in heavy duty vehicles. Therefore, the IPCC default factors used for post-1995 heavy duty vehicles are based on European data (EEA 2011). Prior to the harmonisation with European standards, US Federal Test Protocol standards were used as the basis for ADRs. Therefore, USEPA default factors cited in the IPCC 2006 Guidelines are used for earlier vehicle vintages where required (IPCC 2006).

Australian design rules applied to Australia's vehicle fleet, their date of introduction and the European sources for these standards are outlined in Table 3.17. The age-band structure of the motor vehicle emission model is based on the applicability of a given ADR to a given vehicle vintage.

Table 3.17 Australian petrol passenger car exhaust emission standards, Australian heavy duty diesel exhaust emission standards

Australian Standard	Year introduced	Source standard
Petrol passenger vehicles		
ADR 79/00	2004	Euro 2
ADR 79/01	2006	Euro 3
ADR 79/02	2010	Euro 4
ADR 79/03	2011	Euro 5
ADR 79/04	2016	Euro 5
Heavy duty diesel exhaust		
ADR 70/00	1996	Euro 1
ADR 80/00	2003	Euro 3
ADR 80/01	2005	Euro 4
ADR 80/02	2008	Euro 4
ADR 80/03	2010	Euro 5

Source: (DITRDCA 2022)

There are no country-specific CH_4 EFs available for heavy-duty vehicles. These EFs have been taken from the Australian Methodology for the Estimation of Greenhouse Gas Emissions and Sinks 2006 (DCC 2006) or the 2006 IPCC Guidelines (IPCC 2006). CH_4 EFs for post-2005 vintage vehicles (Euro 3) have been derived based on the Euro 1 COPERT IV EF (EEA 2011) and an emission reduction factor according to the method in the EMEP/EEA air pollutant emission inventory guidebook (EEA 2009).

Emissions of non-CO_2 exhaust gases may increase as the vehicle ages due to the gradual wearing of components, poor maintenance, deactivation of catalyst materials, removal of emission control equipment, oxygen sensor failure, or modification of the engine. The rate of increase in emissions per kilometre per vehicle kilometres travelled is the deterioration rate. Deterioration rates are positive, indicating that emissions increase with mileage. Deterioration rates for each gas, vehicle design category and vehicle type combination are calculated by fitting a linear regression to the scatter of directly measured emissions by vehicle kilometres travelled.

For petrol passenger vehicles and light commercial vehicles manufactured prior to 1986 a study by EPA NSW (EPA NSW 1995) analysed the combined emission test databases of EPA NSW and EPA Victoria to determine deterioration rates and zero VKT (i.e. new car) emissions for the two States' combined fleet. For vehicles manufactured from 1986 onwards the deterioration rates are taken from Orbital Australia's analysis of the *Second National in Service Emissions* study (Orbital Australia 2010) and their review of uncertainty in fuel properties (Orbital Australia 2011).

The inventory model is regularly updated to allow separate deterioration rates to be applied to passenger vehicles and light commercial vehicles.

The deterioration rates derived in the Orbital reports are based on a study of petrol vehicles. A separate study was undertaken to assess the appropriateness of applying the petrol deterioration rates to other fuels (Orbital Australia 2011). Limited information was found on the deterioration rates of many vehicles using other fuels however there was evidence that the deterioration rate of diesel passenger vehicles is less than petrol vehicles. Based on the available information Australia has applied the petrol deterioration rates to the diesel and ethanol consumed in passenger and light commercial vehicles which is believed to be a conservative approach. The deterioration rates used to derive EFs for the passenger and light commercial vehicle fleet are shown in Table A5.3.2.10. The data shows no evidence of deterioration in the level of N_2O emissions, therefore a deterioration rate of 0 is used.

The majority (345 out of 347) of vehicles tested in the *Second National in Service Emissions* study had a VKT between 0 and 300,000km. Most of the deterioration rates used in the transport model are sourced from this data set. Therefore, Australia has applied a limit to the application of the deterioration rate based on total vehicle kilometres travelled. This limit is applied at an accumulated average VKT of 300,000km per vehicle.

N_2O EFs for Australia's petrol-fuelled passenger vehicle fleet are based on CSIRO testing (Weeks, Galbally and Guo-hong 1993) of vehicles of vintage up to 1993, fitted with a range of emissions control technology. Test data on vehicles not fitted with catalysts are used for the pre-1975–76 and the 1975–76 to 1984–85 age groupings and a weighted average of the catalyst equipped emissions used for the 1984–85 to 1996–97 and the post-1996–97 vehicle fleet. The EFs in Weeks et al. are comparable to those reported by the IPCC (2000) and by the USEPA and COPERT IV (2011). N_2O EFs for light duty petrol vehicles of vintage 1994 onwards are estimated on the Orbital Australia (2010) report on NISE 2 data.

Australian emissions standards as set out in Australian Design Rules (ADRs) have tended to lag those applied in Europe and the United States (see Table 3.17). Consequently, the types of emissions control technology employed in Australia also tend to lag as these are introduced to comply with the emissions standards.

There are no country-specific N_2O EFs available for heavy-duty vehicles. These EFs have been taken from DCC (2006) and IPCC (2006).

EFs from the 2006 IPCC Guidelines (IPCC 2006) are used in the road transportation sector when they are the most appropriate factors for the vehicle standards and technology that exist in the Australian road transport fleet.

Australia's IEF for CH_4 from liquid fuels (Fuel Combustion sectoral approach) is most influenced by the contribution of CH_4 emissions for Road Transportation, Cars, and Petroleum. CH_4 implied emission factors for Road Transportation, Cars, and Petroleum have been trending down since the mid-1990s as the inventory reflects improved vehicle emissions control technology performance in the Australian fleet.

Diesel oil implied emission factors, notably for N_2O, tend to fluctuate due to the emission factors for N_2O being highly different for medium and heavy trucks and buses, resulting in implied emission factor fluctuations according to their proportional contributions.

The Australian fleet has a relatively high non-CO_2 emissions profile due to the lag behind source emission standards applied in Europe and the United States – consequently, the types of emissions control technology employed in Australia lags as these are introduced to comply with the emissions standards. This is compounded in the current fleet by a relatively slow fleet turnover and transition to vehicles with improved emission control technologies.

Extensive tables containing the factors and other parameters used for the estimation of emissions from road transport are included in Annex 5.3.2.

Motorcycles (1.A.3.b.iv)

The estimation of emissions for motorcycles is given by equations 3.2 and 3.3. Fleet average EFs for motorcycles are provided in Annex 5.3.2.

Evaporative fuel emissions (1.A.3.b.v)

Road vehicles using automotive gasoline emit NMVOCs both from the exhaust and through evaporation. The evaporative NMVOC emissions include:

- Running losses resulting from evaporative emissions released during engine operation. Running losses occur when the capacity of the vapour control canister and purge system is exceeded by the vapour generation rate and are greatest at low average vehicle speeds. Running losses vary with the age and type of control system of the vehicle and the trip duration;
- Hot soak losses resulting from evaporation of fuel at the end of each trip. These emissions bear little relation to the VKT for an individual vehicle. A more realistic activity on which to base these emissions is the number of trips an average vehicle would make in a given time period;
- Diurnal losses resulting from vapour being expelled from fuel tanks due to ambient temperature rises. These emissions are strongly dependent on the Reid Vapour Pressure (RVP) of the fuel, the daily ambient temperature changes and where the vehicle is parked during the day. Emissions will vary significantly between identical vehicles in different geographical regions. Diurnal emissions only occur when the temperature is rising; and
- Resting losses resulting through the permeation of fuel through rubber hoses or open bottom carbon canisters. Resting losses have often been included in measurements of hot soak, diurnal and running losses (USEPA, 1991a).

EFs for evaporative emissions for each of the three passenger vehicle age classes have been estimated for average Australian temperatures and fuel properties and are presented in Annex 5.3.2.

Urea-based catalysts (1.A.3.b.vi)

The use of urea-based additives (diesel exhaust fluid – DEF) in selective catalytic reduction (SCR) technology to reduce NO_x emissions from diesel-powered vehicles occurs in Australia.

Australia has made a preliminary estimate of emissions from urea-based catalysts and considers it to be an insignificant source in accordance with paragraph 37b of the of the UNFCCC Annex I inventory reporting guidelines.

This assessment was made by considering the potential emissions from all diesel-powered heavy duty trucks, medium trucks, buses, light commercial vehicles and passenger cars in the Australian fleet that conform to Euro IV and Euro V. It was assumed that all these vehicles are equipped with SCR technology and that they consume urea-based catalysts at a rate of 6 per cent of fuel consumption. Both assumptions are highly conservative.

- Australian emission standards mirror Euro emission limits and approaches and do not dictate a particular technology with emission standards met by a range of technological approaches, not just by SCR.

For example, the most popular passenger cars in Australia are the Toyota Hilux and Ford Ranger that do not employ SCR.

- The EMEP/EEA Guidebook suggests that urea consumption is 3–4 per cent of fuel consumption for a Euro IV heavy truck and bus and 5–7 per cent for a Euro V heavy truck and bus (EEA 2009). To be conservative, Australia applied 6 per cent to all vehicle classes.

Even with these conservative assumptions, emissions in 2021–22 are estimated to be 154.5 kt CO_2–e (0.030% of the national total emissions) which is well under the threshold for significance according to paragraph 37b of the UNFCCC Annex I inventory reporting guidelines.

Australia has no immediate plans to report emissions from Urea-based catalysts category (1.A.3.b.vi) - there is a considerable data requirement to estimate the emissions considering fuel consumption rates and penetration of the technology in the fleet. Australia will investigate sources with the aim of addressing this data requirement in a future submission. Given the insignificance of the source, this is not considered to add materially to the completeness of the inventory.

Railways (1.A.3.c)

Emissions are estimated using Tier 2 methods described by equations 3.1 and 3.2. CO_2 EFs are reported in Table A5.3.1.1 and non-CO_2 EFs are reported in Table 3.18. Given data on the composition and engine types in the local fleet, an average fleet EF has been calculated using the individual engine EFs from USEPA (1992). Data on fuel consumption is taken from the Australian Energy Statistics (DCCEEW 2023).

Coal use is confined to historic railways used in tourism operations. Based on information published in the annual report of the Puffing Billy Historic Railway on their coal consumption and associated emissions, which is assumed to be representative of the industry's activities, it is estimated that emissions from solid fuel use in railways would not exceed 24.3 kt CO_2–e .

Table 3.18 Non-CO_2 emission factors for non-road sources

	CH_4	N_2O	NO_x	CO	NMVOC
Source Category			(g/MJ)		
Rail Transport [(a) (c)]					
Diesel	0.004	0.03	1.530	0.202	0.071
Marine Transport [(b) (c)]					
Domestic					
Petrol – Small Craft	0.360	0.001	0.254	20.300	3.240
Diesel	0.007	0.002	1.105	0.246	0.075
Fuel Oil	0.007	0.002	2.000	0.044	0.063
NG	0.243	0.001	0.243	0.095	0.029
Coal	0.032	0.001	0.190	0.220	0.260
International					
Diesel	0.007	0.002	1.580	0.163	0.046
Fuel Oil	0.007	0.002	2.000	0.044	0.063

Source: (a) (USEPA 1992). (b) Lloyd's Register of Shipping (1995, and previous issue). (c) (IPCC 2006)

Domestic navigation (1.A.3.d)

Emissions are estimated using Tier 2 methods described by equations 3.1 and 3.2. CO_2 EFs are reported in Table A5.3.1.1 and non-CO_2 EFs are 2006 IPCC Guidelines Default values (IPCC 2006) or taken from Lloyds Register of Shipping (1995) and are reported in Table 3.18. As discussed in Annex 5.3.1, where IPCC 2006 defaults are adopted their appropriateness for Australia has been validated by Orbital Australia (2011)

Emissions from international bunker fuels are also estimated but are excluded from national emission inventory aggregates by international agreement. Activity data for international bunkers is estimated as part of the Australian Energy Statistics (DCCEEW 2023).

Pipeline transport (1.A.3.e.i)

Australia has an extensive system of long-distance natural gas transmission pipelines. Emissions are estimated using Tier 2 methods described in Annex 5.3.1. Data on fuel consumption is taken from the Australian Energy Statistics (DCCEEW 2023).

3.2.6.3 Uncertainty assessment and time-series consistency

The Tier 1 uncertainty analysis in Annex II provides estimates of uncertainty according to IPCC source category and gas. Time series consistency is ensured using consistent models, model parameters and datasets for the calculations of emissions estimates. Where changes to EFs or methodologies occur, a full time series recalculation is undertaken.

3.2.6.4 Category- specific QA/QC and verification

This source category is covered by the general QA/QC of the greenhouse gas inventory outlined in Annex IV.

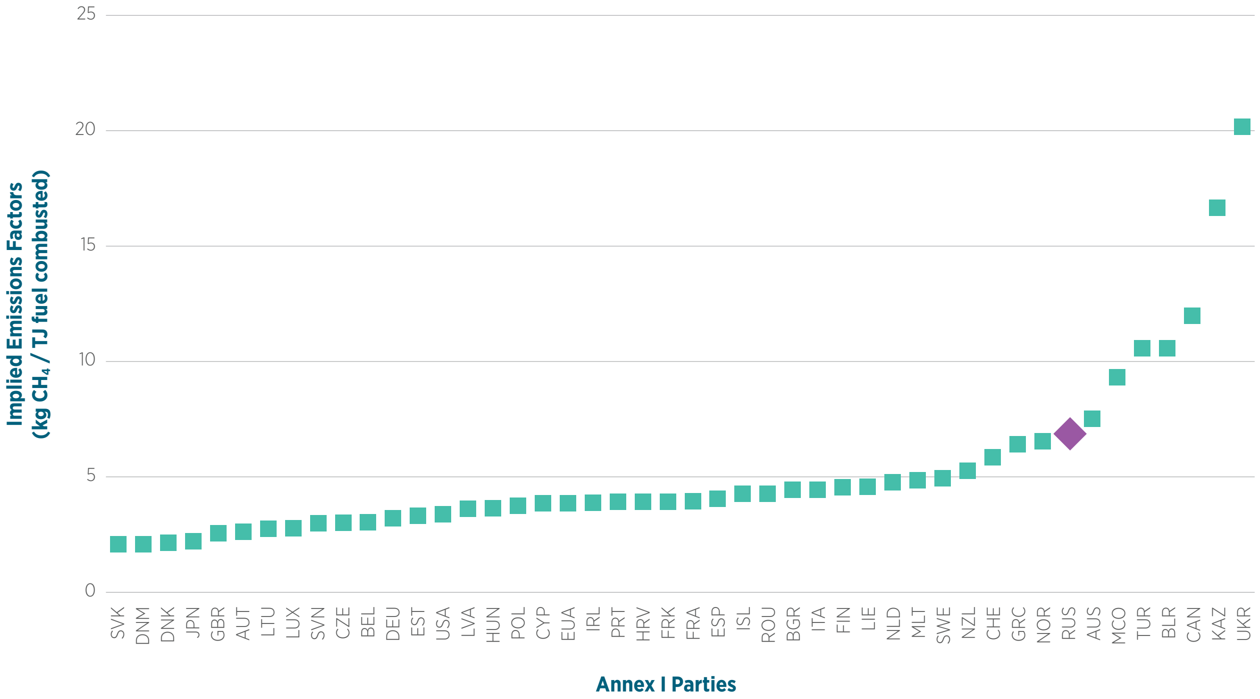
The primary sources of activity data for this sector are from the Department's Australian Energy Statistics (AES), the Bureau of Infrastructure and Transport Research Economics (BITRE) and from the Australian Bureau of Statistics (ABS). These three organisations have systematic quality assurance programmes in place. In addition, there are also several critical user organisations and alternative data sources available for this sector.

Comparisons of IEFs and with international data sources are conducted systematically for the Australian inventory. In the 2022 inventory submission it was found that the IEF for CH_4 from the combustion of liquid fuels in Australia (7.5 kg CH_4/TJ) was higher than those of other Annex 1 parties (4.5 kg CH_4/TJ) (Figure 3.19).

Three studies (Orbital 2010, 2011a, 2011b) have improved the emission estimates for fuel combusted by Australian passenger vehicles and light commercial vehicles (the largest contributors to CH_4 fuel combustion emissions).

Throughout the time series, Australia has introduced progressively stricter emission standards for new motor vehicles sold in Australia. Over time, the fleet composition reflects the improved performance of larger amounts of vehicles operating with sophisticated catalysts and efficient fuelling systems. The steady rollout of these technologies into the fleet has been reflected in a steady decrease in the emissions of CH_4 and other unburnt hydrocarbons from gasoline engines in particular.

Figure 3.19 Implied emission factors from liquid fuel combustion for Annex I countries (2023 submission) and Australia (2024 submission), kg CH_4 per TJ combusted



Note: For the purpose of international comparisons, Australia's IEF of 7.2 kg/TJ on a gross calorific value basis has been converted to an approximate IEF of 7.5 kg/TJ on a net calorific value basis.

Independent emissions modelling

Independent assessments of emissions from air and road transport are undertaken in Australia, providing independent verification of emission estimates prepared in accordance with the 2006 IPCC Guidelines.

Independent of the national inventory, the former Department of Infrastructure and Regional Development (DIRD) has developed a software tool to compute and track the carbon footprint associated with aircraft fuel uplifted in Australia. The DIRD completed an assessment of the robustness of their results by comparing their calculated values with the APS. Their results showed that for domestic aviation, computed CO_2 estimates using the software tool and inventory estimates differed by 0.1 per cent in 2012-13 for domestic consumption, and 2.1 per cent for international consumption in 2012–13. This is considered to be an excellent independent verification of the estimates.

DIRD (now the Department of Infrastructure, Transport, Regional Development, Communications and the Arts) no longer undertakes modelling of aircraft emissions independently. Whilst future comparisons will not be possible, the several years it was possible have served to validate methods that continue to be applied in the inventory.

Additionally, an Australian specific application of COPERT has been developed by the University of Queensland for use in modelling air quality emissions from the Australian road vehicle fleet. Included in this is the ability to model greenhouse gas emissions.

Emission estimates for CO_2 aligned well with the National Greenhouse Accounts, with less than 4 per cent difference in emissions from road transport.

3.2.6.5 Category-specific recalculations

The recalculations reported in the current submission are shown in Table 3.19, and include:

A. Correction to pipeline transport AD

Activity data for 1.A.3.e.i Pipeline transport is sourced from the Australian Energy Statistics' reporting of the amount of natural gas consumed by ANZSIC Sub-divisions 50–53 Other transport, services and storage for gas transportation purposes (DCCEEW 2023).

Previous submissions' estimates of pipeline transport emissions have included natural gas consumed by ANZSIC subdivisions 50–53 for purposes other than gas transportation, emissions which are already reported under 1.A.4.a Commercial/Institutional. This has been corrected in this submission, resulting in a downward revision to pipeline transport emissions between 2002–03 and 2016–17.

B. Missing Domestic Navigation black coal AD

The Australian Energy Statistics reported Domestic Navigation black coal consumption in 2007–08 that was not included in previous submissions' estimates. The missing AD and emissions have been included in this submission, resulting in an upward recalculation of Domestic Navigation emissions in 2007–08.

C. Missing Domestic Aviation gasoline AD

The Australian Energy Statistics reported Domestic Aviation gasoline consumption in 2008–09 that was not included in previous submissions' estimates. The missing AD and emissions have been included in this submission, resulting in an upward recalculation of Domestic Aviation emissions in 2008–09.

D. Minor correction to ethanol allocation

A time series correction to the allocation of ethanol consumption between Domestic Navigation, Road Transport and Off-road Vehicles in 1.A.3 Transport and lawnmowers in 1.A.4.b has resulted in minor recalculations between 2005–06 and 2020–21.

E. Revision to Road Transportation AD in the Australian Energy Statistics

Road transport natural gas consumption for 2020–21 was revised in the latest release of the Australian Energy Statistics (DCCEEW 2023).

F. Revision to motor vehicle stock

Motor vehicle stock data used to calculate road transport non-CO_2 emissions were revised by the Bureau of Infrastructure and Transport Research Economics for the 2020–21 inventory year. This has been corrected for this submission and results in a recalculation in non-CO_2 emissions in road transport in 2020–21.

G. Minor corrections to AD

Several minor corrections to AD across several transport modes and fuels have been implemented to accurately reflect the latest release of the Australian Energy Statistics (DCCEEW 2023).

Table 3.19 1.A.3 Transport: recalculation of total CO_2-e emissions, 1989–90 to 2020–21

	2023 Submission	2024 submission	Change		Reasons for recalculation (Gg CO_2-e)						
Year	Gg CO_2-e	Gg CO_2-e	Gg CO_2-e	%	A	B	C	D	E	F	G
1989–90	61,370	61,370	0.0	0.0	-	-	-	-	-	-	-
1994–95	68,216	68,216	0.0	0.0	-	-	-	-	-	-	-
1999–00	74,026	74,026	0.0	0.0	-	-	-	-	-	-	-
2004–05	82,047	82,015	-31.3	0.0	-36.2	-	-		-	-	4.9
2005–06	83,340	83,266	-74.3	-0.1	-46.5	-	-	-0.1	-	-	-27.7
2006–07	85,292	85,130	-162.0	-0.2	-48.6	-	-	-0.9	-	-	-112.4
2007–08	86,318	86,932	614.3	0.7	-51.8	729.3	-	0.1	-	-	-63.2
2008–09	87,193	87,157	-36.6	0.0	-35.0	-	41.7	-1.6	-	-	-41.8
2009–10	88,653	88,619	-34.1	0.0	-33.7	-	-	-1.3	-	-	0.9
2010–11	91,271	91,247	-23.9	0.0	-32.3	-	-	11.1	-	-	-2.7
2011–12	91,810	91,787	-23.3	0.0	-22.0	-	-	-1.7	-	-	0.4
2012–13	93,157	93,134	-22.9	0.0	-21.9	-	-	-1.3	-	-	0.3
2013–14	93,120	93,090	-30.2	0.0	-25.8	-	-	0.1	-	-	-4.5
2014–15	95,256	95,232	-23.6	0.0	-20.3	-	-	-3.2	-	-	-0.1
2015–16	96,247	96,226	-21.5	0.0	-21.2	-	-	-1.9	-	-	1.6
2016–17	97,874	97,849	-24.3	0.0	-23.6	-	-	-0.6	-	-	-0.1
2017–18	100,148	100,146	-2.2	0.0	-	-	-	-0.2	-	-	-2.0
2018–19	100,205	100,204	-0.2	0.0	-	-	-	-0.1	-	-	-0.1
2019–20	93,178	93,181	3.4	0.0	-	-	-	-1.6	-	-	4.9
2020–21	90,192	90,097	-95.1	-0.1	-	-	-	1.5	-85.2	-2.2	-9.3

3.2.6.6 Category-specific planned improvements

The Orbital Australia reports (2010, 2011) provided detailed vehicle testing data that is at a greater level of disaggregation than is currently supported in the national inventory model. The Department plans to investigate and apply updates, as appropriate, to the issues listed below in future inventory submissions:

- Within the passenger vehicle groups, EFs for large SUVs (sport utility vehicles) can vary significantly between specific vehicle make/models depending on the original ADR to which they are certified. These factors are also significantly different to the other vehicle sub-types in the passenger vehicle group. Separate EFs and DRs for SUV-Large are available. The Department will investigate whether all the activity data is available to support further disaggregation of vehicle classifications in the next annual inventory submission; and
- Passenger vehicle and light commercial vehicle EFs from the *Second National in Service Emissions* study dataset are available for an additional drive cycle (hot extra urban). The Department will investigate whether the required data is available to support the further disaggregation of drive cycles in the next inventory submission.

Australia continues to investigate EFs for new petrol passenger vehicles to take account of the latest exhaust emission standards adopted in Australia.

Australia will investigate sources with the aim to update non-CO_2 emission factors for domestic navigation and railways. Current navigation factors come from Lloyd's Register of Shipping (1995) which has been noted by a previous ERT as being out of date. Similarly, current railway factors are sourced from US EPA (1992). Noting that these are minor sources of emissions this analysis will be prioritised accordingly.

3.2.7 Other Sectors

3.2.7.1 Category description

Source category *1.A.4 other sectors* is an aggregation of the following sources:

- Commercial/Institutional – a diverse category which includes direct emissions from water utilities, accommodation, communications, finance, insurance, property and business services, government and defence, education, health and wholesale and retail trade;
- Residential – emissions from fuel combustion in households, including lawnmowers; and
- Agriculture, forestry and fisheries – emissions from fixed and mobile equipment.

3.2.7.2 Methodological issues

The methodology for this sector consists of tier 2 approaches and country specific CO_2 EFs. Non-CO_2 EFs have been calculated using a sectoral equipment-weighted average approach.

Table 3.20 Summary of methods and emission factors: 1.A.4 Other Sectors

	CO_2		CH_4		N_2O	
Source Category	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**
1.A.4.a Commercial/Institutional						
Liquid Fuels	T2	CS	T2	CS	T2	CS
Solid Fuels	T2	CS	T2	CS	T2	CS
Gaseous Fuels	T2	CS	T2	CS	T2	CS
Biomass	T2	CS	T2	CS	T2	CS
1.A.4.b Residential						
Liquid Fuels	T2	CS	T2	CS	T2	CS
Solid Fuels	T2	CS	T2	CS	T2	CS
Gaseous Fuels	T2	CS	T2	CS	T2	CS
Biomass	T2	CS	T2	CS	T2	CS
1.A.4.c Agriculture, Forestry and Fisheries						
Liquid Fuels	T2	CS	T2	CS	T2	CS
Gaseous Fuels	T2	CS	T2	CS	T2	CS

Notes: T1 = tier 1, T2 = tier 2, T3 = tier 3, CS = country specific, D = default, 🟪 = key category

Activity data are taken from the AES published by the Department (DCCEEW 2023). Non-CO_2 EFs for this sector, by ANZSIC Division, are reported in Table A5.3.2.2.

The Australian Energy Statistics report energy consumption by functional activity and classifies these to industries associated with them as a primary activity using the Australian and New Zealand Standard Industrial Classification (ANZSIC). These activities can be mapped to IPCC classifications (Table 3.21).

Only the liquid fuels from ANZSIC Subdivision 50–53 Other transport, services and storage are included in this category. The natural gas consumption is accounted for within the Transport sector (Natural Gas Transmission) sub-category. The natural gas and LPG consumption from sub-category 47 Railway Transport is included in this category as it is assumed to be for stationary activities and not for mobile purposes.

Table 3.21 Relationship between IPCC source categories and ANZSIC sectors: Other Sectors

	ANZSIC Category		
IPCC Source Category	**Division**	**Subdivisions**	**Description**
4. Other Sectors			
a Commercial/Institutional	Division D	28–29	Water and waste services
	Division I	50–53	Other transport, services and storage
	Divisions F-H & J-S	33–45	Commercial services
b Residential	Residential	54–96	Residential
c Agriculture/forestry/fishing	Division A	1–5	Agriculture, Forestry and Fishing

Commercial & Institutional (1.A.4.a)

Emissions in this category are estimated based on fuel combustion reported in the AES (DCCEEW 2023).

Residential – biomass combustion (1.A.4.b)

The *Residential* sector includes specific treatment of the use of firewood in residential wood heaters and the combustion of fuels in mobile equipment such as lawnmowers.

The tier 2 estimation of emissions from residential firewood use requires a more complex approach to the estimation of emissions from fossil fuels reflecting information on heater design (technology type) and the operation of wood-burning appliances, which influences the mix of emissions per kilogram of firewood consumed. Information on the model is provided in Annex 5.3.3.

Emissions from lawnmowers are estimated using tier 2 methods described in Annex 5.3.1, with additional non-CO_2 EFs provided in Annex 5.3.2. There are no fuel consumption statistics for these activities, instead allocation factors are used to derive this data from known consumption statistics. Lawn mowers are powered by small 2-stroke or 4–stroke engines and assumed to be utilised in the ratio of 60:40 (EPA NSW 1995).

Agriculture, Forestry and Fishing (1.A.4.c)

The AES present a single total figure for diesel fuel consumed in agriculture, fisheries and forestry (DCCEEW 2023). However, the types of equipment used by these industries vary quite widely (tractors, log skidders, fishing boats etc.), and therefore EFs for non-CO_2 gases also vary widely. It is assumed that the agriculture, fisheries and forestry industries account respectively for 77 per cent, 6 per cent and 17 per cent of total diesel fuel consumption by the sector as a whole. This estimate is based on the relative volumes of diesel fuel for which excise rebates were claimed, as advised by the Australian Customs Service, over the period 1987–88 to 1993–94 inclusive, and have been held constant throughout the period.

These ratios were applied to EFs for the different types of diesel engines used in the types of equipment typical of the three sectors, to estimate weighted sectoral EFs (Table 3.22).

Table 3.22 Non-CO_2 emission factors for non-transport uses of transport fuels

	CH_4	N_2O	NO_x	CO	NMVOC
			(g/MJ)		
Other Mobile Sources					
Recreational Vehicles					
Petrol	0.03	0.0009	0.37	7	1.08
Industrial Equipment					
Diesel	0.0057	0.002	1.006	0.39	0.108
LPG	0.022	0.001	0.437	5.465	0.409
Farm Equipment					
Diesel	0.01	0.002	1.36	0.541	0.189
Tractors	0.0096	0.002	1.362	0.543	0.183
Non-Tractors	0.011	0.002	1.351	0.531	0.21
Utility Engines					
Petrol	0.38	0.0009	0.087	13	3.45

Source: IPCC (1997), USEPA (1995a), F. Carnovale pers. comm., 1995.

3.2.7.3 Uncertainty assessment and time-series consistency

The Tier 1 uncertainty analysis in Annex II provides estimates of uncertainty according to IPCC source category and gas.

The time series variability of GHG IEFs are likely to be influenced by changes in fuel mix within categories.

3.2.7.4 Category-specific QA/QC and verification

This source category is covered by the general QA/QC of the greenhouse gas inventory in Annex IV.

3.2.7.5 Category-specific recalculations

The recalculations reported in the current submission are shown in Table 3.23 and include.

A. Updates to the Australian Energy Statistics

Australia's official statistics on energy production and use receives periodic updates to support improved understanding of Australia's energy systems, including for time series consistency. These updates are reflected in the inventory.

B. Minor correction to ethanol allocation

A time series correction to the allocation of ethanol consumption between Domestic Navigation, Road Transport and Off-road Vehicles in 1.A.3 Transport and lawnmowers in 1.A.4.b has resulted in minor recalculations between 2005–06 and 2020–21.

Table 3.23 1.A.4 Other sectors: recalculation of total CO_2-e emissions, 1989–90 to 2020–21

	2023 submission	2024 submission	Change		Reasons for recalculation ($Gg\ CO_2$-e)	
	Gg CO_2-e	Gg CO_2-e	Gg CO_2-e	%	A	B
1989–90	15,884.0	15,884.0	0.0	0.0	-	-
1994–95	17,428.6	17,428.6	0.0	0.0	-	-
1999–00	18,416.7	18,416.7	0.0	0.0	-	-
2004–05	20,212.0	20,212.0	0.0	0.0	-	-
2005–06	20,364.1	20,364.1	0.0	0.0	-	0.0
2006–07	20,197.9	20,197.9	0.0	0.0	-	0.0
2007–08	20,542.1	20,542.1	0.0	0.0	-	0.0
2008–09	20,713.9	20,714.2	0.3	0.0	-	0.3
2009–10	21,044.1	21,044.5	0.4	0.0	-	0.4
2010–11	21,451.8	21,452.5	0.7	0.0	-	0.7
2011–12	21,895.4	21,895.8	0.4	0.0	-	0.4
2012–13	22,319.2	22,319.6	0.5	0.0	-	0.5
2013–14	21,403.4	21,403.9	0.4	0.0	-	0.4
2014–15	22,559.4	22,559.3	-0.1	0.0	-	-0.1
2015–16	22,803.5	22,803.4	-0.1	0.0	-	-0.1
2016–17	23,572.8	23,572.8	0.0	0.0	-	-0.0
2017–18	23,452.9	23,452.9	0.0	0.0	-	0.0
2018–19	21,962.0	21,962.0	0.0	0.0	-	0.0
2019–20	21,377.3	21,377.3	-0.1	0.0	-	-0.1
2020–21	23,723.3	23,748.8	25.4	0.1	25.4	0.0

3.2.7.6 Category-specific planned improvements

The Department continues to investigate applying revisions to the earlier years of the time series in response to improvements incorporated within future Australian Energy Statistics releases.

3.2.8 Other (Not Specified Elsewhere)

Emissions from *1.A.5 Other* are estimated using a mix of tier 1 and tier 2 approaches using EFs set out in Table 3.24.

Table 3.24 Summary of methods and emission factors: Other (Not Elsewhere Classified)

	CO_2		CH_4		N_2O	
1.A.5.b Other (mobile)	Method applied	Emission factor	Method applied	Emission factor	Method applied	Emission factor
Liquid Fuels	T2	CS	T2	CS	T2	CS
Biomass	T2	CS	T2	CS	T2	CS

Notes: T1 = Tier 1, T2 = Tier 2, T3 = Tier 3, CS = country specific, D = IPCC default, NE = not estimated, NA = not applicable, NO = not occurring, ▨ = key category

3.2.8.1 Category description

The source category *1.A.5 other* consists of emissions arising from fuel used in mobile equipment within defence operations.

3.2.8.2 Methodological issues

Emissions from military vehicles are estimated using tier 2 methods described for transport. EFs are reported in Annexes 5.3.1 and 5.3.2.

The allocations of fuel to military transport are based on energy use data provided by the Australian Department of Defence since 2007–08. Allocations for prior years are linearly extrapolated between reported data points in 1993–94 and 2007–08.

The shares used to allocate fuel consumption are reported in Annex 5.3.2.

3.2.8.3 Uncertainty assessment and time-series consistency

The tier 1 uncertainty analysis in Annex II provides estimates of uncertainty according to IPCC source category and gas.

3.2.8.4 Category-specific QA/QC and verification

This source category is covered by the general QA/QC of the greenhouse gas inventory in Annex IV.

3.2.8.5 Category-specific recalculations

Recalculations made to *1.A.5 other* are detailed at the sub-category level in Table 3.25.

Recalculations in this sector are a result of minor corrections to military transport fuel consumption activity data to accurately reflect the latest release of the Australian Energy Statistics (DCCEEW 2023), Australia's official statistics on energy production and use.

Table 3.25 1.A.5 Other: recalculation of total CO_2–e emissions (Gg), 1989–90 to 2020–21

	2023 submission	2024 submission	Change	
	Gg CO_2–e	Gg CO_2–e	Gg CO_2–e	%
1989–90	422.7	422.7	-	-
1994–95	696.0	696.0	-	-
1999–00	627.3	627.3	-	-
2004–05	622.8	624.4	1.54	0.2
2005–06	654.4	651.2	-3.3	-0.5
2006–07	827.0	782.8	-44.2	-5.4
2007–08	845.9	823.0	-22.9	-2.7
2008–09	833.7	834.3	0.6	0.1
2009–10	888.6	888.6	-	-
2010–11	898.0	898.0	-	-
2011–12	871.5	871.5	-	-
2012–13	911.1	911.1	-	-
2013–14	1025.6	1025.6	-	-
2014–15	945.0	945.0	-	-

	2023 submission	2024 submission	Change	
	Gg CO_2-e	Gg CO_2-e	Gg CO_2-e	%
2015–16	1107.5	1107.5	-	-
2016–17	923.8	923.8	-	-
2017–18	928.4	928.4	-	-
2018–19	791.7	791.7	-	-
2019–20	947.1	947.1	-	-
2020–21	816.2	816.2	-	-

3.2.8.6 Category-specific planned improvements

All relevant data is kept under constant review.

3.3 Fugitive emissions from solid fuels and natural gas and other emissions from energy production (CRT category 1.B)

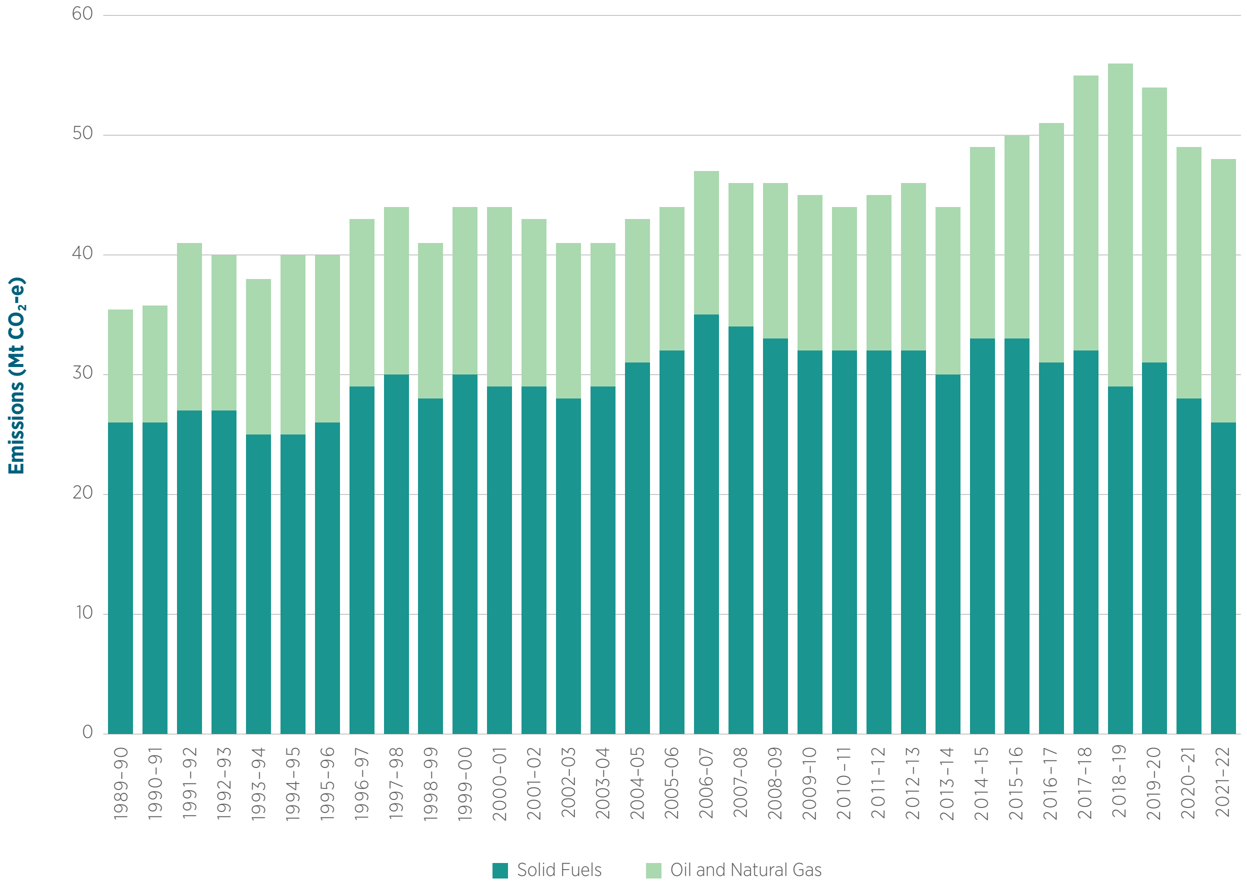
Fugitive emissions are defined by the 2006 IPCC Guidelines as the intentional or unintentional release of greenhouse gases that occur during the extraction, processing and delivery of fossil fuels to the point of final use (IPCC 2006). Unlike combustion emissions, which are predominantly CO_2, fugitive emissions are predominantly CH_4 (Figure 3.20).

Figure 3.20 Fugitive emissions as a share of total Energy emissions, by gas, 2021–22

Fugitive emissions can be grouped into fugitive emissions from solid fuels (1.B.1) and from oil and natural gas (1.B.2).

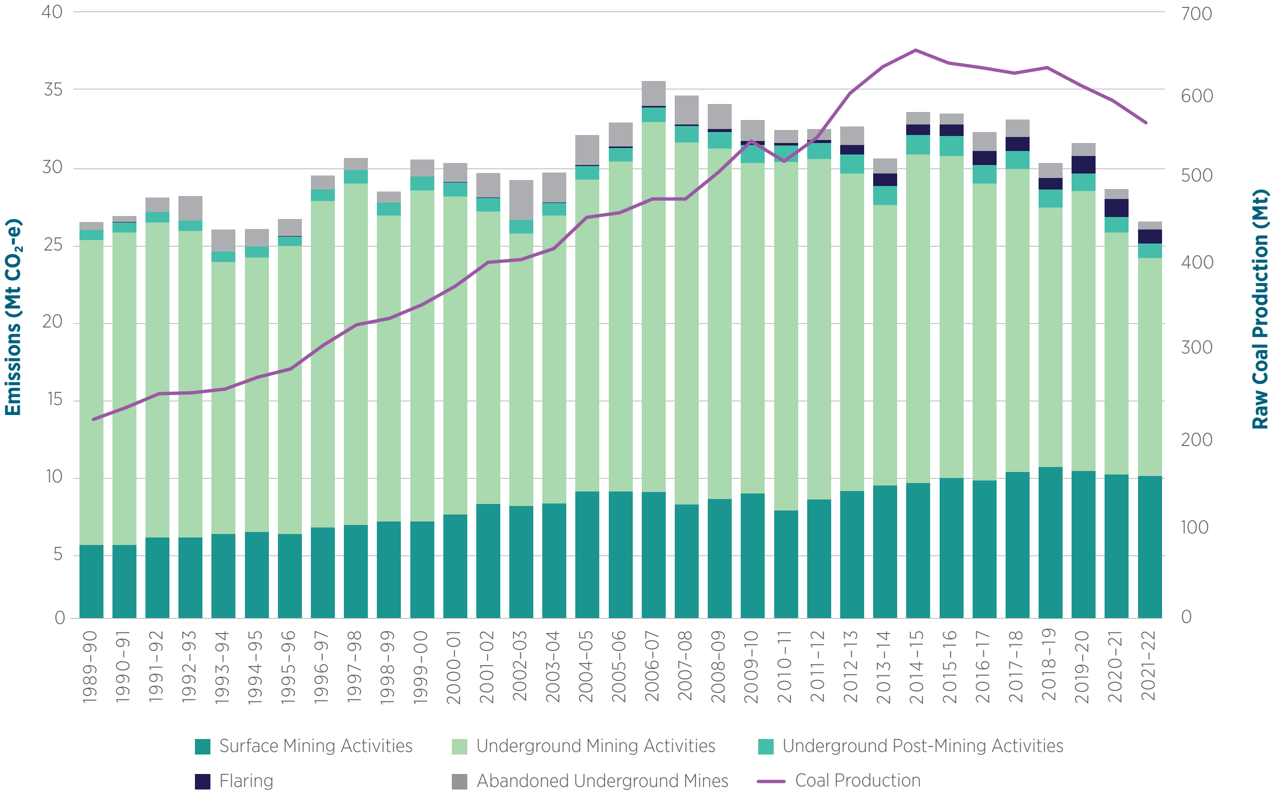
Fugitive emissions have been largely increasing since 1989–90, driven predominantly by increasing coal production. However, activities associated with oil and gas extraction, processing, and distribution are responsible for the most recent growth in fugitive emissions. This correlates with the expansion of onshore and offshore petroleum projects since the mid-2010s to support increasing liquefied natural gas (LNG) exports (Figure 3.21), with the most significant growth occurring between 2014–15 and 2019–20. Decreases in the most recent two years were driven by a reduction in production and associated emissions from underground mining (which tends to be gassier than surface mining).

Figure 3.21 Fugitive emissions by subsector, 1989–90 to 2021–22



Fugitive emissions from solid fuels tend to fluctuate from year to year depending on the volume of coal mined and the share of production from underground mines of varying gas contents. Mine production of coal has increased significantly since 1989–90 and peaked in 2014–15. Methane emissions have not grown as fast as production. This is because there has been an increasing trend in production in surface mines since 1997–98, which emit less gas than underground mines due to their shallower depth (Figure 3.22). Within underground mines, there has been a decreasing share of production from the gassiest southern coal field. In addition, the flaring of pre-drainage gas and technologies to recover and utilise coal mine waste gas for electricity generation have been increasingly adopted in underground mining, particularly in recent years.

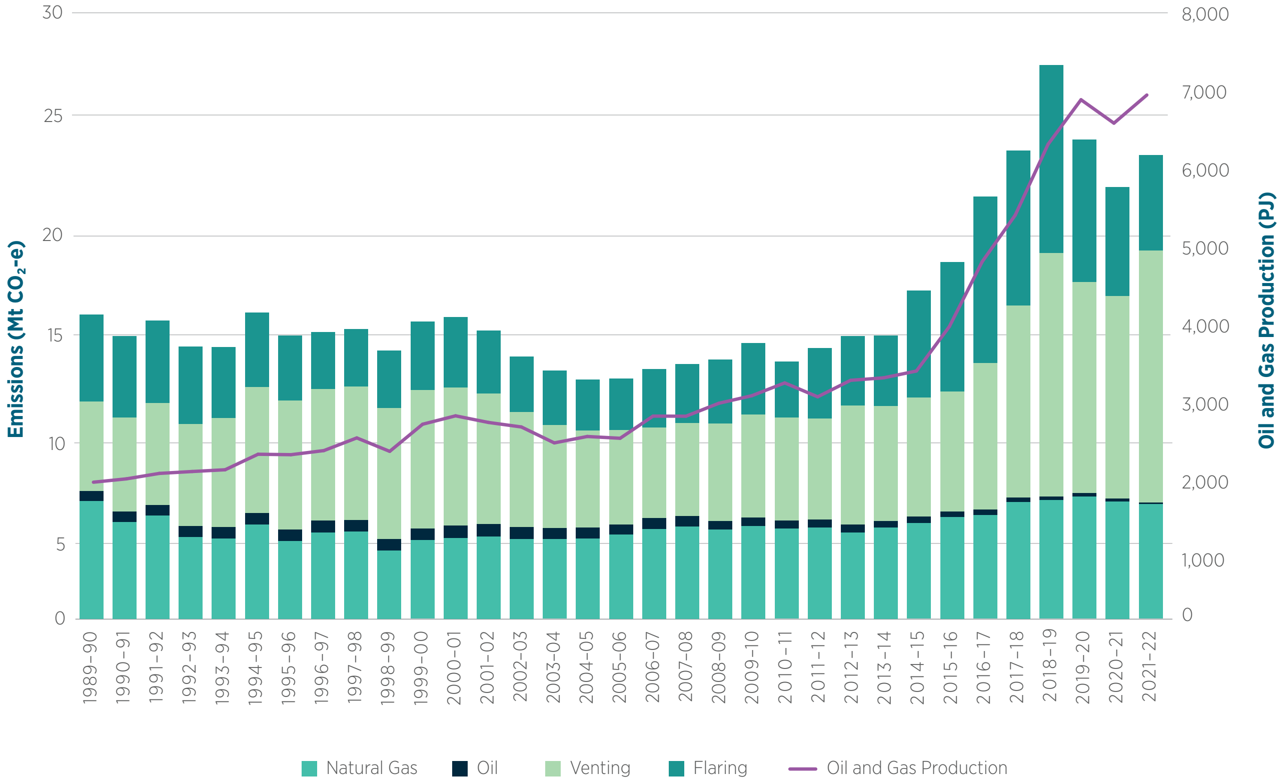
Figure 3.22 Fugitive CO_2–e and coal production from coal mining activities, 1989–90 to 2021–22



Source: Coal production data are from various State government departments (1989-90 to 2007-08) and the NGER Scheme (2008-09 to 2021-22).

Until around 2013–14, emissions from oil and natural gas fugitive emissions were relatively stable despite increasing production (Figure 3.23). The reduction in emissions intensity for this sector is driven by improvements in gas distribution and the commencement of large and efficient Liquified Natural Gas (LNG) production, processing, and export facilities. The increase in emissions since 2013–14 is attributable to increased venting and flaring associated with significantly increasing production. The Gorgon Carbon, Capture and Storage (CCS) project had it's first full year of CO_2 injection in 2020-21, driving a fall in venting emissions compared to 2019-20. Technical issues resulted in lower injection volumes in 2021-22 and correlated with higher venting emissions in that year. Peak venting and flaring occurred in 2018–19, the first year of ramp up of production at the Ichthys and Prelude LNG facilities. Once those facilities reached full production, this resulted in emergency and process venting and flaring falling from their peak.

Figure 3.23 Fugitive CO_2–e emissions and production volumes from oil and gas, 1989–90 to 2021–22



Source: Oil and gas production data are from the *Australian Energy Statistics 2023*, DCCEEW

3.3.1 Solid fuels

3.3.1.1 Category description

This source category covers fugitive emissions from the production, transport and handling of coal, and emissions from decommissioned mines. It does not include emissions arising from the conversion of coal into coke. Coverage of emissions for 1.B.1 Solid Fuel emission categories are shown in Table 3.26. Both methane and carbon dioxide emissions are reported under the NGER scheme for both underground and surface coal mines. Carbon dioxide, methane and nitrous oxide emissions are also reported from flaring.

At the end of the current reporting year, there were 36 underground mines and 73 surface mines operating nationally, while emissions are estimated for 131 decommissioned mines.

Table 3.26 1.B.1 Solid Fuels – Emissions source coverage

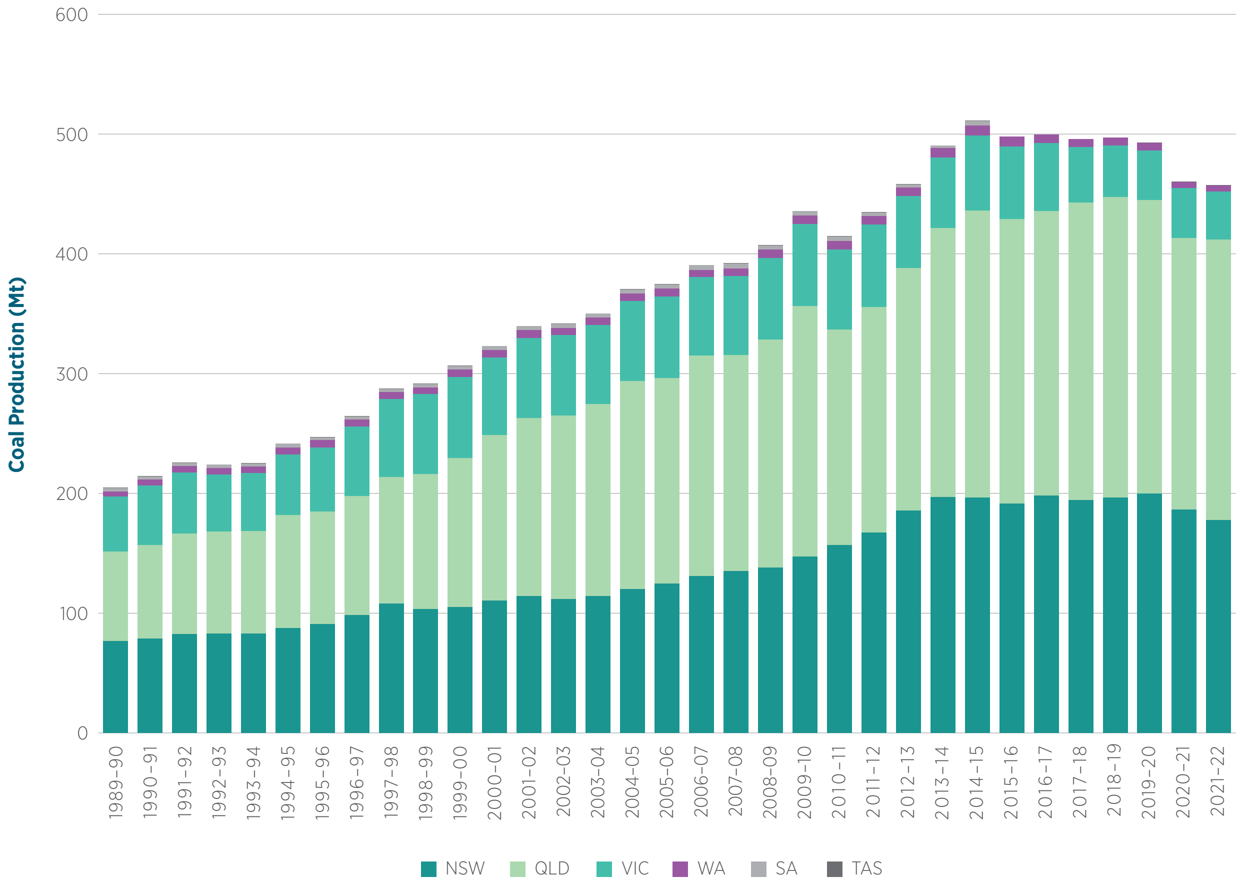
IPCC Category	CO_2 emissions	CH_4 emissions	N_2O Emissions
1.B.1.a.i Underground mines			
Mining	YES	YES	
Post-mining		YES	
1.B.1.a.ii Surface mines			
Mining	YES	YES	
Post-mining		IE (surface mining)	

IPCC Category	CO_2 emissions	CH_4 emissions	N_2O Emissions
1.B.1.b Solid fuel transformation		**IE (IP – metals)**	
1.B.1.c Other			
Decommissioned mines		YES	
Flaring	YES	YES	YES

A decrease of 7.5 per cent was observed in the current reporting year compared with the previous year. Black coal production fell by 0.6 per cent compared with the previous year, and was 6.6 per cent lower than in 2020, due to infrastructure damage from floods and storms, and the disruptions caused by the restrictions of exports to China (DCCEEW 2023).

The great majority of Australia's resource and production of black coal are located on the east coast of Australia in New South Wales and Queensland. A very small quantity of black coal is also mined in Tasmania. In Victoria, large quantities of brown coal are mined in surface operations. A relatively small quantity of sub-bituminous coal is mined in Western Australia. Coal production in South Australia ceased in 2015–16. The shares of coal production from Australian states are shown in Figure 3.24.

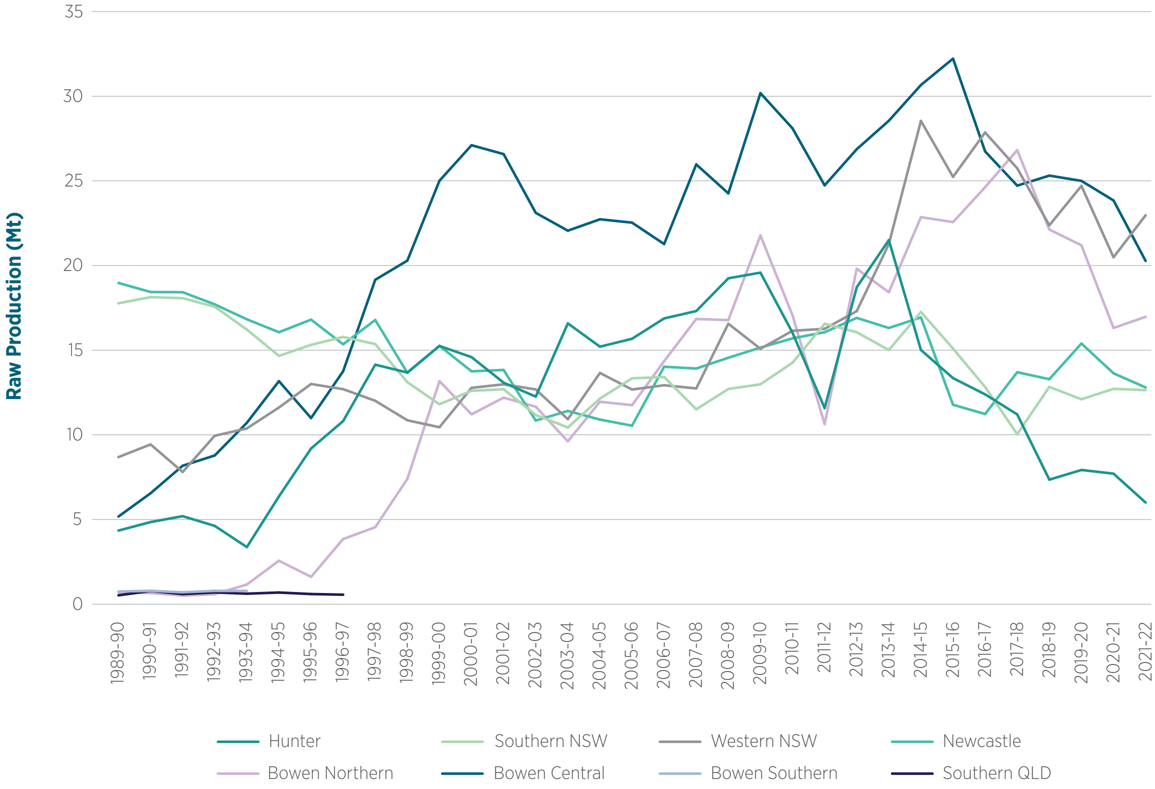
Figure 3.24 Coal production by State since 1989–90, million tonnes (Mt)



Source: Australian Energy Statistics (DCCEEW 2023)

In New South Wales, the principal coal fields are the Southern, Newcastle, Hunter and the Western New South Wales Basins. In Queensland, the main coal fields are the Central Queensland, Northern Bowen Basin, the Central Bowen Basin and the Southern Basin. Since 2009–10, there has been strong growth in underground production from the Western New South Wales and Northern Bowen basins and declines from the Hunter and Southern New South Wales basins (Figure 3.25).

Figure 3.25 Underground black coal production by coal field since 1989–90



Source: Production data is from the NGER Scheme

There can be wide variations in both the gas content and the composition of the gas across Australian coal basins, and across coal fields within the basins. The variability and characteristics of coal gas in eastern Australia have been described by Thomson (2010) as a response to several distinct geological and biogenic processes, namely:

- the coalification processes,
- tectonic history,
- magmatic activity,
- groundwater flow, and
- biogenesis.

The methane in coal layers has its origins largely in the coalification process that arises from pressure and heat associated with the deep burial of biomass within sedimentary basin deposits. The burial of biomass reached a peak depth during the mid-cretaceous period when it was estimated to be around 2.5 to 4 km deep, resulting in coal layers reaching saturation with thermogenic CH_4. As gas is generated during the coalification process, coal can store the gas within its micropore structure. The upper limit of gas able to be held within coal follows an adsorption isotherm, which describes the pressure/temperature relationship at the point where the coal is fully saturated with gas. The isotherm is useful for representing a theoretical cap on the gas content of coal at any given depth. In the Permian coal basins of Australia's east coast, coal layers greater than 500–600 m in depth will tend to be close to saturation with thermogenic methane (Thomson 2010).

It is rare, however, for coals saturated with methane to be mined. This is because uplifting and rifting of the strata in geological periods following the coalification process provided opportunities for gas to escape through fracture systems, resulting in the upper coal layers becoming under-saturated with methane. For Australia, this started from the late Cretaceous period with New Zealand rifting away from the Australian east coast, with the associated uplifting and subsequent erosion of the coal bearing regions.

The under-saturated coal layers were then receptive to new sources of gas. Extensive magmatism activity in the Paleogene period introduced CO_2 into the upper, under-saturated Permian coal layers. In more recent times, methanogen bearing groundwater flows through the surface fracture system have introduced biogenic methane into the upper coal layers (Thomson 2010).

A generalised model to describe the variation of gas in coal along the east coast coal bearing regions because of these processes has been described (Thomson 2010) and is shown in Table 3.27. Localised geological features can also have a large influence on subsurface gas characteristics at a mine level scale. For example, faults and dykes can provide opportunities for gas to escape or be trapped and influence groundwater flows for biogenesis. In summary, the coal gas type and distribution characteristics of the eastern coalfields can be viewed as a result of the history of large-scale processes overlaying localised geological features. Most near surface coal deposits on the east coast are under-saturated, as a function of their geological history. The surface zone is characterised by a very low gas content, predominantly in the form of CO_2.

Table 3.27 Generalised model of gas variation in the subsurface for east coast Australia

Zone 1	A surface zone extending to a depth of about 150m, which contains negligible gas. The gas that is present is often CO_2.
Zone 2	The "Biogenic Window", containing shallow methane and extending from a depth of approximately 150m to about 250–350m. The gas content of this zone increases with depth.
Zone 3	A "Mixed Gas Zone", below Zone 2 and extending to a depth of approximately 600–700m. The gases in this zone are both methane and CO_2, but mostly CO_2.
Zone 4	The "Thermogenic Zone" of high methane below Zone 3.

Source: Thomson (2010)

Coal mining on the west coast of Australia is confined within a small coal field within the Collie basin. The Collie basin coal deposits were formed by the transport of material rather than the bed forming *in situ.* The coal beds are also commonly associated with a sandstone roof providing opportunities for gas to escape over time. The understanding of the geological characteristics, current and historical mining practices, and anecdotal evidence suggested the basin is characterised by low gas content. Mine specific emission data based on measurement is now available through NGER scheme reporting and is incorporated in this inventory. The data confirms that the Collie Basin coal deposits are characterised by very low gas.

3.3.1.2 Methodological issues

Fugitive emissions from coal mining activities are estimated using a mix of tier 3 and tier 2 methods.

Estimates for underground mines are prepared using a tier 3 method. Data on measured CH_4 emissions for individual mines are obtained from coal mining companies reporting under the NGER scheme. For the current reporting year, data on measured CH_4 and CO_2 emissions is available for all 38 underground mines. Time series consistency has been maintained for the underground mine emissions estimates with the use of NGER scheme data (see section 3.3.1.3).

Fugitive emissions from surface mining are estimated using state-specific default CH_4 emission factors, as well as incorporating facility-specific NGER scheme data for CH_4 and CO_2 emissions, where available and appropriate.

For decommissioned mines, a country-specific tier 2 approach is used with EFs (m^3 CH_4/tonne coal produced) derived from measurement data obtained for mines with similar characteristics. Flaring uses a tier 2 approach and a country-specific CO_2 EF.

Table 3.28 Summary of methods and emission factors: 1.B.1 Solid Fuels

	CO_2		CH_4		N_2O	
Source Category	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**
1.B.1.a Coal mining and handling						
I Underground mining						
1 Mining activities	T3	PS	T3	PS	NA	NA
2 Post-mining activities	NA	NA	T2	CS	NA	NA
3 Abandoned underground mines	NA	NA	T2, T3	CS	NA	NA
4 Flaring of drained methane	T2	CS	T2	CS	T2	CS
II Surface mining						
1 Mining activities	NE, T2	NA, M	T2	CS, M	NA	NA
2 Post-mining activities	NE	NA	IE	NA	NA	NA
1.B.1.b Fuel transformation	**NO/IE**	**NA**	**NO/IE**	**NA**	**NO/IE**	**NA**

Notes: T1 = Tier 1, T2 = Tier 2, T3 = Tier 3, CS = country specific, PS = plant specific, D = default, M = model, NO= not occurring, NA = not applicable, IE = included elsewhere, 🟪 = key category

Activity data

Data on coal production provides activity data for the sector and are used as drivers for the estimation of emissions from mines in years where directly measured emissions data is not available. The production data for each mine are published annually in the statistical publications of:

- Australia – Department of Industry, Science and Resources (DISR 2023),
- New South Wales – Coal Services Pty Ltd (2022) (formerly the Joint Coal Board) and NGER scheme data,
- Queensland – Department of Resources (2023) and NGER scheme data,
- Western Australia – Department of Mines, Industry Regulation and Safety (DMIRS 2022) NGER scheme data, and
- Victoria – Various State goverment departments and NGER scheme data.

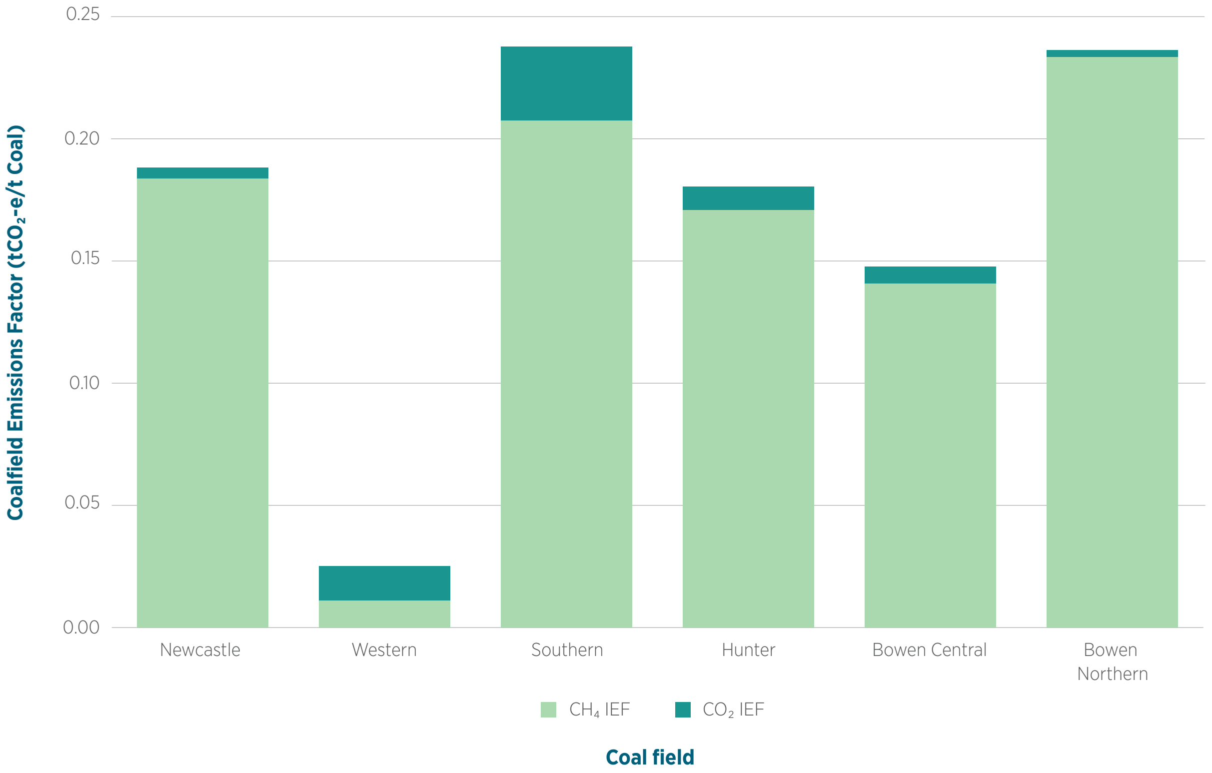
Mining activities – underground mines (1.B.1.a.i.1)

Emissions derived from direct measurement account for the majority of emissions from underground mines reported in the inventory. Emissions are estimated using methods set out in the Determination and are based on the measurement of gas concentration and flow within mine ventilation systems. In addition, mines are subject to state government legislation, including the *Coal Mine Health and Safety Act 2002 (NSW), Coal Mine Health and Safety Regulation 2006 (NSW), Coal Mining Safety and Health Act 1999 (Qld)* and the *Coal Mining Safety and Health Regulation 2001 (Qld),* which establish mandatory monitoring regulations for mines. The Determination builds on these existing state regulatory processes.

Coal companies reporting measured CH_4 from underground mines under the NGER scheme are also required to measure and report CO_2 emissions. This is significant as, prior to NGER scheme reporting, there was little data available on fugitive CO_2 emissions from Australian coal mining.

The NGER scheme emission data for underground mine emissions has shown that the gas type and content of different coal fields varies significantly. This is evident in Figure 3.26, which details the average gas content profile of underground production by coal field. The gassiest coal field is the Southern New South Wales, while the least gassy field is the Western New South Wales (which is mainly CO_2).

Figure 3.26 The gas content profile of Australian underground production by coal field, 2021–22



Choice of emission factor

Estimates based on direct measurements were reported for all underground mines under the NGER scheme. Emissions for underground coal mines, which were closed prior to the introduction of the NGER scheme, and for which tier 3 data were not available, have been estimated by applying an average IEF for their respective coal fields.

This is consistent with the decision tree for use of facility-specific EFs, as set out in Figure 1.3 of Chapter 1.3. In applying the decision tree, it was decided that the NGER scheme data demonstrated that facility-specific EFs, aggregated into subgroups based on spatial correlation (i.e. by coal field), were sufficiently different from the national country-specific EFs and drew on the general understanding that mines within coal fields shared common characteristics due to their shared geological history and structure. Information on how time series consistency has been maintained with the inclusion of NGER scheme data for underground mines is given in chapter 3.3.1.3.

Post-mining activities – underground mines (1.B.1.a.i.2)

Emissions from post mining activities reflect the fugitive escape of gases from the coal after mining, i.e. during preparation, transportation, storage or crushing, and are based on the measurements of Williams et. al (1993) and Williams et al. (1996). In these studies, the amount of gas retained in coal from gassy underground mines in New South Wales and Queensland, once the coal reached the surface, was analysed. Most of this gas is likely to desorb from the coal before combustion (i.e. during preparation, transportation, storage or crushing) and can therefore be classified as fugitive emissions from post mining activities. These studies related emissions E_{pm} to the quantity of black coal from underground Class A (gassy) mines QTY an emission factor EF_{pm} and C_{pm} the volume-to-mass conversion factor for post mine emissions, which equals 0.6767 kg/m^3.

$$E_{pm} = QTY_a \cdot EF_{pm} \cdot C_{pm} \qquad (3.8)$$

The emission factor, E, is the average of the results of the two empirical studies. It was found that the amount of gas retained was quite variable, but adopted an average gas EF of 1.7 m^3/t raw coal, of which 75 per cent was CH_4 and 25 per cent CO_2 (Williams et al. 1993). An estimated factor, equal to 20 per cent of the *In situ* CH_4 content of coal (6.78 m^3/tonne in this case), is applied (Williams, Lama and Saghafi 1996). It is assumed that post mining emissions are associated only with black coal mined in underground gassy mines, and not with black coal mined in underground Class B (non-gassy) mines.

Abandoned underground mines (1.B.1.a.i.3)

Methane emissions are also known to occur under certain conditions following closure of coal mines. Leakage into the atmosphere through fractured rock strata, open vents and seals occurs over daily to decadal timescales.

The Australian methodology is based on the approach developed in the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). The decline of emissions following mine closure are modelled using emission decay curves (EDCs) for dry gassy and non-gassy mines. In addition, the EDCs are adjusted on a mine-by-mine basis, according to the flooding characteristics of each mine.

Key data required for the approach include:

- mine closure history;
- emissions at time of closure;
- dry mine EDCs for gassy and non-gassy Australian mines;
- mine void size; and
- mine water inflow rates.

The approach seeks to maximise the use of publicly available data and is best described as a high tier 2 and tier 3 approach. It is consistent with a tier 3 approach in that it estimates emissions on an individual mine basis. However, other mine-specific data characteristic of higher-level tier 3 approach are absent, such as characteristics of the mined coal seam, permeability and direct measured emissions.

The EDC methodology used for estimating CH_4 emissions from decommissioned mines can be described as:

$$E_{dm} = (E_{tdm} \cdot EF_{dm} \cdot (1 - F_{dm})) - E_{rec} \qquad (3.9)$$

Where E_{dm} is the emissions (Gg methane/year) for a mine at a particular point in time

E_{tdm} is the annual emission rate of the mine at point of decommissioning (Gg methane/year)

EF_{dm} is the emission factor for a mine at a point in time since decommissioning. It is derived from the EDC (formulae 3.10 and 3.11). The EF is dimensionless

F_{dm} is the fraction of mine flooded at a point in time since decommissioning

E_{rec} is the quantity of methane emissions avoided by recovery

Emission Decay Curves (EDCs)

An EDC describes the decline in fugitive CH_4 emissions over time following mine closure. Hyperbolic curves have been found to function best in portraying the rapid decline in emissions in first few years, followed by a slow decline over time of the remaining emissions.

Australian-specific EDCs were utilised for gassy and non-gassy mines respectively. The EDCs represent the dry mine case and have been developed from studies of long term (1982–2006) direct gas emission measurements from Australian mines (Lunarzewski 2005) (Armstrong, Lunarzewski and Creedy 2006). The EDCs are shown in Figure 3.27, and are described in the following formulae:

Gassy mines

$$EF_{dm} = (1 + A * T)_b - C \qquad (3.10)$$

Non-gassy mines

$$EF_{dm} = (1 + A * T)_b - C \qquad (3.11)$$

Where EF_{dm} is the emission factor (Gg methane/year) for a mine at any point in time since decommissioning (the emission factor is dimensionless)

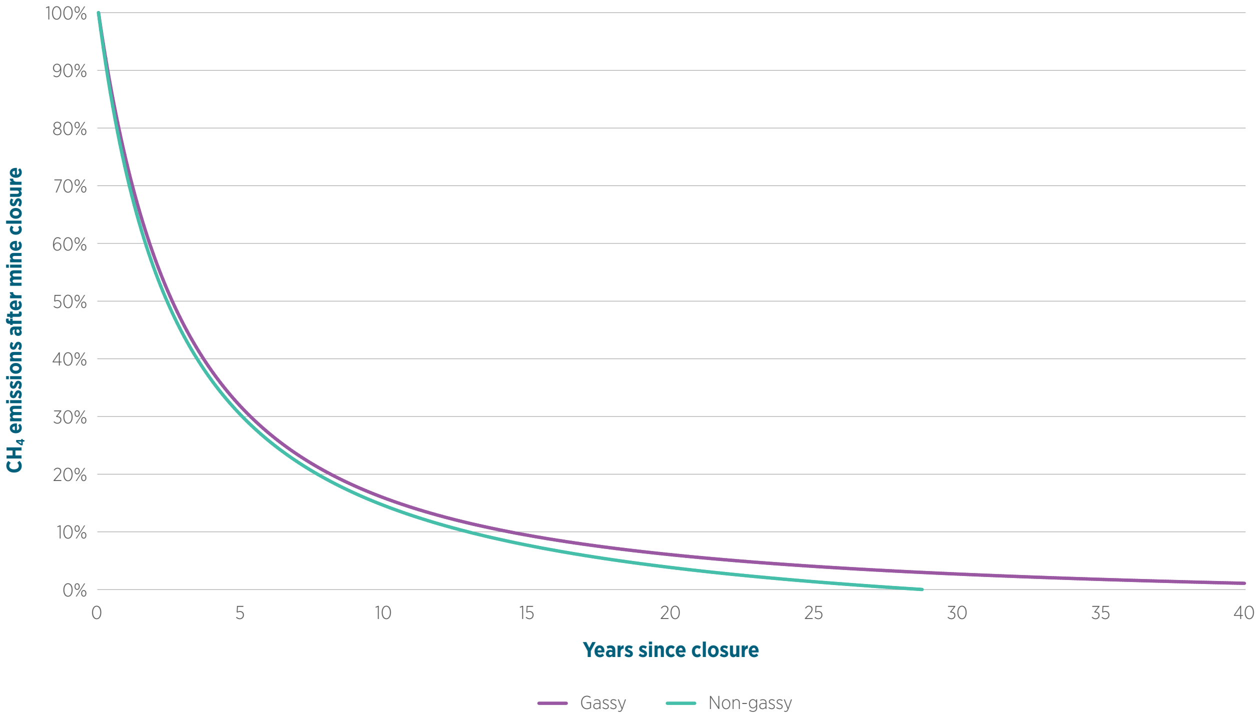
T is the time (years) elapsed since decommissioning of mine

A, b and C are coefficients unique to the decline curves (see Table 3.29)

Table 3.29 Coefficients used in Australian emission decay curves from decommissioned mines

	Coefficients		
Mine category	**A**	**B**	**C**
Gassy Mines	0.23	-1.45	0.0242
Non-Gassy mines	0.35	-1.01	0.0881

Figure 3.27 CH_4 decay curves for gassy and non-gassy Australian decommissioned coal mines



Source: Lunarzewski 2005 and Armstrong et al. 2006.

Mine Production Data

Mine production data are obtained from:

- NGER scheme for all mines from 2008–09;
- Coal Services Pty Ltd, for New South Wales mines from 1971–72; and
- Department of Resources for Queensland mines from 1978–79.

In both datasets, details were obtained for mine type (underground/surface), annual run-of-mine production, and time of closure. Only underground mines were included in the study. Surface mines were not included in the study as they are associated with relatively low CH_4 emissions. This approach is consistent with that presented in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

Emissions at Closure

To estimate the decline of emissions over time following closure, it is first necessary to establish emissions at year zero, i.e. emissions at the point prior to closure. The approach used is consistent with that used to estimate CH_4 emissions from active underground coal mines. Final mine production at closure is taken as the last full year of production.

Decommissioned mines are defined as Class A (gassy), or Class B (non-gassy) based on existing classifications used to calculate previous *National Greenhouse Gas Inventories*. For earlier mines, for which class tends to be unknown, mines were classified according to their geological proximity to other mines for which class was known.

Adjustment of EDC for flooding mines

It is common for decommissioned mines to become flooded over time. The flooding of mines is known to result in a very rapid decline in the release of CH_4, thus having a substantial impact on the shape of the EDC, and on overall emissions.

The approach uses emission values calculated using dry mine EDCs (formulae 3.10 and 3.11) and makes adjustments based on the proportion of the mine flooded at that time. For example, if a mine is 50 per cent flooded 10 years post-closure, then the emission value derived from the EDC is adjusted at that point in time by 50 per cent.

The following information is required to estimate the flooding rate of any particular mine:

- size of the mine void volume; and
- rates of mine water inflow.

Estimating mine void volume

The quantity of run-of-mine coal production removed from the mine is used as a basis for estimating the mine void volume remaining at the time of closure. Total historical mine run-of-mine coal production is converted from tonnes to cubic metres by dividing the total tonnage by 1.425, representing the specific gravity of an average Australian worked coal seam (Lunarzewski 2006).

Mine water production data are difficult to obtain on a mine by mine basis, particularly for older, decommissioned mines. The approach taken is to develop a set of basin/state average mine water inflow rates based on available data.

The primary source of mine water production rates for individual mines were obtained from publicly available Environmental Impact Statements (EIS) for mining development projects. EIS provides a good coverage of groundwater hydrology, providing data on mine water production rates for proposed mines, extensions, nearby existing mines, and the flooding status of surrounding mines.

Water production rates for three regions were calculated using these data sources. The Southern New South Wales region contained mine water production rates ranging between 1 – 5.0 ML/Day and an average value of 2.5 ML/Day. The Central New South Wales region ranged between 0.4 and 3 ML/Day and an average value of 1.2 ML/Day and Queensland ranged between 0.1 and 0.4 ML/Day and an average value of 0.2 ML/Day.

The following assumptions were necessary in estimating mine water inflow rates:

- the mine floods at a linear rate;
- mine water production is the same for each mine on a basin/state scale; and
- CH_4 is produced evenly throughout the mine and flooding reduces the emissions proportionately to the void volume flooded.

Fully Flooded Mine Emissions

Once a mined void area has been fully flooded, the associated primary gas sources can no longer release gas into the workings. However, remaining free gas in the strata and desorbing gas from unflooded secondary gas sources could continue to leak into the atmosphere (ground surface) via fractured rock strata i.e. geological faults, cracks, and fissures (structurally induced pathways). A constant of 2 per cent of the emissions at the time of mine closure has been adopted to represent emissions once fully flooded (L. Lunarzewski 2006).

Flaring of drained methane (1.B.1.a.i.4)

Data for 2008–09 to the current reporting period on the recovery and flaring of CH_4 from coal mines is available from mines reporting under the NGER scheme. Time series consistency for coal mine flaring is maintained by the inclusion of flaring data obtained from a 2006 unpublished report on coal mine methane prepared for the Australian Greenhouse Office (AGO 2006), which provided flared gas quantities by mine for 2004–05.

For those respective mines, the 2004–05 flared quantity was then prorated according to the total mine methane emissions for other years to produce a time series. Information regarding when flaring systems were first installed at the respective mines were also considered in producing the time series.

The emission estimation methodology utilises a default combustion CO_2 EF of 51.9 Gg/PJ and an energy content of 37.7 GJ/m^3 for coal mine waste gas flared, derived from industry data. Facility CO_2 EFs are utilised from the NGER scheme data where available. A flaring efficiency factor of 98 per cent is used, consistent with the 2006 *IPCC Guidelines* (IPCC 2006).

Surface mining (1.B.1.a.ii)

A mix of tier 3 and country-specific tier 2 methods are used to estimate fugitive methane and carbon dioxide emissions across Australia's regional coal basins. Emissions associated with post-mining activities are included in the estimation of mining activities, or in Public Electricity Generation when the mine is directly attached to a power plant.

Table 3.30 Summary of methods and emission factors: 1.B.1 Solid Fuels: Surface mining

	CO_2		CH_4	
Coal field	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**
Bowen (Qld)	T3	PS	T2	CS
Surat (Qld)	T3	PS	T2, T3	CS, PS
Hunter (NSW)	T3	PS	T2, T3	CS, PS
Newcastle (NSW)	T3	PS	T2, T3	CS, PS
Western (NSW)	T3	PS	T2, T3	CS, PS
La Trobe (Vic)	IE	IE	T2	CS
South Australia	IE	IE	T2	CS
Collie (WA)	T3	PS	T3	PS
Tasmania	T3	PS	T3	PS

Notes: T2 = tier 2, T3 = tier 3, CS = country-specific, PS = plant-specific, IE = included elsewhere

Higher tier, facility-specific, NGER scheme method

Australia has invested in a comprehensive program of measurement technique research and development since 2006–07 to underpin emissions estimation processes under the NGER scheme. An important outcome of the program has been the development of guidelines for the application of the existing NGER scheme mine-specific (method 2/3) approach to estimating emissions from surface mines. A detailed summary of this methodology is provided in Annex 5.3.4.

Black coal mine production

A study of methane flux measurements from surface coal mines in New South Wales (Williams et al. 1993) and a database of in-situ measurements from Queensland gas seams (Department of Resources – Queensland 2021) forms the basis for Australia's country-specific, default emission factors. The study used the empirical results to estimate EFs (in m^3/tonne raw coal) applicable to surface black coal mining, as shown in Table 3.31.

Brown coal (lignite) mine production

Surface mining of brown coal (lignite) occurs in Victoria for combustion in electricity generation. A methane emission factor for Victorian brown coal mining of 0.0162 m^3 per tonne of raw coal mined is applied. The emission factor is based on a gas measurement program conducted in 2013, which consisted of 96 samples taken from six boreholes across three brown coal mining deposits (HRL 2013).

Surface mining of a low rank sub-bituminous coal occurs in South Australia for combustion in electricity generation. Coal mined in South Australia has an energy content of 13.5 GJ/t. Based on the IEA fuel type classification, which classes non-agglomerating coals under 17.435 GJ/t as being lignite (IEA 2005), the methane EF from surface brown coal mining of 0.0162 m^3/t (as used for Victorian brown coal) has been applied.

Table 3.31 Tier 2 default CH_4 emission factors for surface mining

State	EF CH_4 m^3/t raw coal mined	Volume-to-mass conversion factor[d] kg/m^3
NSW	3.2[a]	0.6767
Bowen (Qld)	1.65[b]	0.6767
Tasmania	1.0[c]	0.6767
South Australia	0.0162[e]	0.6767
Victoria	0.0162[e]	0.6767

(a) Source: Williams et al. (Williams et al. 1993) and confirmed by Australian Coal Association.
(b) Source: Derived from Queensland Petroleum Exploration Data (2021).
(c) Source: D Cain, Australian Coal Association, pers. comm. (1993).
(d) These factors are derived by treating CH_4 as an ideal gas, i.e. 16 g (1 gmole) occupies 23.645 at 15°C and 1 atmosphere.
(e) Source: HRL (2013).

3.3.1.3 Uncertainty assessment and time-series consistency

The tier 1 uncertainty analysis in Annex II provides estimates of uncertainty according to IPCC source category and gas.

Underground Mines

NGER scheme data is used for inventory years since 2008–09. To ensure time series consistency in the transition from industry surveys and company reports to NGER scheme data for underground coal mines, the surrogate method from the 2006 IPCC Guidelines, involving the use of coal production data and an EF derived from actual mine measurements, was chosen as the most appropriate splicing technique (IPCC 2006). This choice was made because run-of-mine coal production data is available for individual mines for all years and is an underlying activity data parameter that best explains emission trends.

Interpolation was considered as a complementary approach where emissions data are available from non-NGER scheme sources for a previous year, and which could be used to provide an EF per unit of coal production for earlier years. Interpolated estimates were compared with surrogate data as a QA/QC check.

For years before NGER scheme data became available, data on emissions for certain underground mines were available from estimates published within company environmental reports or from industry reports to the Australian Greenhouse Office (AGO 2006). This emissions data has been used for each mine for the years for which they are available.

For earlier years, where such emissions data are not available, an EF per unit of production for each mine was established and applied to production levels back through the time series from 1989–90 to the year when data on emissions first becomes available. For the years between the latest company report and the year of the NGER scheme data, the EF for each mine was calculated by interpolating between the EF for the latest year for which company data was available and the EF based on NGER scheme data for the year 2008–09.

A small number of underground mines closed in the period 1989–90 to 2004–05 for which there are no mine-specific measured data available. Emissions for each year were recalculated using a basin-specific factored, calculated from the NGER scheme data for 2008–09 and multiplied by production. A similar approach has been adopted for the inclusion of emissions of CO_2 for all mines (Table 3.32 and Table 3.33).

Table 3.32 Time series consistency method for determining underground coal mine emission factors – CH_4

Methane	1989–90 to 2003–04	2004–05 Industry 2005–06 to survey 2007–08	2008–09 to 2021–22 NGER scheme	2021–22 NGER scheme
“Actual” data reported EFs held by companies represents constant the best available and most representative for the year – back cast based on latest available year of actual data.	Actual data	Actual data Interpolated EFs	Actual data	NGER scheme data back cast only until an actual emissions data year is available using interpolation to fill intervening years.
Basin specific factors (based on NGER scheme data) used for mines for which NGER scheme data was not available				

Table 3.33 Time series consistency method for determining underground coal mine emission factors – CO_2

Carbon dioxide	1989–90 to 2007–08	2008–09 to 2021–22 NGER	2021–22 NGER
Basin specific factors (based on NGER scheme data) used for mines for which NGER scheme data was not available.	EFs held constant	Actual data	Emissions for all earlier years are estimated using the production EF based on mine-specific NGER scheme data.

Surface mines

NGER scheme data is used for inventory years since 2008–09. The transition to NGER scheme data for surface coal mines in this inventory submission is undertaken in a manner that maintains time series consistency. A set of rules has been applied that considers the new understanding of gas content gained from NGER scheme data and maintains the relevance of the original 1993 study for mines and basins where measurements were previously undertaken.

Where the NGER scheme data is an improvement on the country-specific Tier 2 EF because coal fields are outside the area of the original study (Gunnedah, Western, Surat coal fields), then the earliest NGER scheme facility-specific EF has been applied through the entire time series. Where the new data improves on the old EF because comprehensive NGER scheme measurement provides updated and improved data of the original study area measured in 1993 (Hunter and Newcastle) then, for methane, the earliest NGER scheme facility-specific EF back through the time series by interpolating back until year of original study (1992–93) or, if mine was not part of original study, then the NGER scheme derived factor is applied to the entire time series.

For carbon dioxide, where no measurements previously exist, then the earliest NGER scheme facility-specific EF is applied to the entire time series.

3.3.1.4 Category-specific QA/QC and verification

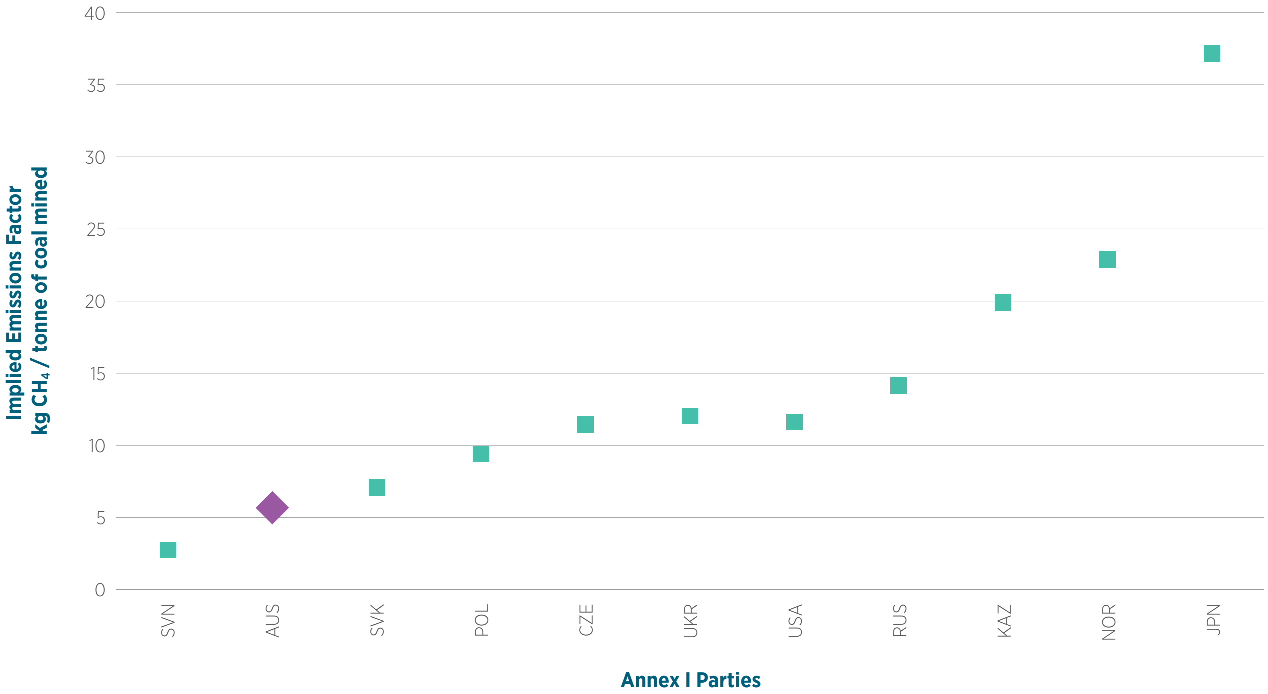
This source category is covered by the general QA/QC of the greenhouse gas inventory in Chapter 1.

Implied emission factors

International comparability

Analysis of methane implied emission factors (IEFs) for Australian coal mines to compare statistically with the IEFs reported by other countries is undertaken in accordance with the Quality Assurance-Quality Control Plan (Figure 3.28 and Figure 3.29).

Figure 3.28 Underground coal mining implied emission factors for Annex I countries (2023 submission) and Australia (2024 submission), kg CH_4 per tonne of coal mined



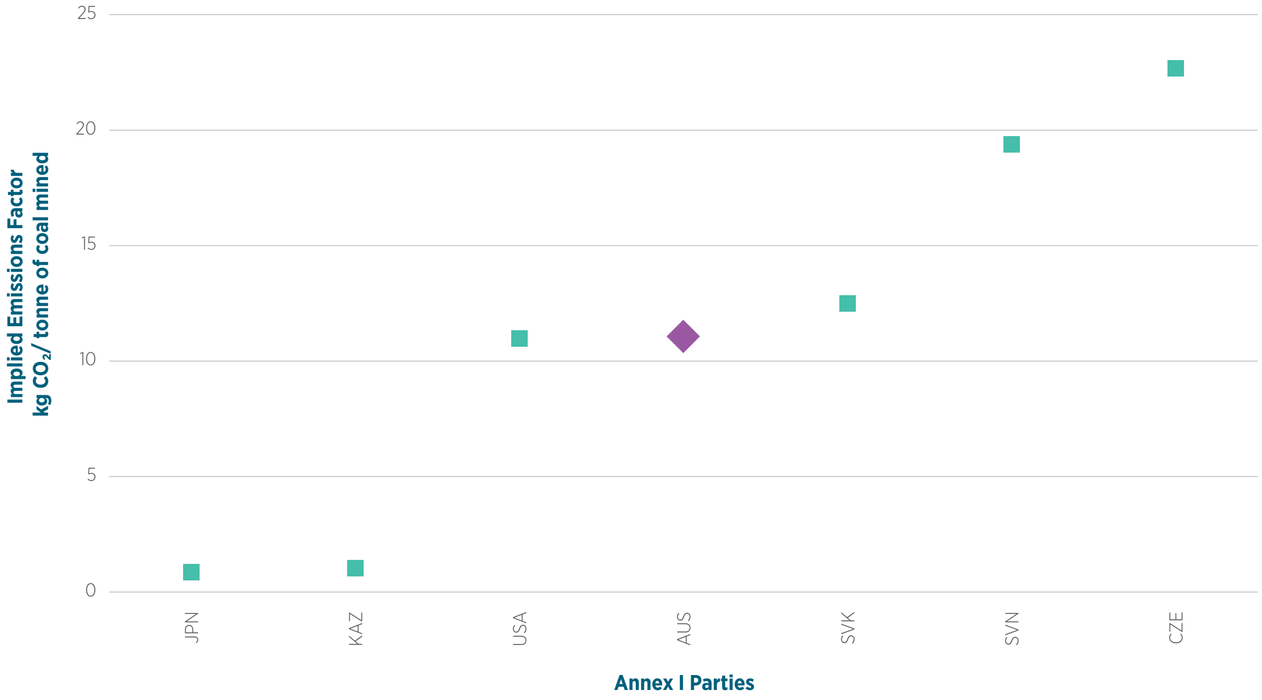
Note: The above data as reported to the United Nations Framework Convention on Climate Change. Parties above are Slovenia (SVN), Australia (AUS), Slovakia (SVK), Poland (POL), Czechia (CZE), Ukraine (UKR), United States of America (USA), Russia (RUS), Kazakhstan (KAZ), Norway (NOR), and Japan (JPN). Outliers have been excluded from the graph for readability purposes (Turkey, 0.01, Great Britain, 443.17 and Romania, 790.59).

Figure 3.29 Surface coal mining implied emission factors for Annex I countries (2023 submission) and Australia (2024 submission), kg CH_4 per tonne of coal mined

Note: The above data as reported to the United Nations Framework Convention on Climate Change. Parties above are Hungary (HUN), Germany (DEU), Great Britain (GBR), New Zealand (NZL), Norway (NOR), Australia (AUS), Canada (CAN), United States of America (USA), Bulgaria (BGR), Greece (GRC), Japan (JPN), Kazakhstan (KAZ), Poland (POL), Romania (ROU), Turkey (TUR), and Czechia (CZE). Please note that an outlier has been excluded from the graph (Russia, 3.86).

Australia's current-year IEF for methane from underground mines was 5.08 kg CH_4/t compared with 13.09 kg CH_4/t (n =14) for the previously-published median of Annex 1 Parties, and 99.82 kg CH_4/t (n =14) for the previously-published mean of all Annex 1 Parties. Australia's current-year IEF for methane from surface mining was 0.68 kg CH_4/t compared with 0.87 kg CH_4/t (n = 17) for the previously-published median and 0.90 kg CH_4/t (n=17) for the previously-published mean of Annex 1 Parties. In the case of underground mining, Australia's IEF is the third-lowest of reporting parties, which reflects the relatively low gas composition of Australian coal fields.

Figure 3.30 Underground coal mining implied emission factors for Annex I countries (2023 submission) and Australia (2024 submission), t CO_2 per tonne of coal mined



Note: The above data as reported to the United Nations Framework Convention on Climate Change. Parties above are Japan (JPN), Kazakhstan (KAZ), Australia (AUS), United States of America (USA), Slovakia (SVK), Slovenia (SVN), and Czechia (CZE). Please note that an outlier has been excluded for Norway (69.9).

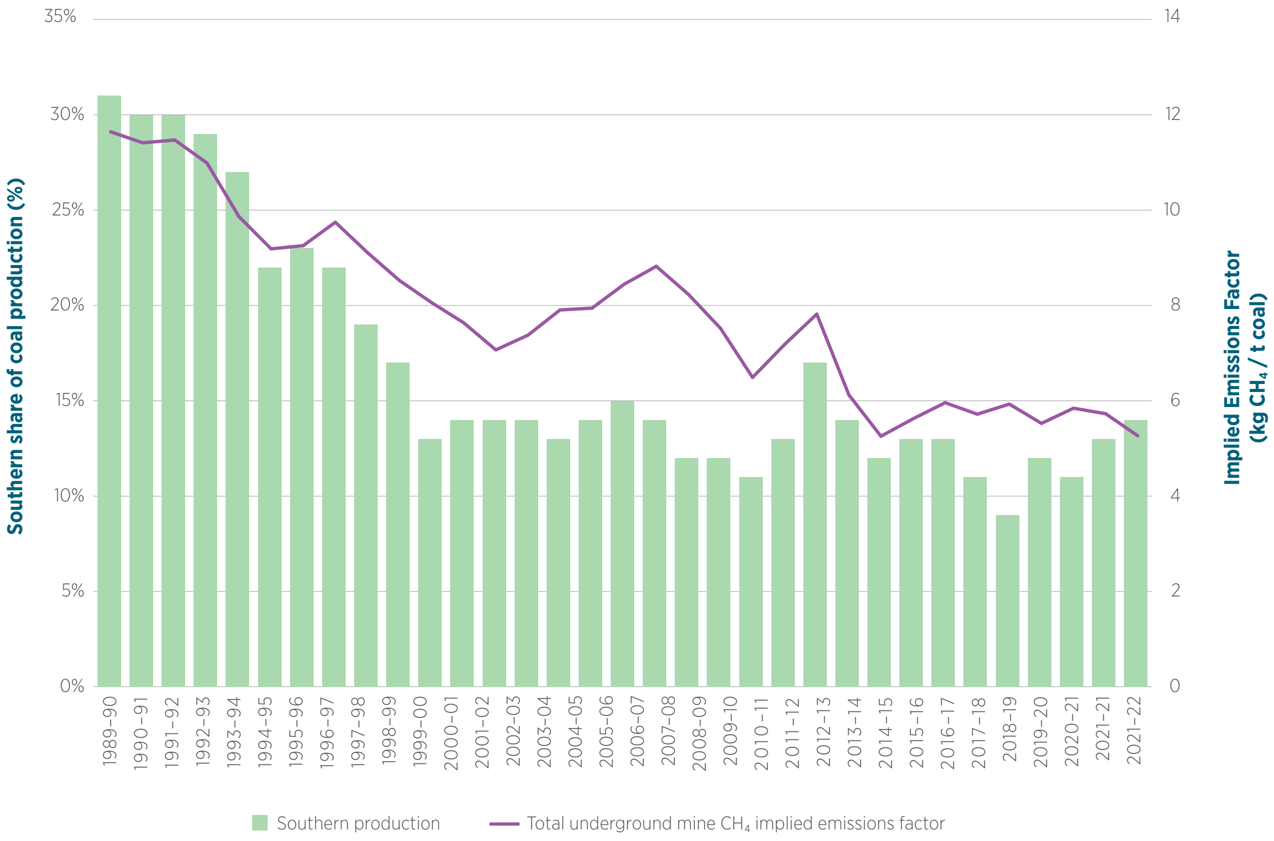
For carbon dioxide emissions from underground mining, implied emissions factors are variable from country to country. However, Australia sits within the range of non-outlier reporting parties, with an IEF of 11.06 kg CO_2 per tonne of coal mined, which is comparable to the USA (11.0 kg/t).

Time series consistency – trends in implied emission factors

Estimates are tested for time-series consistency in accordance with the QA/QC Plan. The IEFs from total coal mining activities for Australia are influenced over time by changes in the share of production from mines of varying gas content and gas type and the quantity of methane recovered. This is evident in a declining trend of the methane IEF for underground mines, which reflects a relative increase in production from less gassy mine regions compared to production from high gas coalfields. The trends in fugitive emissions and emissions intensities from coal production remain driven by emissions from gassy underground mines, many of which have taken actions to flare or capture and use this waste coal mine gas in power stations. Emissions intensities of underground mining can also be impacted by the particular coalbed being mined. For example, the Southern Coal field in NSW has the highest IEF of all Australian coalfields, and higher or lower mining activity in this field has a noticeable impact on trends.

Figure 3.31 details the declining trend of the underground coal mine IEF since 1989–90 and the corresponding fall in production from the New South Wales Southern Coalfield. In more recent years the increasing use of flaring to combust methane that otherwise would have been vented has acted to reduce the IEF for underground mines in total.

Figure 3.31 Decline of the overall underground coal mine methane implied emission factor compared with the fall in production from the high gas content Southern Coalfield



Note: Production data are sourced from the NGER scheme (CER 2022)

Black coal production in NSW, the second largest coal-producing state in Australia, saw a 3 per cent decrease in surface production and steady production in underground mines, between the current and previous reporting years (Coal Services Pty Ltd 2022). The gassiest coal seam in the southern gas fields saw a 0.6 per cent decrease over this period. NSW emissions have had an 13.8 per cent increase in emissions from surface mining, a 4.5 per cent decrease in underground mining emissions, and a 33 per cent decrease in emissions from flaring.

The IEF for all coal mining activities has also declined since 1989–90 reflecting the additional influence of a relative increase of surface mine production compared to underground production. The trend in production also varies over time, reflecting the effects of opening and closure of large mines, commodity prices and global demand. While emissions peaked in 2007, production peaked in 2015, with the increase in production offset by a change in extraction method. Since peak emissions in 2007, underground coal production has declined by 1 per cent, while open-cut production has grown by 22 per cent.

Measurement audits

The NGER scheme facility-specific method for surface mines involves extensive measurement of in-situ gas within each respective coal mines coal and carbonaceous rock strata, via borehole drilling and sampling. All measurements used to support facility-specific estimates of emissions are subject to at least three controls.

The NGER scheme legislation sets out minimum qualifications of the estimator of surface mine emissions using the NGER scheme higher tier method. The Estimator is a person, or team of persons, meeting the minimum qualifications described below, who estimates the fugitive emissions from a surface coal mine.

The minimum qualifications of an Estimator are 5 years' experience in the assessment of coal deposit continuity and dimensions including the identification of geological features that affect coal seam geometry such as seam splitting, subcrop lines, washouts, and otherwise deterioration in thickness of the coal seams, including (but not limited to) the presence of any adverse structural features (for example faults, folds or igneous intrusions).

Historically, NGER scheme data submitted during the operation of the carbon pricing mechanism (2011–12 to 2014–15), companies that had annual emissions exceeding 125,000 Gg CO_2–e were required to undertake a pre-submission audit report to provide assurance over their NGER scheme emissions report. Audit reports had to have been submitted to the Clean Energy Regulator by the reporting due date of 31 October. The audit had to have been a reasonable assurance engagement, it must have been conducted in accordance with the *National Greenhouse and Energy (Audit) Determination 2009,* and it must have been undertaken by a Category 2 or 3 registered greenhouse and energy auditor.

The Clean Energy Regulator is empowered under the *National Greenhouse and Energy Reporting Act 2007* to investigate any emission estimates at any time and has a program to undertake a risk-based audit process to provide assurance on the quality of data reported under the NGER scheme.

Use of NGER scheme facility level data in the national inventory

The use of NGER scheme data addresses comments made in previous ERT reports which have both recommended and encouraged Australia to incorporate NGER scheme data for surface mines.

Nonetheless, the application of NGER scheme facility data must be undertaken with care to ensure that issues of selection bias are controlled for. To manage these risks, the Department has aggregated the available data into a national account in accordance with principles established in the 2006 IPCC Guidelines (IPCC 2006), and as described in Chapter 1.3.

In the case of surface mines, not all facilities have undertaken facility specific measurements. In Queensland, apart from the Surat Basin, insufficient facility-specific estimates have been obtained and, in the absence of a sufficient sample of data, the national inventory continues to apply default values for emission factors for coal basins in Queensland (other than the Surat Basin). Factors such as cost could deter the measurement of emissions by some companies. It is not clear, consequently, that the default value used to estimate emissions from Queensland is not an unbiased estimate of emissions.

While the effect of selection bias remains possible for Queensland coal basins other than the Surat Basin, this small risk has been mitigated through the country-specific value – recently updated to 1.65 CH_4 m^3/t raw coal mined – which is within the range of IPCC default values available.

3.3.1.5 Category-specific recalculations

Recalculations are shown in Table 3.34. For the purposes of like-for-like comparison, emissions reported to the UNFCCC in 2022 were converted to AR5 GWPs.

The recalculations relate to correcting data relating to a single mine.

Table 3.34 1.B.1 Solid Fuels: recalculation of total CO_2–e (Gg), 1989–90 to 2020–21

	2023 submission	2024 submission	Change	
	(Gg CO_2–e)		(Gg CO_2–e)	%
1989–90	25,578	25,578	-	-
1994–95	25,094	25,094	-	-

	2023 submission	2024 submission	Change	
	(Gg CO_2-e)		(Gg CO_2-e)	%
1999–00	29,613	29,613	-	-
2004–05	31,210	31,210	-	-
2005–06	32,015	32,015	-	-
2006–07	34,684	34,684	-	-
2007–08	33,739	33,739	-	-
2008–09	33,207	33,207	-	-
2009–10	32,147	32,147	-	-
2010–11	31,516	31,516	-	-
2011–12	31,579	31,579	-	-
2012–13	31,727	31,727	-	-
2013–14	29,673	29,673	-	-
2014–15	32,682	32,682	-	-
2015–16	32,567	32,567	-	-
2016–17	31,387	31,387	-	-
2017–18	32,212	32,212	-	-
2018–19	29,393	29,393	-	-
2019–20	30,666	30,666	-	-
2020–21	27,838	27,712	-126	-0.5

3.3.1.6 Category-specific planned improvements

Uptake of the higher tier method is expected to continue over future years as new mining areas are opened, resulting in an increase in mine-specific emission data available for compiling surface mine emissions for the inventory. The Department will continue to investigate options for determining mining depth of individual mines to enable the development of facility-specific emissions factors which considers that facility's mining practices, enabling a Tier 3 approach for estimating emissions from Australian surface coal mines. The Department will also investigate opportunities to apply the improved Queensland method to other jurisdictions, where sufficient geological data is available.

The Department is planning to undertake the development of a methodology for estimating emissions from coal exploration boreholes. The method will aim to incorporate country-specific data where possible.

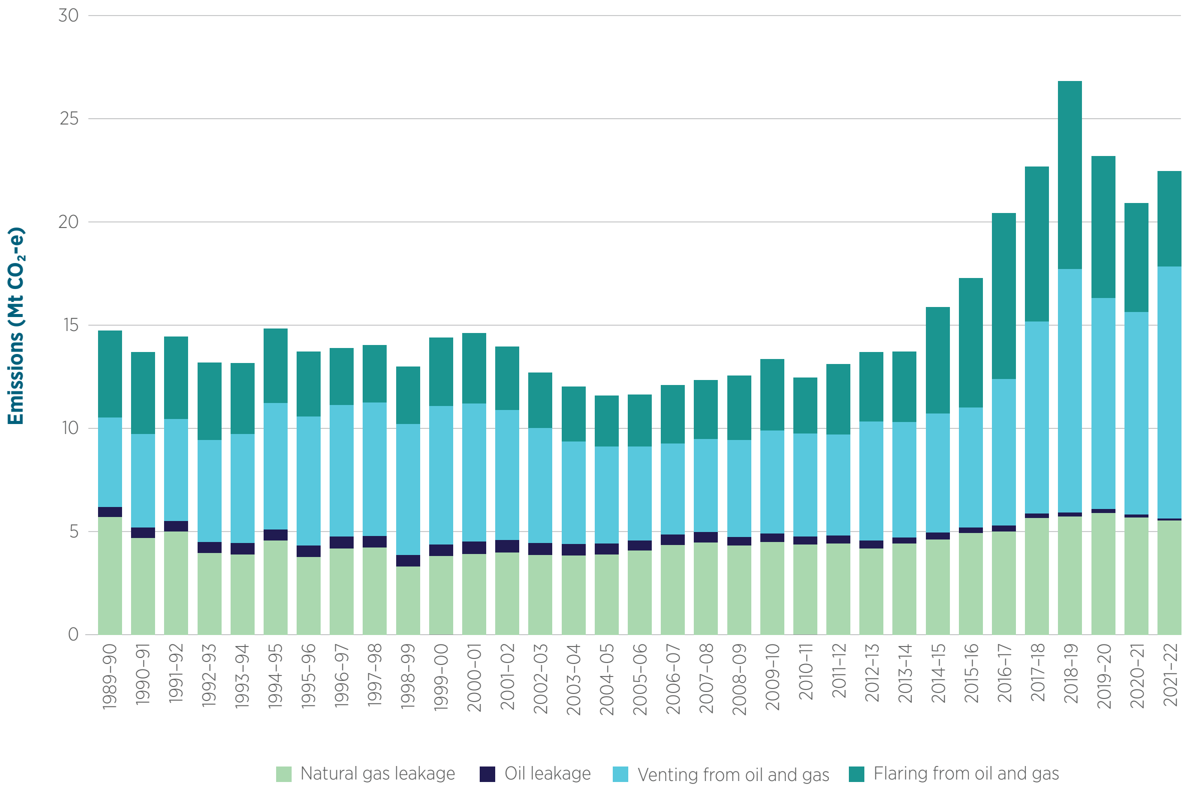
3.3.2 Oil, Natural Gas and other emissions from energy production (CRT category 1.B.2)

3.3.2.1 Category description

Leakage, venting, and flaring associated with oil and natural gas extraction are categorised as fugitive emissions. Fugitive emissions may be unintentional or controlled, and the quantity and composition of emissions is generally subject to significant uncertainty. Oil and natural gas systems include all infrastructure required to produce, collect, process, refine, and deliver natural gas and petroleum products to market. The system begins at the well head or oil and gas source and ends at the final sales point to the consumer.

Australia is a leading exporter of liquefied natural gas (LNG) and a minor producer of crude oil. Most emissions from this category come from the natural gas industry (Figure 3.32).

Figure 3.32 Fugitive emissions from oil and gas, million tonnes of carbon dioxide equivalent (Mt CO_2–e), 1989–90 to 2021–22



Note that the following related emissions sources are included elsewhere, as per the 2006 IPCC Guidelines (IPCC 2006): fuel combustion for production of useful heat or energy (CRT category 1.A), fugitive emissions from carbon capture and storage projects (CRT category 1.C), fugitive emissions associated with facilities from other industries (CRT category 2), and fugitive emissions from waste disposal outside of the oil and gas industry (CRT category 5).

Oil and gas fugitive emissions have trended strongly upwards since 2012–13, corresponding to the rapid growth of LNG production. Fugitive emissions in this category are dominated by venting and flaring of gas and liquids. Peak venting and flaring occurred in 2018–19, the first year of ramp up of production at two large LNG facilities. Once those facilities reached full production, this resulted in emergency and process venting and flaring falling from their peak. Much of the growth in oil and gas fugitive emissions for the 2021–22 year is driven by increased CO_2 venting emissions at LNG facilities.

Natural gas production grew 6 per cent in 2021–22, driven by a return to normal that was less impacted by COVID-19, scheduled outages and maintenance (DCCEEW 2023). LNG exports grew 7 per cent in the 2021–22 year due to a combination of a rebound from outages and maintenance in the previous year, and increased global demand for Australian gas, driven by disruptions to Russian exports and higher post-lockdown demand in Asia. Domestic demand for gas remained steady, with growth in LNG consumption offset by lower electricity and alumina refining use.

Crude oil and condensate production grew 1 per cent in 2021–22 with minimal changes since the previous year. Crude oil imports fell by 29 per cent in 2021–22, following the closure of Kwinana and Altona Refineries, while refined product imports grew by 17 per cent to meet the demand no longer supplied by domestic refining, to account for around 74 per cent of total refined product consumption (DCCEEW 2023).

3.3.2.2 Methodological issues

Key categories for oil, natural gas and other emissions from energy production are shown in Table 3.35.

The emissions factors are presented in NIR 2023 Volume 2, Annex V.

Table 3.35 Summary of methods and emission factors: 1.B.2 Oil and Natural Gas

	CO_2		CH_4		N_2O	
Source Category	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**	**Method applied**	**Emission factor**
1.B.2.a Oil						
i Exploration	T2	CS/PS	T2	CS/PS	T2	CS
ii Production	T2/T3	CS	T2/T3	CS		
iii Transport	T2	D	T2	D		
iv Refining/storage	T2	PS	T2	PS		
v Distribution	NE	NA	NE	NA		
vi Other – Abandoned Wells	T2	CS	T2	CS		
1.B.2.b Natural Gas						
i Exploration	T2	CS/PS	T2	CS/PS	T2	CS
ii Production	T2/T3	CS/PS	T2/T3	CS/PS		
iii Processing	T2/T3	CS/PS	T2/T3	CS/PS		
iv Transmission and Storage	T2	CS	T2	CS		
v Distribution	T3	PS	T3	PS		
vi Other						
1 Gas post-meter	T2	CS	T2	CS		
2 Abandoned Wells	T2	CS	T2	CS		
3 Other – LNG Terminals	T2	CS	T2	CS		
3 Other – LNG Storage	T2	CS	T2	CS		
3 Other – Natural Gas Storage	T2	CS	T2	CS		
1.B.2.C Venting and Flaring						
i Venting – Combined	T2/T3	CS/PS	T2/T3	CS/PS	T2/T3	CS/PS
ii Flaring						
1 Oil	T2/T3	CS/PS	T2/T3	CS/PS	T2/T3	CS/PS
2 Gas	T2/T3	CS/PS	T2/T3	CS/PS	T2/T3	CS/PS

Notes: T1 = Tier 1, T2 = Tier 2, T3 = Tier 3, CS = country specific, PS = plant specific, D = default, M = model, NO= not occurring, NA = not applicable, IE = included elsewhere, 🟪 = key category

Oil (CRT category 1.B.2.a)

In Australia, emissions from oil refining and storage (CRT category 1.B.2.a.4) and oil flaring (CRT category 1.B.2.c.2.i) are key categories.

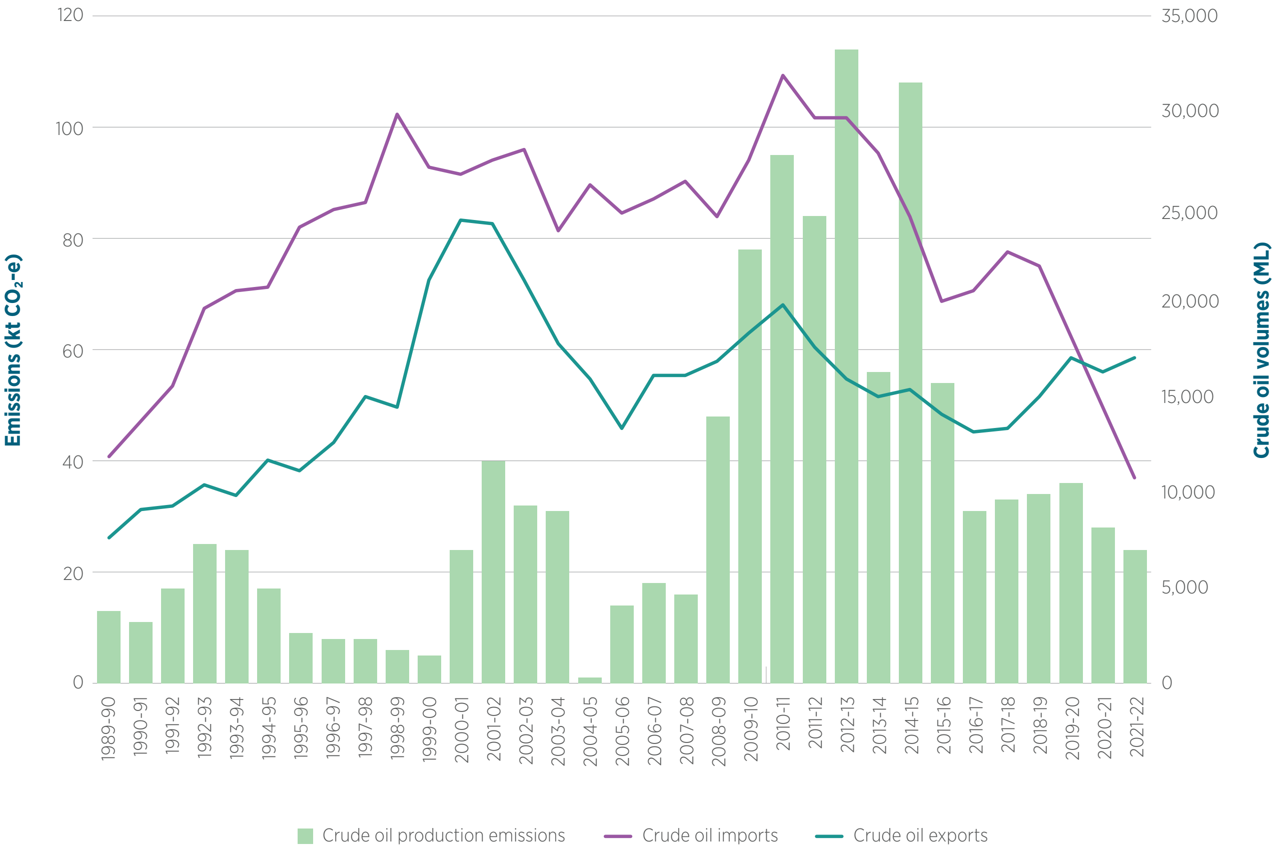
Australia's oil industry is described in the annual Australia's Energy Commodity Resources (AECR) report, published by Geosciences Australia (GA 2022).

Australia is a net importer of oil, with limited identified conventional oil resources. Most production is a vast distance from the domestic east coast refining facilities, and domestically produced grades of crude oil are not suited for local refineries. Additionally, the number and capacities of domestic oil refineries have been generally reducing since 1989–90.

Most oil production occurs in the Carnarvon and Browse basins in north-western Australia, with remaining production from fields in the Gippsland and Cooper basins in south-eastern Australia.

Australian oil production has been declining since 2008–09 as new reserve developments have failed to match the rate of depletion in existing fields. However, production and emissions have grown since the trough in 2016–17 following the start-up of the Greater Enfield, Ichthys and Prelude projects on the North West Shelf (Figure 3.33).

Figure 3.33 Crude oil production fugitive emissions and trade volumes 1989–90 to 2021–22



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Oil and Gas Exploration (CRT categories 1.B.2.a.i and 1.B.2.b.i)

Fugitive emission sources from oil and gas exploration activities include well drilling, drilling mud degassing, and well completions.

Short term testing activities of hydrocarbon flows and pressure may be undertaken following drilling. In the absence of collection infrastructure, which is generally the case in exploration, the hydrocarbons will usually be flared as a means of disposal. Emissions occur during drilling via the degassing of drilling mud. On drilling through hydrocarbon strata, methane gas can be entrained within the drilling mud and vented at the surface.

Crude Oil Production (CRT category 1.B.2.a.ii)

Emissions of CH_4 and NMVOCs may occur during oil production, including field processing, as a result of:

- leakages at seals in flanges, valves, and other components in a variety of process equipment; and
- storage tanks and losses of gases during oil production.

Crude Oil Transport (CRT category 1.B.2.a.iii)

The marine, road, and rail transport of crude oil results in CH_4 and NMVOC emissions. The extent of emissions depends on the gas control technology employed during transfer operations, fuel properties (e.g. vapour pressure and gas composition), ambient temperatures, trip duration, and the leak integrity of tanks.

Emissions associated with the marine transport of crude oil are of three types: loading, transit, and ballasting. Fugitive emissions from the cargoes of ships engaged in international trade are reported as a memo item under international marine bunker fuels (CRT category 1.D.1).

Crude Oil Refining and Storage (CRT category 1.B.2.a.iv)

Crude oil is refined into numerous petroleum products through a variety of physical and chemical processes. During such processing, fugitive emissions of CH_4 and NMVOC emissions are generated. Fugitive emission sources at crude oil refineries may be released as leaks from valves, flanges, pump and compressor seals, process drains, cooling towers, and oil/water separators.

Crude oil is stored at pipeline pump stations and refineries. During storage, CH_4 and NMVOC emissions are emitted through normal processes such as tank breathing, and working and standing losses. Storage or tank losses are a complex function of several variables including tank characteristics, fuel properties, meteorological conditions, vapour emission control, and liquid throughput.

In the absence of data at the individual refinery level, national CH_4 emissions from crude oil refining and storage may be calculated using default EFs according to IPCC Guidelines. The mid-range IPCC default EFs are adopted for crude oil refining and storage, i.e. 745 kg/ PJ for refining and 140 kg/PJ for storage.

Fugitive emissions of NMVOCs resulting from crude oil refining and storage were estimated for Victoria (Carnovale, et al. 1991), one of the primary states where oil is refined and stored. It was estimated that NMVOC emissions associated with fugitive and tank storage/loading is 20,000 kg/PJ of oil refined.

NGER scheme data have provided information on the emissions associated with the burning of refinery coke to restore the activity of the catalyst during the petroleum refining process. Consistent with previous practice, and to maintain time series consistency, this source of emissions has continued to be included within petroleum refinery fuel combustion 1.A.1.b.

Oil refinery flaring

The composition of refinery flare feed-gas is highly variable and depends on plant processing, process upsets and flare operation. In this inventory the composition of refinery gas directed to flares is assumed to be 30 per cent CH_4, 30 per cent NMVOCs and 40 per cent H_2 (by volume) (NGGIC 2004). An average flare combustion efficiency of 98 per cent is used, based on studies by USEPA (USEPA 1995).

For the years 1989–90 to 2007–08, the quantity of gas flared is calculated as 0.6 per cent of the total ABARE annual refinery feedstock as no detailed data has been available on refinery flaring volumes. The methodology (E&P 1994) considered the range and age of technologies of the Australian refining industry and publicly available information on annual flaring emissions from Australian facilities.

Facility level data on flaring volumes became available for the first time in 2008–09 through the NGER scheme. Analysis has shown that facility-level flared quantities are consistent with the assumptions used to derive the activity data prior to 2008–09. Given that flaring quantities depend on facility-specific technology types and processes, as well as the episodic nature of flaring, it was not considered appropriate to interpolate NGER scheme activity data back through the time series.

Distribution of oil products (CRT category 1.B.2.a.v)

The 2006 IPCC Guidelines (volume 2, chapter 4, table 4.2.4) (IPCC 2006) do not provide CH_4 or CO_2 emissions factors for this source. Australia uses country-specific emissions factors and a combination of facility-level and state-level activity data to estimate NMVOC emissions from this category.

The distribution of petroleum products represents a significant source of fugitive NMVOC emissions. Emission sources include motor vehicle refuelling, service station tank filling and breathing losses, major fuel-terminal storage, tank filling losses, refuelling of aircraft, and other mobile sources.

The NMVOC emissions factors for fuel storage tanks are a complex function of several variables and are shown in Table 3.35 based on emissions per sales volumes of each product distributed in Australia. These emissions factors were calculated from a weighted average analysis of fuel transfer and storage regulations in different regions of Australia.

Table 3.36 NMVOC emission factors for petroleum product distribution

	Emission factor (kg/kL distributed)		
Emission Sources	**Petrol**	**Diesel**	**Avgas**
Motor Vehicle/Equipment Refuelling	1.40 (a)	0.84 (b)	NA
Service Station/Premises, Storage/Transfer	0.66 (c)	0.006 (d)	NA
Bulk Fuel Terminal, Storage/Transfer	1.08 (c)	0.009 (d)	NA
Aircraft, Refuelling/Storage	NA	NA	2.69 (e)
Total of all sources	3.14	0.099	2.69

Sources: (a) USEPA (1995) Uncontrolled refuelling and spillage. (b) USEPA (1992) Uncontrolled refuelling and spillage. (c) See Table A5.3.2.22 and A5.3.2.23. (d) Scaled according to ratio of diesel/petrol emission rate for tank breathing and emptying as reported in USEPA (1992). (e) Australian Environment Council (AEC 1998).

Several assumptions were made in compiling these emissions factors. Emissions from refined petroleum products in storage and in transit are assumed to be negligible, meaning that all emissions are associated with transfer and fuelling operations (USEPA 2015). Emissions associated with the normal distribution of LPG are also assumed to be negligible (Carnovale, et al. 1991; EPA NSW 1995). From a consideration of emissions factors (USEPA 1992), and the predominant modes of distribution of aviation turbine fuel and fuel oil, emissions of NMVOCs from the distribution of these fuels are assumed to be negligible.

Other – Abandoned oil and gas wells (CRT categories 1.B.2.a.vi and 1.B.2.b.vi)

Abandoned wells are defined as wells that are no longer producing petroleum or exploration activities have ceased. The 2019 IPCC Refinement (volume 2, chapter 4, p.4.62) (IPCC 2006) describes that these wells may be abandoned for many reasons such as the resource is drained, surrender of a production license, or geological, technical, or ecological factors.

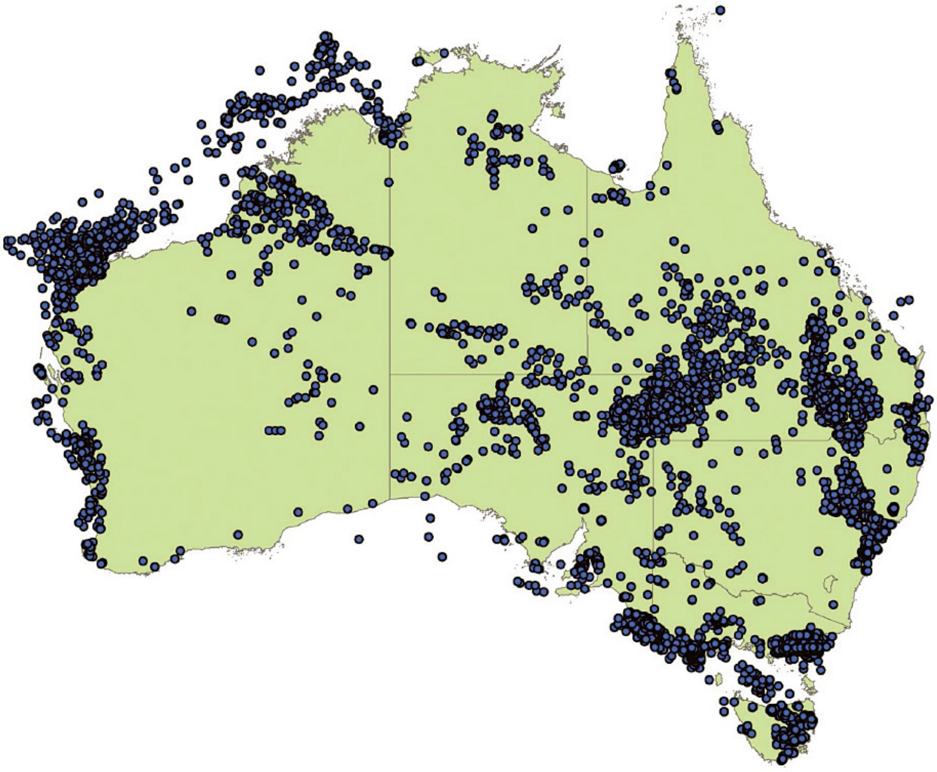
In 2019, Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) undertook analysis of methane flows in the Surat Basin – a region of Queensland and northern New South Wales rich in methane-intensive economic activity.

The review analysed domestic and international scientific literature and found that the emissions factors for abandoned oil wells published in the IPCC 2019 Refinement (volume 2, chapter 4, table 4.2.4E) (IPCC 2019) represented the best available data relevant to Australia's national circumstances.

Activity data on the number of abandoned oil wells and the plugging status of those wells were obtained from State and Territories governments, who manage data reported by the petroleum wells' responsible entities. Entities are generally obligated to report data through State and Territory regulations. The State and Territories datasets contain historical well data, often dating back to the early 1900s. Well locations are shown in Figure 3.34.

Australia currently has around 22,000 identified abandoned oil and gas wells in 2021–22, compared to over 3 million in the USA in 2020–21 (USEPA 2022).

Figure 3.34 Map of the locations of Australia's abandoned oil and gas wells, 2021–22



Sources: DCCEEW using data from DRNSW, Vic GSV, WA DMIRS, Qld DR, SA DEM, NT DITT, and Tas DSG.

Activity data are counts of the abandoned wells for each year from 1989–90. As the rig release date was not available in all source data, the rig spud date was used to identify the number of abandoned wells for the year. The abandoned wells count was then further categorised into plugging status (plugged, unplugged, unknown), production type (oil, gas) and location (onshore, offshore).

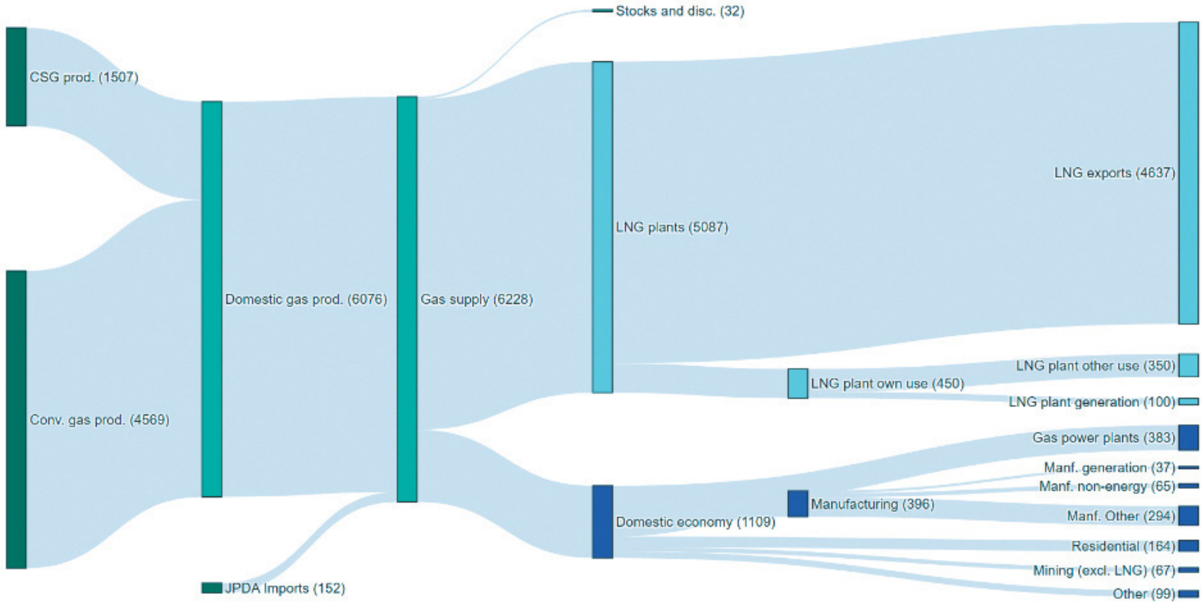
Where a well was identified as having oil and gas, or where the production type is unknown, the abandoned well was allocated to gas (CRT category 1.B.2.b.vi) as larger volumes of natural gas are produced in Australia.

Natural gas (CRT category 1.B.2.b)

CRT category 1.B.2.b consists of leakage emissions associated with natural gas systems. Leakage emissions of CH_4 from natural gas production, processing, and distribution are key categories of CH_4 emissions for Australia. Venting and flaring emissions associated with the natural gas industry are also key categories and, in accordance with the 2019 IPCC Refinement, these are reported under CRT category 1.B.2.c (IPCC 2019).

Gas production occurs predominantly from offshore conventional gas resources; however, Australia also produces significant onshore unconventional gas resources (coal seam gas). Australia is a net exporter of natural gas, with recent record high exports making it the largest exporter of liquefied natural gas (LNG) in 2019–20 (GA 2022; GA 2023) (DCCEEW 2023). The natural gas flows for the current reporting year are presented in Figure 3.35.

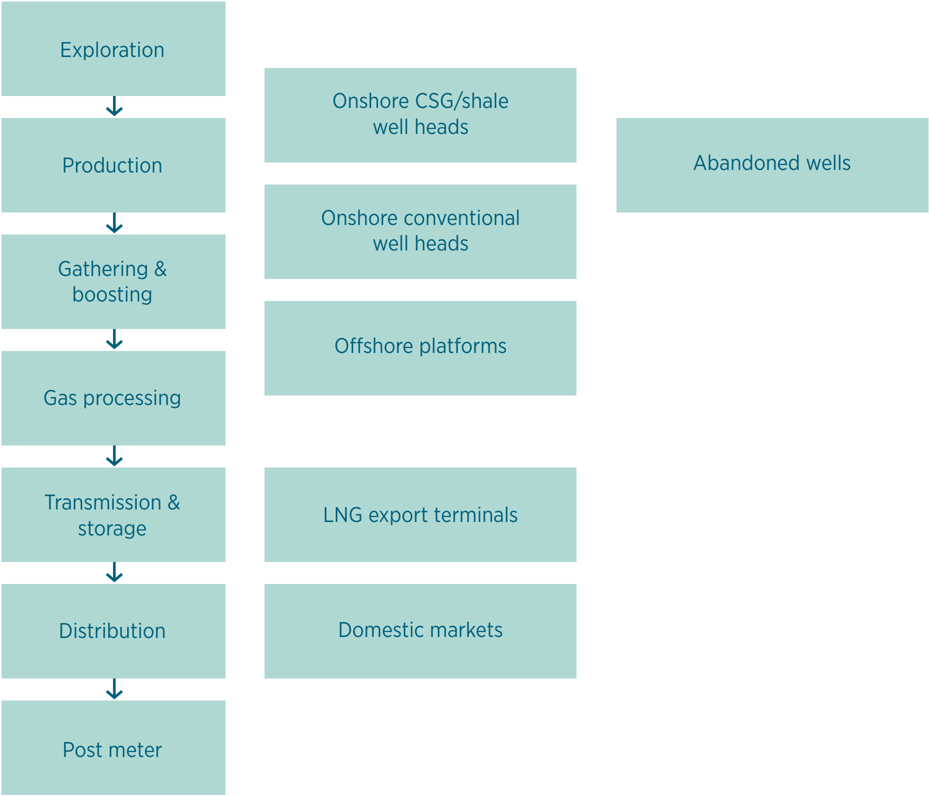
Figure 3.35 Australian natural gas energy flows, PJ, 2021–22



Source: *Australian Energy Update Report 2023* (DCCEEW 2023).

Australian LNG exports commenced in 1989 based on long-term contracts with the Japanese market, which remains a primary importer of Australian LNG. LNG exports have expanded through time with several other countries becoming important destinations, predominantly across the Asia region (BREE 2014) (GA 2022).

Figure 3.36 Emission estimation segments for the gas supply chain



The emission factors for leakages are derived from the following sources:

18. Australia-specific factors derived from research by the CSIRO, where available;
19. Application of more complex NGER scheme methods – ‘method 2’, where appropriate using factors taken from API (2009), consistent with IPCC default factors;
20. Factors derived from US and international research, including those that update or supplement factors in API (2009):
    a. Well completions for fractured wells (USEPA 2016);
    b. Offshore gas platforms (USEPA 2015);
    c. Gathering and boosting stations (Zimmerle, et al. 2020);
    d. Gas processing plants (Mitchell, et al. 2015);
    e. Storage and export terminal infrastructure (USEPA 2016); and
    f. Appliance leakage in the commercial and residential sector (Merrin and Francesco 2019).
4. Factors derived from the 2019 Refinement to the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019):
    a. Abandoned oil and gas wells; and
    b. Industrial plants and power stations and natural gas vehicles.

Gas Exploration (CRT category 1.B.2.b.i)

Fugitive emissions for offshore/onshore testing and drilling exploration activities for oil and gas are estimated in the same way – more information can be found above under oil and gas exploration (CRT categories 1.B.2.a.i and 1B.2.a.i).

Well completions and workovers

Methane emissions occur in association with final well clean-ups, production testing and well stimulation associated with the transition of a well to gas production. The emission factors for well completions and workovers are technology-specific.

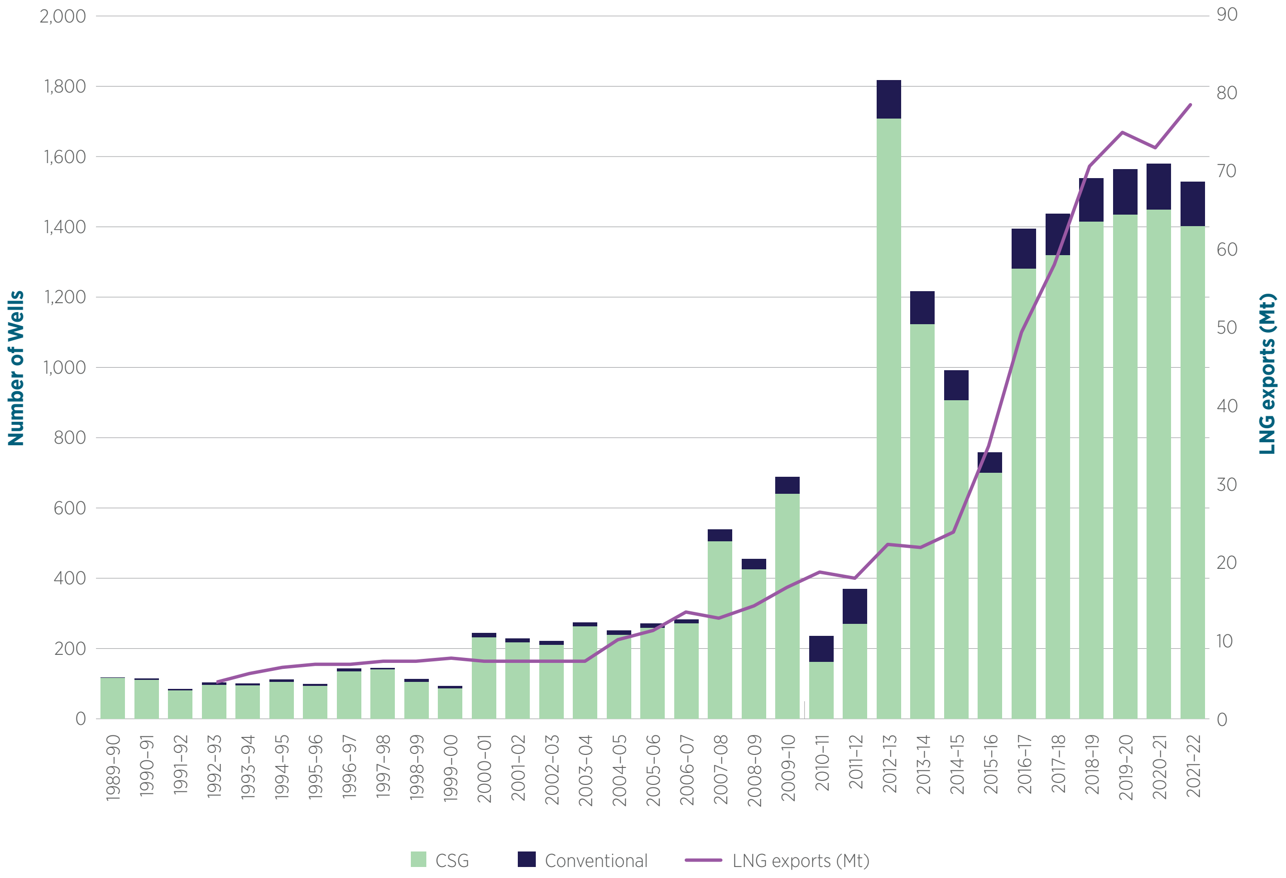
The factor for well completions without the stimulation of fracking is derived from a study of Australian well completions by Day et al. 2017.

In cases of well completions where stimulation of production though fracking occurs, the factors in the US NIR (USEPA 2016) are applied in the absence of any IPCC default factors for these types of events, which include:

- With fracturing and venting,
- With fracturing and flaring, and
- With fracturing and green capture.

The number of well completions was derived from production well activity data obtained from APPEA, state agencies, and industry project sources. It includes conventional, coal seam gas, and shale gas wells from both onshore and offshore locations. The number of well completions by year is shown in Figure 3.37. The recent expansion of the coal seam gas industry, largely to support growing LNG exports, is evident in the sharp increase in the number of production wells since 2007–08.

Figure 3.37 CSG and conventional wells drilled, and LNG exports, since 1989–90



Sources: Well counts are sourced from APPEA, NOPTA and ABS exploration investment report. LNG exports are sourced from the REQ.

Natural Gas Production (other than venting and flaring) (CRT category 1.B.2.b.ii)

The 2019 IPCC Refinement (IPCC 2019) provides a greater disaggregation of emissions from this category than those presented in the 2006 IPCC Guidelines (IPCC 2006). As a significant gas producer, Australia updated its methods in previous submissions to provide more granular emissions estimates for this category.

Leakage emissions from natural gas production arise from the unintentional equipment leaks from valves, flanges, pump seals, compressor seals, relief valves, sampling connections, process drains, open-ended lines, casing, tanks, and any other leakage sources from pressurised equipment not defined as a vent.

Australia reports emissions in this category from onshore conventional and unconventional (coal seam gas) production, offshore production in shallow and deep waters, and onshore gathering and boosting stations.

Onshore natural gas well production leakage

The leakage rate for operating coal seam gas wells is derived from Day et al. 2014. This study collected field data measurements from 43 coal seam gas wells in coal seam gas producing states in Australia and found the mean emission leakage rates from gas producing wells corresponded to an emission factor of 4.7×10^{-5} tonnes of CH_4 per tonne of unprocessed natural gas that passes through the wellhead. A molar conversion was used on this factor to derive a CO_2 emissions factor of 1.3×10^{-4} tonnes of CO_2 per tonne of unprocessed natural gas that passes through the wellhead.

In the absence of a source-specific factor, these Australia-specific leakage rates were also applied to conventional onshore natural gas wells.

Onshore Gathering and boosting stations and pipelines

Unprocessed natural gas is transported from wellheads either directly to the processing facility, or through field compressor boosting stations via gathering pipeline systems.

Leakage emissions from the pipeline system are estimated based on pipeline length and methane emission factor from the 2009 API Compendium (section 6.1.2, table 6.4).

Leakage emissions from the gathering and boosting stations are estimated using factors derived from Zimmerle et al. (2020), who collected measurements from 180 gathering and boosting stations across the United States.

Based on the analysis of data from Zimmerle et al. (2020), a non-linear relationship has been identified between the fugitive leakage emission rate emitted to the atmosphere and the quantity of unprocessed natural gas that passes through the station. Stations with low throughputs were found to have higher leakage rates, whereas stations with high throughputs were found to have lower leakage rates. Despite this relationship, high throughput stations were observed to have higher emissions overall caused by the larger quantities being moved.

The equation adopted for the Australian inventory is:

$$E_{ij} = 2.386 \text{ x } Q_{ij}^{\ -0761}$$

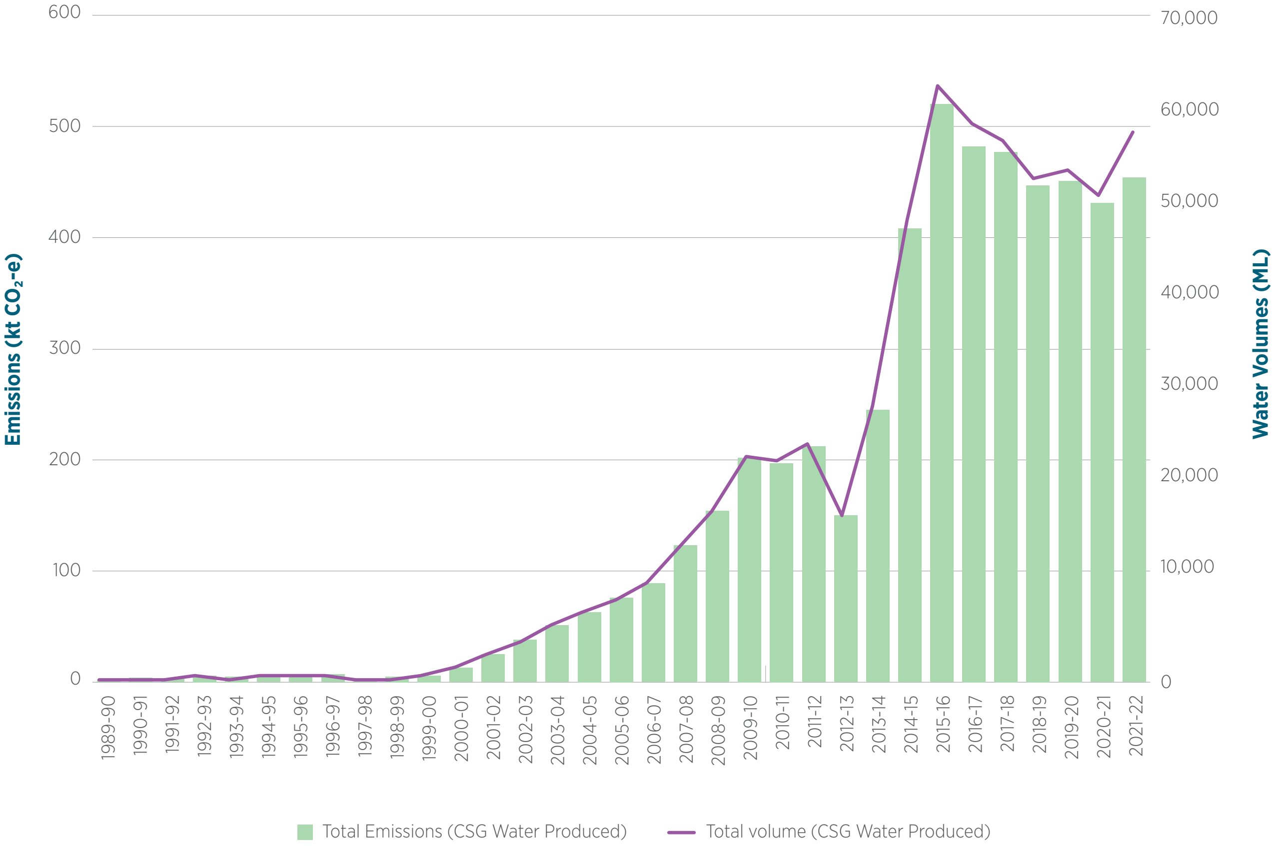
Where E_{ij} = estimated fugitive leakage emissions of methane from gas gathering and boosting stations; and
Q_{ij} = quantity of gas throughput at the gas gathering and boosting station.
2.386 = scaling factor from Zimmerle et al. (2020)
-0.761 = exponential factor from Zimmerle et al. (2020)

Coal seam gas – produced water

Wells drilled into underground coal seams bring water from the seams to the surface. This process reduces pressure in the seams, allowing coal seam gas to be released (Qld DES 2022). Significant water volumes are produced from coal seams and are regulated by state and territory governments (DCCEEW 2022). This water is pumped into treatment tanks and dams with a view for the water being reusable for some alternative purpose. Residual dissolved methane in the produced water escapes into the atmosphere throughout the treatment process (Figure 3.38).

The 2019 IPCC Refinement (IPCC 2019) does not provide emissions factors for produced water. A leakage rate taken from the API Compendium (2009), Table 5–10 of 0.31 tonnes of methane per million litres of produced water was used to estimate emissions from this source.

Figure 3.38 Water produced coal seam gas extraction and associated methane emissions, 1989–90 to 2021–22



Sources: Volume of water produced data from NGER scheme (CER 2022)

Offshore platforms

Offshore natural gas production is any platform structure that houses equipment to extract hydrocarbons from the ocean and that processes and/or transfers such hydrocarbons to storage, transport vessels, or onshore. Emission factors are taken from the US EPA 2016 in the absence of Australian data or IPCC default factors. For shallow water platforms (less than 200 metres of water), the emission factor is 62.6 tonnes of methane per platform per year while for deep water platforms, the factor is 661.1 tonnes of methane per platform per year. In the current reporting year, there were 35 shallow platforms and 7 deep water platforms in Australian waters.

Gas Processing (CRT category 1.B.2.b.iii)

The emission factor function for gas processing plants is derived from Mitchell et al. (2015), whose data on gas processing plants confirms that facilities with the highest emission rates tend to be those with the smallest gas throughputs. Analysis of Mitchell's data indicates a non-linear, negative relationship between emission rates and the size of gas processing throughput – in general, higher emission rates are experienced by plants with lower gas throughput and lower emission rates for plants with high gas throughput (Figure 3.39).

$$Y = 0.6369 . X^{-0.48}$$

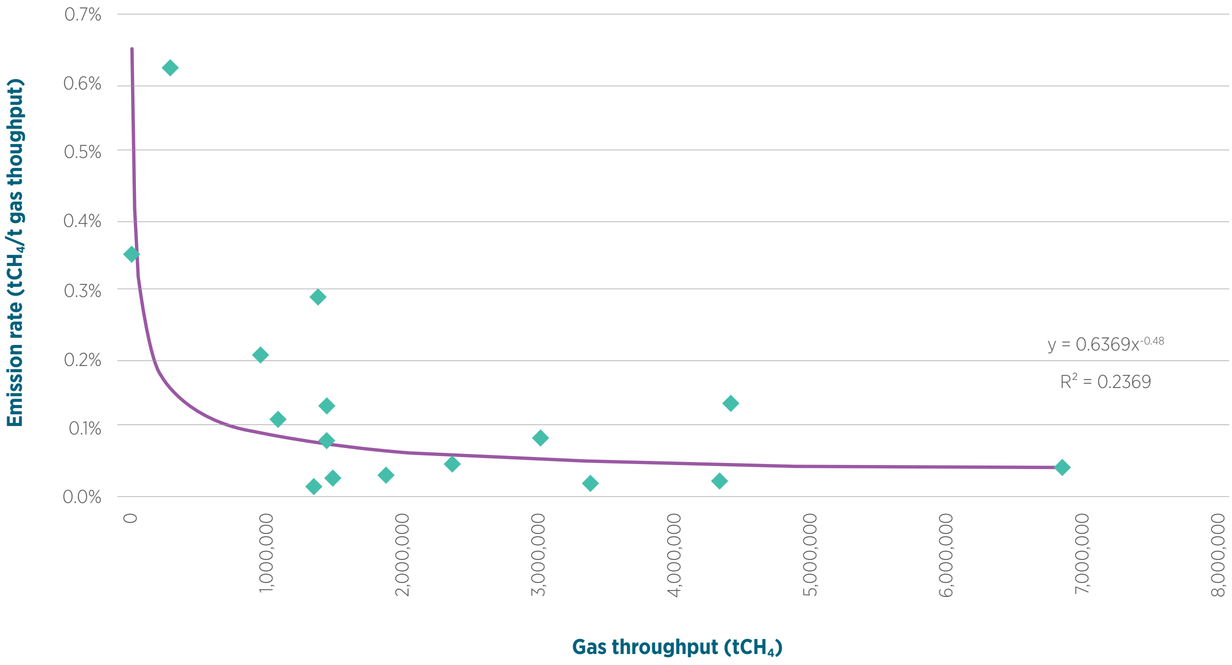
Where Y = emission rate in tonnes of emissions per tonne of gas throughput

X = gas throughput in tonnes

0.6369 = scaling factor from Mitchell et al. 2015

-0.48 = exponential factor from Mitchell et al. 2015

Figure 3.39 Gas processing plants with reported high emission rates are likely to have negligible gas throughputs



Source: Derived from Mitchell et al. (2015).

Using this equation, the modelled emission rate for the smallest plant was 0.0065 tonnes of CH_4 per tonne of gas throughput and the modelled emission rate for the largest, 0.0004 tonnes of CH_4 per tonne of gas throughput.

Table 3.37 Fugitive emission factors for natural gas

		Factor		
Inventory category	**Unit**	**CO_2**	**CH_4**	**Source**
Abandoned gas wells	tonnes of emissions / well		Various	Australian Petroleum Production and Exploration Association, 2020 Annual Report
Post-meter leakage	Various	Various	Various	2019 IPCC Refinement- Table 4.2K, Merrin and Francesco 2019, Unburned Methane Emissions from Residential Natural Gas Appliances

Natural Gas Transmission and Storage (CRT category 1.B.2.b.iv)

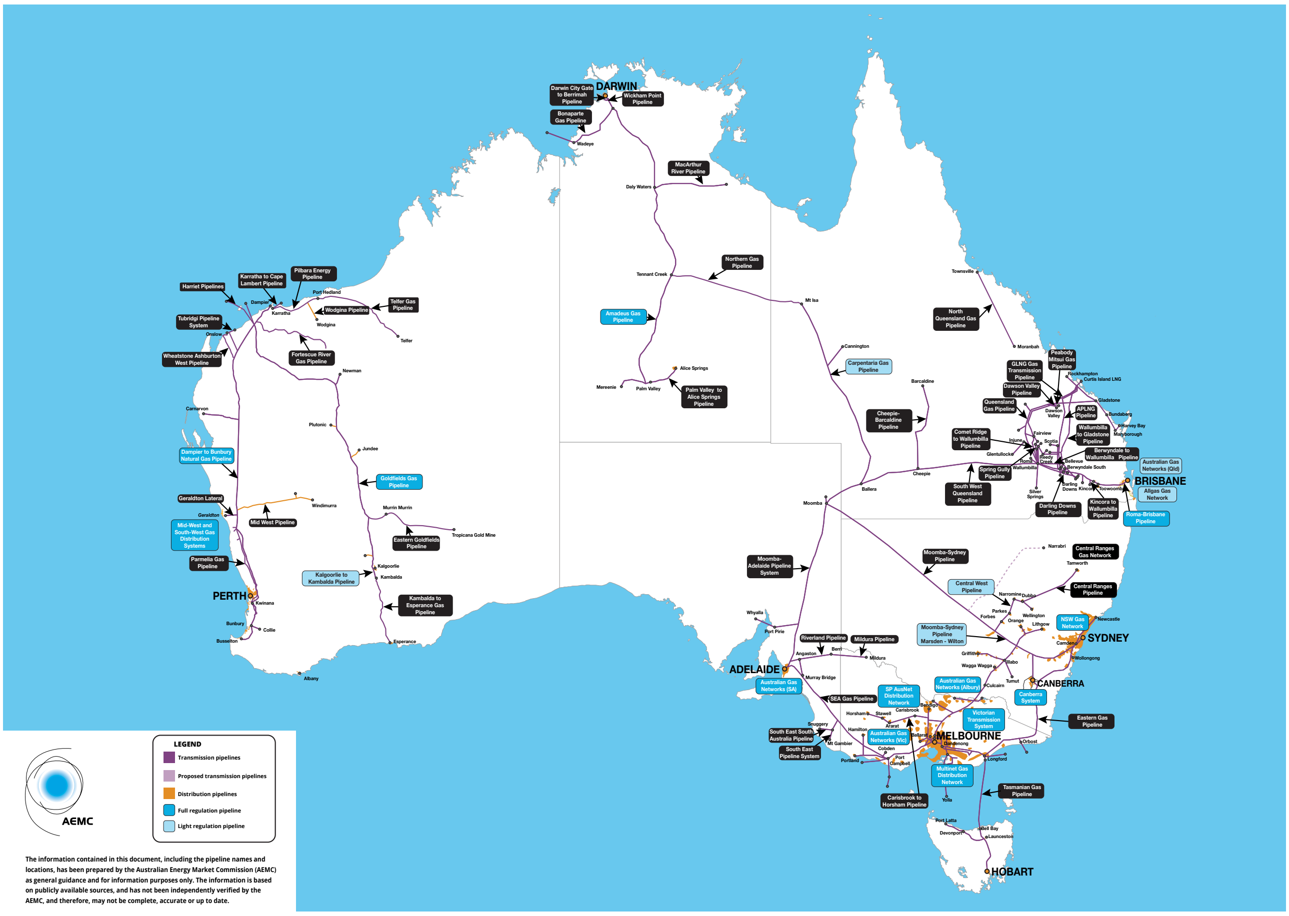
The 2019 IPCC Refinement (IPCC 2019) describes that this category comprises leakage emissions from systems used to transport processed gas to market to industrial consumers and distribution systems. Leakage emissions from related storage systems are also included.

To support transparency, emissions from storage that are not directly related to transmission are reported in the CRT tables under category *1.B.2.b.vi Other.*

Natural gas transmission pipelines

Australia has more than 39,000 kilometres of high-pressure natural gas transmission pipelines that transport gas from where it is produced to the outskirts of cities for use (APGA 2022). This system is of relatively recent vintage (the oldest line dates from 1969), built to high quality standards and is well maintained.

Figure 3.40 Map of Australia's gas pipeline network



The information contained in this document, including the pipeline names and locations, has been prepared by the Australian Energy Market Commission (AEMC) as general guidance and for information purposes only. The information is based on publicly available sources, and has not been independently verified by the AEMC, and therefore, may not be complete, accurate or up to date.

Source: AEMC 2020

Emissions may occur as a result of compressor starts (for which gas expansion is typically used to start gas turbine power units), blowdowns for maintenance at compressor stations, maintenance on pipelines, leakage, and accidents.

Australia-specific CO_2 and CH_4 emissions factors were developed by multiplying a loss factor by average pipeline gas composition by state and territory. These loss factors were then converted from loss per petajoule of gas transmitted to loss per kilometre of pipeline.

Work undertaken by the Pipeline Authority, the organisation formerly responsible for operation of the Moomba to Sydney pipeline (EMC 2022), concluded that losses from Australia's significant Moomba to Sydney pipeline (MSP) gas transmission pipeline are approximately 0.005 per cent of throughput (NGGIC 2004). As no other country-specific data was available, the losses from this pipeline were considered to be representative of other major pipelines in Australia.

Natural gas composition factors of transmitted gas by state were last reported by the Australian Gas Association in 2019–20. As no new factors have become available, and this is not a key category for Australia, the 2019–20 composition factors have been applied to all years.

The activity data is kilometres of pipeline per year, which have been published by the AEC and collected through the NGER scheme.

Natural gas storage

Along with high pressure pipelines, natural gas transmission pipelines include storage facilities. Such facilities include transmission pipelines themselves through linepack, aboveground storage tanks, and underground storage facilities (e.g. depleted gas fields). Storage facilities are used to manage peak demand or emergencies, able to inject gas into the transmission system at short notice .

In the absence of 2019 IPCC Refinement (IPCC 2019) default factors, the following factors were sourced from the US NIR (USEPA 2016):

- gaseous storage emission factor of 370 tonnes of CH_4 per facility per year,
- liquefied natural gas storage emission factor of 920 tonnes of CH_4 per facility per year.

A CO_2 factor of 2,527 tonnes of CO_2 per LNG storage facility per year was derived from the CH_4 factor using molar conversion (44.01/16.04).

Liquefied natural gas export terminals

In the absence of 2019 IPCC Refinement (IPCC 2019) default factors, a CH_4 factor of 1,109 tonnes per terminal per year was sourced from the US NIR (EPA 2016). A CO_2 factor of 3,043 tonnes per terminal per year was derived from the CH_4 factor using molar conversion (44.01/16.04).

Natural Gas Distribution (CRT category 1.B.2.b.v)

The boundary between natural gas transmission and distribution is generally taken to be the city gate regulator stations at which gas pressures are reduced from transmission pressures (up to about 15 MPa) to sub-transmission pressures. Most of the gas lost from gas transmissions and distribution systems is by way of leakage from the low-pressure network. The amount of leakage depends on the number and condition of joints in the pipes. The high pressure and trunk main pipes are welded steel, so flanged joints are typically only at valves and compressors. Pressures are so high that any major leaks that might occur are obvious, dangerous, and quickly attended. Other causes of fugitive emissions from gas distribution systems (up to and including customer meter) are:

- third party damage (e.g. excavators),
- purging of new mains,
- unburnt gas from gas compressors (if there are any on the distribution system),
- gas lost to atmosphere on start-up and shut down of compressors, and
- regulating and relief valves.

Emissions from the distributor side of the meter are not measured directly but must be based on estimates of unaccounted for gas (UAG). Components of UAG include: leakage emissions, meter inaccuracies, use of gas within the system itself, theft of gas, variations in temperature and pressure and differences between billing cycles and accounting procedures between companies delivering and receiving the gas. Leakage emissions from distribution systems are dependent on the age and composition. Older, metal pipelines have higher leakage factors than newer PVC pipelines (2009 API Compendium).

Since 2008–09, the NGER scheme has been collecting activity data and emissions factors for natural gas distribution. The NGER scheme allows natural gas distributors to choose one of three methods to calculate their natural gas distribution emissions. Each of the NGER scheme methods apply a variety of country or plant-specific emissions factors and assumptions to activity data (total gas sales for NGER scheme methods 1 and 3, and quantities of gas throughput by equipment type for NGER scheme Method 2), resulting in IPCC tier 2 method estimations of both CO_2 and CH_4 from this source.

Plant-specific information, reported through NGER scheme, is used for the majority of this source category, using equipment emissions factors from Section 6-1-2 of the 2009 API Compendium (API 2009). Where plant-specific information isn't available through the NGER scheme, distribution emissions are estimated using the following formula:

$$E = S \times \%UAG \times LF \times C$$

Where: ***E*** is the total leakage emissions resulting from the natural gas distribution pipeline system, measured in tonnes of CO_2-e.

S is the total gas sales during the year from the distribution pipeline system in a State or Territory, measured in terajoules. Total annual gas utility sales were derived from the AES for 1989–90 to 2007–08 in lieu of direct data relating to natural gas distribution. By removing gas components known to be used in other sectors (i.e. Divisions A, B, D and I of the AES data), it was assumed that the remainder of gas sales fell under the natural gas distribution sector. For 2007–08 onwards, natural gas sales data was used, collected under the NGER scheme, or through company annual reports.

%UAG is the percentage of unaccounted for gas in the pipeline system in a State or Territory Facility-specific %UAG is used where available, sourced from annual reports by companies, and data published in the 5-year projected estimates developed by the Australian Energy Regulator for access arrangements. Where a facility does not have a facility-specific %UAG reported as part of their access arrangements or annual reports, the %UAG is estimated as per Table A3.38.

LF is the leakage factor, representing the proportion of UAG that is attributed to leakages in the distribution system. This factor is 0.55 for 1989–90 to 2006–07, and 0.373 for 2017–18 onwards. In 2020, an internal review of literature, including the 2017 Zincara *Review for Victoria's Essential Services Commission* and public submissions by distribution companies, concluded that the proportion of unaccounted for gas attributable to distribution leakages was in the range of 35–40 per cent. Based on available reported unaccounted for gas breakdowns from the annual reports of relevant companies, the Australian Energy Regulator, and the Zincara review, the estimate for the leakage proportion of total UAG was set to 37.3 per cent from 2017–18 onwards. A linear interpolation of historic data for the time period 2005–06 to 2017–18 was also be applied to account for improvements to distribution pipelines in the time period between 2004–05 and 2017–18 (Table A5.3.5.6 in Volume 2).

C_{jp} is the natural gas composition factor for CO_2 and CH_4 for a pipeline system in a State or Territory (Table 3.38). The state-based factors were provided by the Australian Gas Association (AGA 2000).

Table 3.38 Unaccounted for gas percentages and pipeline natural gas compositions by state and territory

	Unaccounted for gas %	Natural gas composition factor (tonnes CO_2-e/TJ gas sales)	
State	UAG	CO_2	CH_4
NSW and ACT	2.2	0.8	437
Vic	3.0	0.9	435
Qld	1.7	0.8	423
WA	2.9	1.1	408
SA	4.9	0.8	437
Tas	0.2	0.9	435
NT	2.2	0.0	352

Sources: (AEC 2016–2021), (APIA 2009)

Post-meter emissions (CRT category 1.B.2.b.vi.1)

As per the 2019 IPCC Refinement (IPCC 2019), this category includes gas leakage emissions from consumer appliances, power plants, and natural gas-fuelled vehicles.

Appliance leakage

Leakage emissions that occur downstream from the meter are estimated for natural gas appliances used in the residential and commercial sectors, such as cooktops, water heaters and space heating.

An Australia-specific method was applied using emissions factors by appliance type derived from a measurement study by Merrin and Francesco (2019), which looked at non-combustion emissions from residential natural gas appliances.

Activity data for appliances in the residential sector was sourced from the *2021 Residential Baseline Study for Australia 2000–2040* (November 2021) commissioned by the former Department of Industry, Science, Energy and Resources. Activity data for appliances in the commercial sector was inferred from residential data in conjunction with relative natural gas consumption in both sectors (DISER, 2021).

Industrial and power plants

Australia uses the emission factors for leakages at industrial plants and power stations published in the 2019 IPCC Refinement (volume 2, chapter 4, table 4.2.4K). Fugitive leakage is already calculated for oil production, oil refining, gas production and processing, natural gas transmission (CRT category 1.B.2.b.iv), and natural gas distribution (CRT category 1.B.2.b.v). Activity data relating to these categories were excluded to avoid double-counting.

Natural gas vehicles

Australia uses the emission factors for leakages at industrial plants and power stations published in the 2019 IPCC Refinement (volume 2, chapter 4, table 4.2.4K).

Leakage emissions from natural gas vehicles include releases from dead volumes during fuelling, emptying of gas cylinders of high-pressure interim storage units, execution of pressure tests, relaxation of residual pressure from vehicles' gas tanks, and pressure tests or decommissioning.

Activity data were obtained from New South Wales State motor vehicle registration statistics (Transport NSW 2023). A national time series of natural gas vehicles was then inferred by using the consumption of natural gas in the transport sector, derived from the Australian Energy Statistics, to ensure time series consistency and completeness.

Abandoned gas wells (CRT category 1.B.2.b.vi.2)

Available information on abandoned oil and gas wells do not indicate a clear distinction between the practices and emissions factors for abandoned oil and abandoned gas wells (2019 IPCC Refinement, (IPCC 2019) volume 2, chapter 4, p4.83). As such, please refer to Other – Abandoned oil and gas wells (CRT categories 1.B.2.a.vi) for details on emissions estimated for this category.

Other (CRT category 1.B.2.b.vi.3)

The 2019 IPCC Refinement (IPCC 2019) describes that anomalous leak events can occur across natural gas systems, such as leakage of storage wells, emergency pressure releases, and unintentional gas spills. To support transparency, Australia reports emissions associated with storage activities that are not directly associated with transmission activities against this category in the common reporting tables. Refer to the above section on Transmission (CRT category 1.B.2.b.iv).

Oil and gas production venting and flaring (CRT category 1.B.2.c)

Gas and waste gas/vapour streams at oil and gas facilities are disposed of via venting or flaring.

Venting – combined (CRT category 1.B.2.c.i.3)

Venting refers to emissions that are the result of process or equipment design or operational practices. Venting at oil and gas processing facilities is mainly associated with the release of CO_2, which is extracted from the raw gas stream during gas processing. As separation of the other components of the gas stream from the CO_2 is incomplete, the vented CO_2 contains small quantities of CH_4. The quantities of CO_2 and CH_4 vented will depend on the concentration of CO_2 in the raw gas, which varies significantly between production fields, and on the mode of operation and efficiency of the CO_2 stripping plant. Gas processing facilities monitor the volumes of the vent gas and the CO_2 and CH_4 concentrations as a part of routine plant operation. The venting of CH_4 also occurs from gas assisted pumps and cold process vents.

Due to difficulties in separating venting emissions associated with oil production from those associated with gas production, Australia reports venting emissions using the combined reporting option in the common reporting tables.

Tonnes of gas vented associated with oil and gas production are reported through industry reporting (APPEA 1989–90 to 2007–08, NGER scheme 2008–09 and onwards). From 1989–90 to 2007–08, estimates of emissions are based on industry data (APPEA 1998–2008). These data consist largely of direct monitored emissions associated with control vent releases as well as estimates of emissions from cold process vents. The NGER scheme approach for 2008–09 onwards has enhanced the methodologies available for technology types by utilising the American Petroleum Institute Compendium (API 2009) methodologies for vents.

Methane vented from condensate production was estimated from the average factor in the US NIR (USEPA 2017), and from production published by the Australian Petroleum Statistics.

Flaring (CRT categories 1.B.2.c.ii.1 and 1.B.2.c.ii.2)

Where there is no market for hydrocarbons separated from the wellhead production stream, the hydrocarbons may be reinjected or flared. Typically, gas sent to flare is mostly CH_4 with smaller concentrations of other volatile hydrocarbons and is usually different in composition to pipeline gas. Condensates and other petroleum liquids may also be flared in small quantities for disposal.

Emission factors are country-specific, sourced from industry (APPEA 1998–2008) and were applied to the entire time series.

Prior to 2008–09, APPEA did not provide splits for flaring between oil and gas sources and, therefore, flaring emissions were reported in the oil/gas combined category. With the introduction of the NGER scheme, separate emissions data became available for the individual oil and gas flaring categories for 2008–09 onwards. Disaggregation of flaring associated with oil and gas operations was achieved by calculating the average implied emissions per petajoule of crude oil and ORF (oil refinery fuel) produced (AES) for NGER scheme years (2008–09 onwards) and applying this factor back through the production time series (1989–90 to 2007–08). These derived oil flaring emissions were subtracted from the combined total of oil and gas flaring emissions, resulting in no net change in emissions from flaring.

3.3.2.3 Uncertainty assessment and time-series consistency

The tier 1 uncertainty analysis in Annex II provides estimates of uncertainty according to IPCC source category and gas.

Time series consistency is maintained by using consistent methodologies and data over time across multiple datasets. Methods consistent with IPCC Section 5.3.3.2 and Section 5.3.3.3 were used as the primary approaches to ensuring time series consistency when integrating data for years prior to the start of the NGER scheme in 2008–09.

3.3.2.4 Category-specific QA/QC and verification

This source category is also covered by the general QA/QC of the greenhouse gas inventory in Annex IV.

Results from top-down studies and inverse modelling of methane in Australia's coal seam gas (CSG) fields have been used for QA for validation of national inventory estimates. Australia's coal seam gas (CSG) fields in the Surat Basin of Queensland generate methane emissions from gas leakages, deliberate losses from gas venting or flaring, and from incomplete oxidation of gas during combustion.

In Australia's national inventory, methane losses from CSG production are estimated to be 0.40 per cent of gas production for the upstream supply chain and 0.56 per cent of gas production for the export supply chain in Australia.

In recent years, independent assessments of methane losses from CSG operations in the Surat Basin have been undertaken by researchers at the CSIRO Atmospheric Division (A. Luhar, et al. 2020), and at the UNSW, sponsored by the UN Environment Program (Neininger, et al. 2021). These studies use techniques that attempt to monitor the methane plumes observed in the Surat Basin directly (known as a top-down approach). Working under the Gas Industry Social and Environmental Research Alliance (GISERA) program, the CSIRO study used flux towers stationed at different points in the Basin while the UNEP study used plane flyovers to map and quantify the extent of the methane plumes observed in the Surat Basin.

The CSIRO GISERA program made its own assessment of the extent of the methane losses from CSG production in the Surat Basin, derived from the work of the CSIRO Atmospheric Division, and concluded that methane losses were less than 0.5 per cent of natural gas production (CSIRO GISERA 2019). The UNEP study concluded that CSG sources in the Surat Basin emit about 0.4 per cent of the produced gas (Neininger et al. 2021).

The convergence of methane loss results from both the CSIRO GISERA assessment and the UNEP study with the national inventory provides strong quality assurance that the national inventory estimates of methane losses from CSG gas supply are robust.

3.3.2.5 Category-specific recalculations

The recalculations reported in the current submission are shown in Table 3.39 and include:

A. **Update to Natural Gas Distribution for 2007–08 to 2019–20**

   Updates were applied to resolve an error in the application of global warming potentials in the calculation of Method 2 reporting facilities. Additional updates were applied for 2014–15 to 2019–20 due to new historic facility-specific UAG% data becoming available in NSW and Victoria.

B. **Recalculation in the estimate of well counts for Natural Gas Exploration**

   Improvements were made to activity data for 1.B2.b.1 Natural Gas Exploration in 2016–17 to 2018–19.

C. **Updated Activity data for produced water volumes for 2014–15 to 2019–20**

   An update to the historic time series for produced water activity data to improve the time series consistency with the newly reported NGER scheme data, through Equation 5.1 of Chapter 5 of the 2006 IPCC Guidelines.

D. Update to Post-meter gas

An update to the activity data source for the household and commercial appliance use – the *2021 Residential Baseline Study for Australia and New Zealand for 2000–2040,* was published in November 2022. This replaces the activity data reported under the *2015 Residential Baseline Study*, and results in a small recalculation for the time series from 1999–00 onwards.

E. Recalculations in venting and flaring emissions for 2020–21

Improved activity data were incorporated for condensate vending.

Additionally, an unintentional double-count in NGER scheme data of flaring at a single facility was removed.

F. Updates to Abandoned Wells

The source data associated with abandoned oil and gas wells have been updated, resulting in a small recalculation for the full time series of estimates.

Table 3.39 1.B.2 Oil and Natural Gas: recalculation of total CO_2–e emissions, 1989–90 to 2020–21

	2023 Submission	2024 submission	Change		Reasons for recalculation (Gg CO_2–e)				
Year	Gg CO_2–e	Gg CO_2 -e	Gg CO_2 -e	%	A	B	C	D	E
1989–90	14,734	14,734	0	0.0	-	-	0.2	-	-
1994–95	14,819	14,819	0	0.0	-	-	0.2	-	-
1999–00	14,399	14,399	0	0.0	-	-	0.3	-	-
2004–05	11,582	11,581	0	0.0	-	-	0.3	-	-
2005–06	11,628	11,628	0	0.0	-	-	0.3	-	-
2006–07	11,942	12,087	145	1.2	145	-	0	-	-
2007–08	12,186	12,331	145	1.2	145	-	0	-	-
2008–09	12,386	12,542	156	1.3	157	-	-1	-	-
2009–10	13,181	13,362	181	1.4	181	-	0	-	-
2010–11	12,210	12,444	234	1.9	233	-	1	-	-
2011–12	12,901	13,107	206	1.6	205	-	1	-	-
2012–13	13,430	13,699	269	2.0	267	-	2	-	-
2013–14	13,428	13,713	285	2.1	287	-	-1	-	-
2014–15	15,592	15,881	289	1.9	291	-	-2	-	-
2015–16	16,967	17,281	313	1.8	322	-1	-1	-7	-
2016–17	20,159	20,441	282	1.4	284	10	-1	-11	-
2017–18	22,302	22,667	365	1.6	319	50	-1	-4	-
2018–19	26,453	26,825	372	1.4	373	-	-1	0	-
2019–20	22,904	23,196	292	1.3	294	-	0	-2	-
2020–21	20,964	20,921	-43	-0.2	16	-	8	-1	- 67

3.3.2.6 Category-specific planned improvements

The National Greenhouse and Energy Reporting Act 2007 requires all major companies in Australia to make estimates of methane emissions from their gas supply operations. The NGER scheme methods for estimating of fugitive methane emission losses were updated in 2021. The updated methods significantly improved the granularity of natural gas production and processing reporting, drawing on domestic and international research, including results of Leak Detection and Repair programs (Australian Government 2021). Data using these methods was first reported through the NGER scheme in October 2022 covering the 2021–22 reporting year. These new data will be analysed with a view to incorporate them in future submissions.

A new Method 2 was also introduced into the NGER scheme for 2021–22 allowing reporters to estimate emissions from coal seam methane produced water degassing (reported under 1.B.2.b.2 natural gas production) using facility-specific factors. Most reporters adopted the Method 2 option, suggesting that the water pressure and salinity assumptions made in developing the Method 1 emissions factor (taken from the 2009 API compendium) may not align with Australia's circumstances. The Method 2 emissions estimates were 90 per cent lower than emissions from this source in the previous year. These new data will be analysed for accuracy and comparability, and to consider how they could be adopted in the future ensuring time series consistency as per Section 5.1 of the 2006 IPCC Guidelines. In the interim, the conservative Method 1 approach has been applied across the entire time series.

The CSIRO GISERA program is also undertaking a new 'bottom-up'' empirical study examining leakage measurements of CSG equipment at sites in the Surat Basin. This study will provide additional data on leakage rates of equipment in Australian conditions and will add significantly to the existing empirical knowledge base. The Department expects this study will provide valuable data to inform the development of leakage factors for future national inventory method updates.

New empirical and remote sensing studies of methane emissions in Australia will continue to emerge over time and are expected to provide valuable information in relation to methane sources. The implications of these new studies will be considered in future national inventory method development as part of the inventory's continuous improvement processes. As reported in the special topics to the March 2021 Quarterly Inventory (DCCEEW 2021) and September 2021 Quarterly Inventory (DCCEEW 2022), technical challenges prevent satellite data alone producing reliable emission estimates at this time. Consistent with Chapter 6 of Volume 1 of the IPPC 2019 Refinement (IPCC 2019), Australia is exploring how the emerging availability of higher resolution satellite data could improve national emission estimates in the energy sector through enhanced quality assurance.

3.4 Carbon Dioxide Transport and Storage (CRT category 1.C)

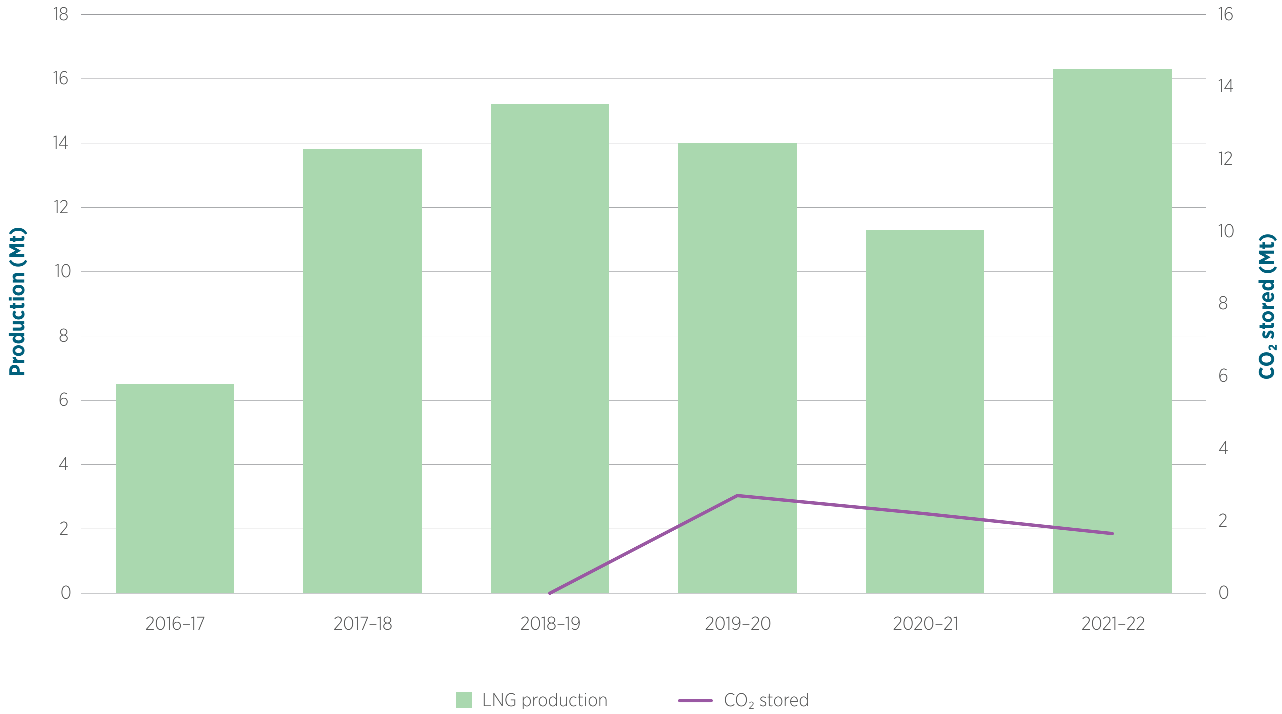
3.4.1 Category description

The 2006 IPCC Guidelines define carbon capture and storage (CCS) as a chain subdivided into four systems – capture and compression, transport, injection, and geological storage.

Existing projects

Australia has one commercial CCS project – the Gorgon Project – operated by Chevron Australia. The project commenced LNG exports in March 2016, with trials of the CO_2 underground injection system commencing in August 2019. Injection to date has reduced the emissions intensity of LNG production at the facility (Figure 3.41).

Figure 3.41 Gorgon LNG production and CO_2 injected for storage



Source: Production at Gorgon LNG facility data from EnergyQuest Reports. Note that CO_2 injection began in August 2019, and therefore injection did not occur prior to 2019–20.

The Gorgon Project is developing the Gorgon and Jansz-lo gas fields, located within the Greater Gorgon area, between 130 and 220 kilometres off the northwest coast of Western Australia. It includes a liquefied natural gas (LNG) plant and a domestic gas plant. The project was developed in accordance with approvals under the project specific legislative instrument the *Barrow Island Act 2003* (WA).

Carbon dioxide is separated from the natural gas and captured at the Barrow Island gas processing plant and transported by a 7 km pipeline to the injection site – the Dupuy saline aquifer, 2.3 km beneath Barrow Island. The project involves nine injection wells and includes long-term monitoring with several surveillance wells and seismic surveying.

Research projects

CO_2CRC operates the Otway International Test Centre in Nirranda South in Victoria (CO_2CRC 2022 to 2023). This CCS demonstration and research program commenced CO_2 sequestration in 2006. The project has injected small quantities of gas since commencement, including:

- 65,000 tonnes of CO_2–rich gas into 25–metre-thick sandstone at a depth of 2,000m between 2006 and 2011,
- 150 tonnes of pure CO_2 and 450 tonnes of CO_2 saturated formation water into a single well in 2011,
- 15,000 tonnes of CO_2–rich gas into the Paaratte Formation saline aquifer in 2016, and
- 15,050 of buttress gas into the Paaratte Formation saline aquifer in 2020–21.

This demonstration project does not constitute a CCS activity in accordance with the 2006 IPCC Guidelines (IPCC 2006) (volume 2, chapter 5, section 5.3) because naturally occurring CO_2 is extracted from a geological reservoir of CO_2 and is not captured for abatement purposes. The CO_2 is dried, purified, and transported by a short 2 km pipeline for reinjection into a nearby depleted natural gas field and a deeper saline aquifer. This research project is reinjecting small quantities of naturally occurring reservoir CO_2 that has been extracted from nearby geological formation and does not involve capture or abatement. An insignificant quantity of fugitive emissions would be associated with the processing, transport, and reinjection. Australia does not estimate emissions from this project.

3.4.2 Methodological issues

In line with the 2006 IPCC Guidelines (IPCC 2006) (volume 1, chapter 5, section 5.7), Australia uses tier 3, facility-specific modelling to estimate emissions from this category.

Table 3.40 Summary of methods and emission factors: Carbon Dioxide Transport and Storage

	CO_2	
1.C Carbon Dioxide Transport and Storage	**Method applied**	**Emission factor**
1 Transport of CO_2	T3	PS
2 Injection and Storage	T3	PS
3 Other	NO	NA

T3 = Tier 3, PS = plant specific, NO = not occurring, NA = not applicable, IE = included elsewhere, ▨ = key category

Emissions data from commercial CCS projects is collected under the NGER scheme. The NGER scheme provides methods for estimating emissions from CCS projects that have been developed to be consistent with IPCC 2006 Inventory Guidelines (IPCC 2006).

For estimating fugitive emissions from the transport and injection phases of CCS, NGER scheme methods reference existing guidance for the natural gas industry, providing for the use of industry best practice methods for pipeline and injection well operations.

In Australia, any CCS project is undertaken under a licence provided under state or commonwealth legislation depending on the jurisdiction the project in located in. Under these licences, strict project specific condition for monitoring and reporting of leaks are given. Hence, for estimating leakage from the storage formation, the NGER scheme mirrors estimates made in accordance with the measurement, reporting, and verification (MRV) requirements of the licence. This is particularly important given the project-specific nature of monitoring and reporting requirements for CCS projects.

Emissions from the Transport of CO_2 are identified as Not Occurring on the basis that the pipelines at Gorgon are short and no leaks have been identified for inclusion in reporting to date.

3.4.3 Uncertainty assessment and time-series consistency

The Tier 1 uncertainty analysis in Annex II provides estimates of uncertainty according to IPCC source category and gas. Time series consistency is ensured by using consistent models, model parameters and datasets for the calculations of emissions estimates.

3.4.4 Category-specific QA/QC and verification

This source category is covered by the general QA/QC of the greenhouse gas inventory in Annex IV.

3.4.5 Category-specific recalculations

There are no recalculations to this category in this submission.

3.4.6 Category-specific planned improvements

There are no planned improvements for this category in this submission.

4. Industrial Processes and Product Use

4.1 Overview of the sector and background information

The industrial processes and product use category covers greenhouse gas emissions resulting from industrial processes, the use of gases in products, and from non-energy uses of fossil fuels.

The industrial processes and product use sector as a portion of total emissions (excluding LULUCF) is presented in Figure 4.1.

Figure 4.1 **Share of national emissions (excluding LULUCF) for the industrial processes and product use sector, by gas, 2021–22**

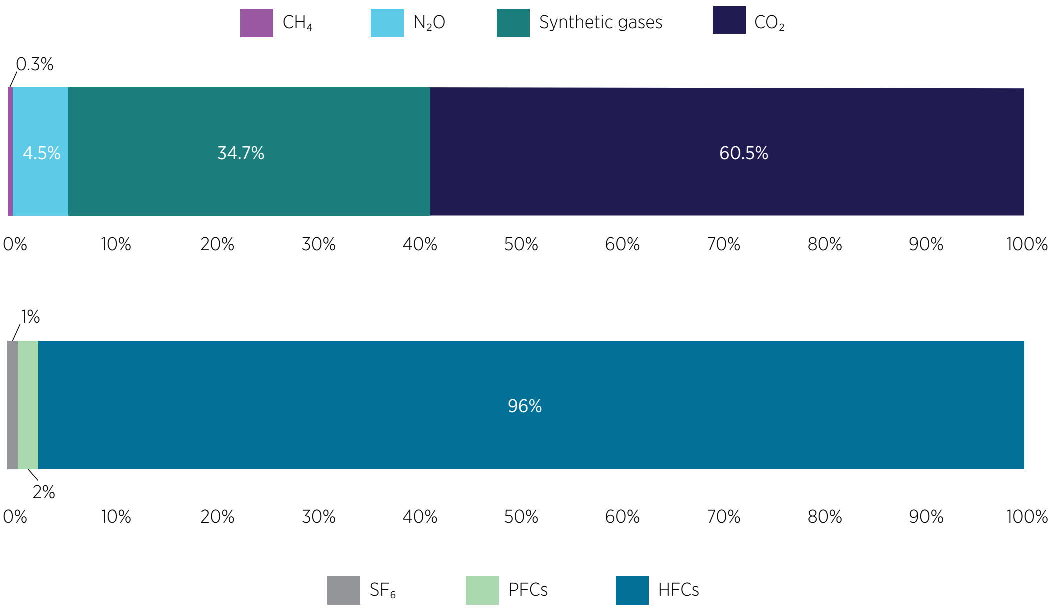
Note: Synthetic gases refers to SF_6, NF_3, HFCs, and PFCs.

Emissions in this sector occur:

- as the result of chemical or physical transformation involved in the production of mineral, chemical and metal products such as cement, ammonia and steel;
- from the use of products, including emissions of HFCs used as refrigerants and SF_6 from electrical equipment, and from the use of fossil fuels for purposes other than to produce energy (for example as lubricants).

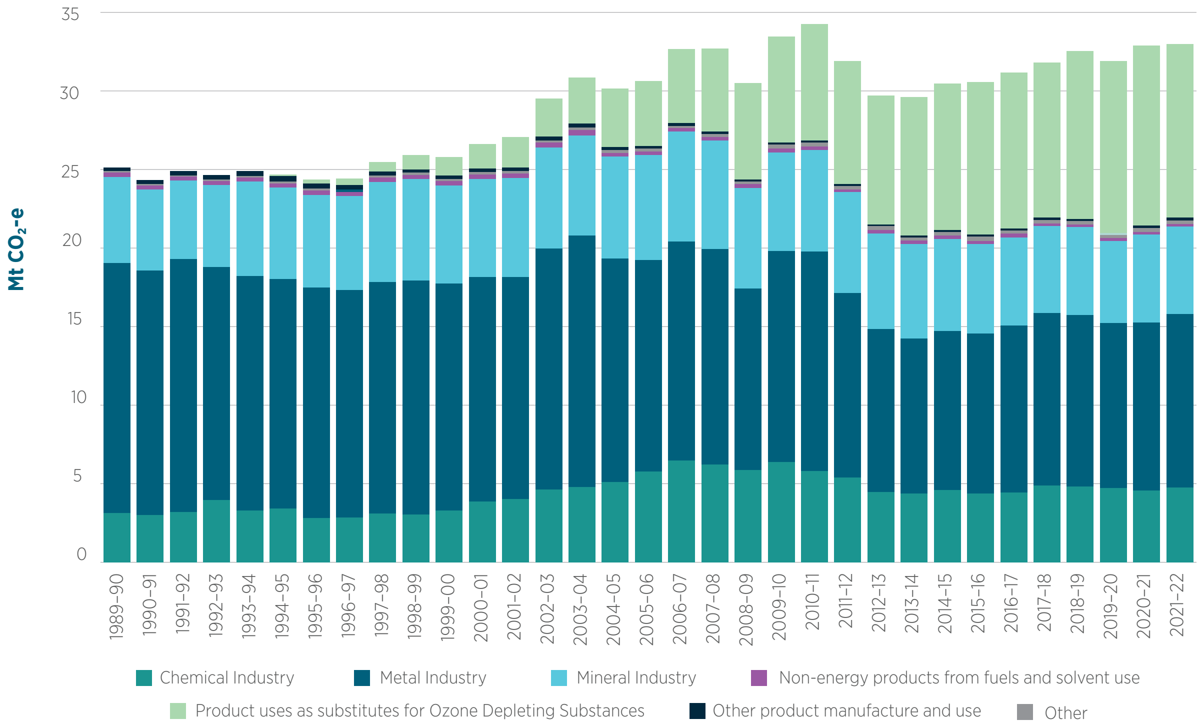
The most significant gases emitted by this category are CO_2 and HFCs, with emissions from N_2O, CH_4, and PFCs also occurring. All emissions of synthetic gases (HFCs, PFCs, and SF_6) in the Australian inventory occur in the industrial processes and product use category. NF_3 is also a reportable synthetic gas, however, Australia reports these emissions as NO (see chapter 4.6).

Figure 4.2 Gases as a share of total emissions within the Industrial Process and Product Use sector, CO_2–e basis, 2021–22 (top: all gases, bottom: synthetic greenhouse gases)



The manufacturing industry, producing metals, chemicals and mineral products such as cement clinker, is a major source of emissions from this category. The full time series of industrial processes and product use emissions by subsector are presented in Figure 4.3. The largest source of emissions is from products used as substitutes for ozone depleting substances, followed by the metal, mineral and chemical industries.

Figure 4.3 Industrial Process and Product Use emissions by subsector, 1989–90 to 2021–22



Changes in emissions by industrial processes and product use subsector between 2020–21 and 2021–22 are shown in Figure 4.4.

Figure 4.4 Comparison of 2021–22 emissions with past emissions levels from key industrial processes and product use (IPPU) subsectors, million tonnes of carbon dioxide equivalent (Mt CO_2–e) and percentage change (%)

IPPU Subsectors	2021–22 emissions	Change in 2021–22 emissions since:		
		1989–90	2004–05	2020–21
2.A Mineral Industry	6 Mt	▲ +2% +0.1 Mt CO_2-e	-1 Mt CO_2-e ▼ -14%	<-0.1 Mt CO_2-e ▼ -1%
2.B Chemical Industry	5 Mt	▲ +51% +2 Mt CO_2-e	-0.4 Mt CO_2-e ▼ -7%	▲ +4% +0.2 Mt CO_2-e
2.C Metal Industry	11 Mt	-5 Mt CO_2-e ▼ -31%	-3.2 Mt CO_2-e ▼ -22%	▲ +3% +0.4 Mt CO_2-e
2.D Non-energy Products from Fuels and Solvent Use	0.2 Mt	-0.1 Mt CO_2-e ▼ -37%	-0.1 Mt CO_2-e ▼ -29%	▲ +10% <+0.1 Mt CO_2-e
2.E Electronics Industry	NO	–	–	–
2.F Product Uses as Substitutes for Ozone Depleting Substances	11 Mt	▲ +100% +11 Mt CO_2-e	▲ +199% +7 Mt CO_2-e	-0.4 Mt CO_2-e ▼ -3%

IPPU Subsectors	2021–22 emissions	Change in 2021–22 emissions since:		
		1989–90	2004–05	2020–21
2.G Other Product Manufacture and Use	0.2 Mt	-0.1 Mt CO_2-e ▼ -31%	<-0.1 Mt CO_2-e ▼ -22%	<-0.1 Mt CO_2-e ▼ -18%
2.H Other	0.2 Mt	▲ +170% +0.1 Mt CO_2-e	▲ +33% +0.1 Mt CO_2-e	<-0.1 Mt CO_2-e ▼ -1%

Note: NO = not occurring. Icons in this figure are sourced from nawicon, smartline, smashicons, iconjam, surang, Freepik, Vectors Tank, GOWI, and Creatype on flaticon.com.

Changes in emissions by industrial processes and product use subsector between 1989–90 and 2021–22 are shown in Figure 4.5. Emissions from the sector have increased over this period, with increased emissions HFC refrigerants and increased emissions from manufacturing of chemicals offsetting reduced emissions offsetting reductions in metal manufacturing driven by lower emission rates of PFCs from aluminium production.

Key categories for Australia in this sector include emissions from cement production, iron and steel production, aluminium production and leakages of HFC refrigerants (‘Product uses as substitutes for ODS’).

The Australian methodology tiers and EFs are outlined in Table 4.1.

In certain sub sectors within industrial processes and product use, activity data are commercial-in-confidence and, due to the direct relationship between activity and emissions, emissions estimates by gas species are also confidential. Where this is the case, it is necessary to aggregate subsectoral emission estimates in order to preserve confidentiality.

Emissions of CO_2 from *magnesia production* (2.A.4.c) have been aggregated with CO_2 from *other product uses of carbonates* (2.A.4). CO_2 *emissions from carbide production* (2.B.5) and *soda ash production* (2.B.7) under 2.B.10 – *confidential chemical industry emissions.* Emissions of N_2O from the *use of* N_2O *in anaesthesia and aerosols* (2.G.3) have been aggregated with N_2O from *nitric acid production* (2.B.2). Emissions from *iron and steel production* (2.C.1) are aggregated with emissions from the production of *ferroalloys* and *other metals* (2.C.2 and 2.C.7).

Table 4.1 Summary of methods and emission factors: Industrial processes and product use

	CO_2		CH_4		N_2O		HFCs		PFCs		SF_6	
Greenhouse Gas Source and Sink Categories	**Method applied**	**EF**	**Method applied**	**EF**	**Method applied**	**EF**	**Method applied**	**EF**	**Method applied**	**EF**	**Method applied**	**EF**
2. Industrial Processes and Product Use												
A. Mineral Industry												
1. Cement Production	T2	CS										
2. Lime Production	T2	CS										
3. Glass Production	TS	CS										
4. Other Process Uses of Carbonates	T2	CS										
B. Chemical Industry												
1. Ammonia Production	T2/3	CS,D										
2. Nitric Acid Production					T3	CS						
3. Adipic Acid Production					NO	NO						
4. Caprolactuam, Glyoxal and Glyoxix acid Production					NO	NO						
5. Carbide Production	T2	CS	NA	NA								
6. Titanium Dioxide Production	T2	CS										
7. Soda Ash Production	T2	CS										
8. Petrochemical and Carbon Black Production	T1	CS	T2	CS								
9. Fluorochemical Production							T1	D	NA	NA	NA	NA
10. Other [(b)]												
C. Metal Industry												
1. Iron and Steel Production	T2/3	CS	T2	CS	T2	CS						
2. Ferroalloys Production	T2	CS	T2	CS	T2	CS						
3. Aluminium Production	T2/3	CS							T2/3	CS	NA	NA
4. Magnesium Production	NA	NA					NA	NA	NA	NA	T2	CS
5. Lead Production	T2	CS	T2	CS	T2	CS						
6. Zinc Production	T2	CS	T2	CS	T2	CS						
7. Other [(b)]	T2	CS	T2	CS	T2	CS	NA	NA	NA	NA	NA	NA
D. Non-Energy Products from Fuels and Solvent Use												
1. Lubricant Use	T2	CS										
2. Paraffin wax Use	NE	NE										

	CO_2		CH_4		N_2O		HFCs		PFCs		SF_6	
Greenhouse Gas Source and Sink Categories	**Method applied**	**EF**	**Method applied**	**EF**	**Method applied**	**EF**	**Method applied**	**EF**	**Method applied**	**EF**	**Method applied**	**EF**
3. Other (c)												
E. Electronics Industry							NO	NO	NO	NO	NO	NO
F. Product Uses as Substitutes for Ozone Depleting Substances												
1. Refrigeration and Air Conditioning							T2	CS	NA	NA	NA	NA
2. Foam Blowing							T2	D	NA	NA	NA	NA
3. Fire Protection							T2	D	NA	NA	NA	NA
4. Aerosols							T2	D	NA	NA	NA	NA
5. Solvents							T2	D	NA	NA	NA	NA
6. Other Applications (d)							NA	NA	NA	NA	NA	NA
G. Other Product Manufacture and Use												
1. Electrical Equipment							NA	NA	NA	NA	T2	CS
2. SF, and PFCs from Other Product Uses									NA	NA	T1,T2	CS
3. N_2O from Product Uses					T2	CS						
H. Other												
1. Pulp and Paper Industry												
2. Food and Beverage Industry	CS	CS										

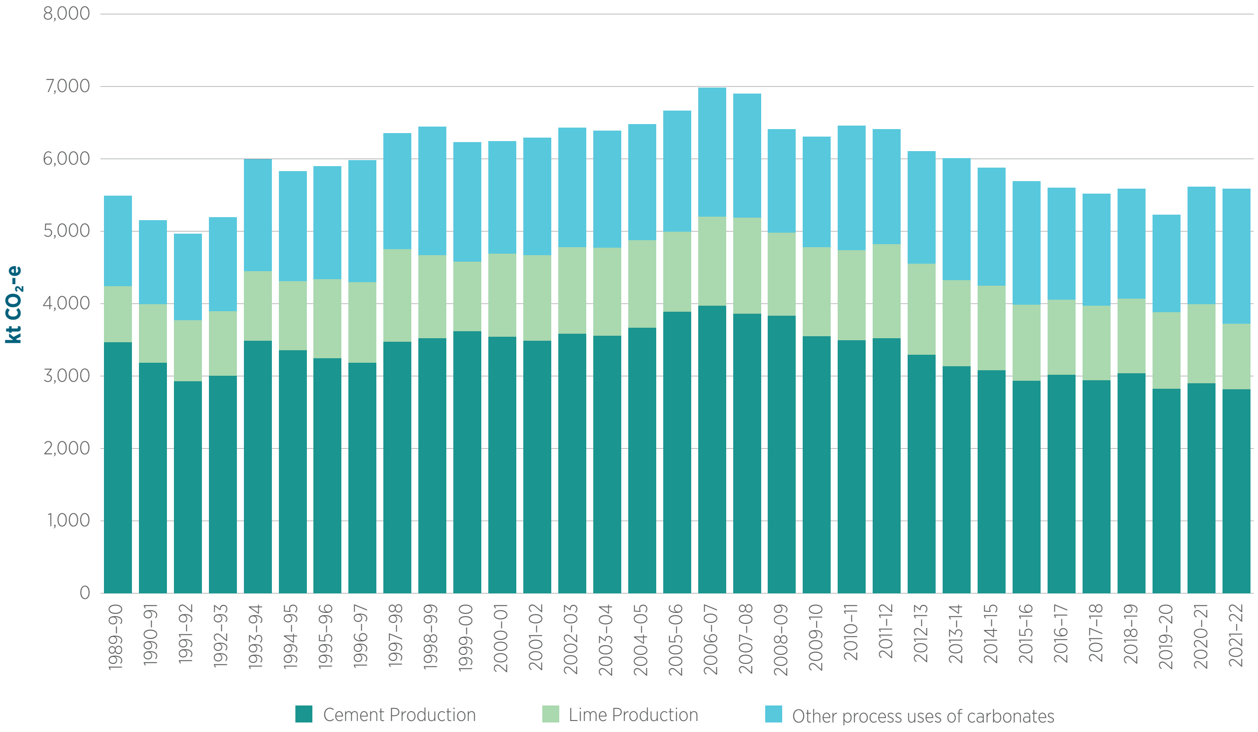
Notes: EF = Emission Factor, TI = tier 1,T2 = tier 2, T3 = tier 3, CS= country-specific, D= IPCC default, M = model, NE = not estimated, NA= not available, NO = not occurring,
IE = included elsewhere, 🟪 = key category
(a) Emissions reported under 2. A.3 *limestone and dolomite use;* (b) Confidentialised emissions are reported in the Other category; (c) Aerosols, consumer cleaning products and other domestic applications; (cl) Other uses of SF_6.
Note: gray cells indicate where no methodological guidance is provided by IPCC guidelines and no emissions are reported.

4.2 **Mineral Industry** (CRT category 2.A)

4.2.1 Category description

The mineral industry produces CO_2 emissions due to the use of carbonate-based minerals. All reported CO_2 emissions categories from the mineral industry constitute key categories for the inventory. Emissions associated with the mineral industry are shown in Figure 4.5.

Figure 4.5 Emissions from the mineral industry, Australia, 1989–90 to 2021–22, kt CO_2–e



Cement production (2.A.1)

CO_2 is produced during the manufacture of portland clinker, which is an intermediate product in the production of cement. CO_2 emissions are essentially proportional to the lime content of the clinker. On exit from the cement kiln, and after cooling, the clinker is ground to a fine powder and up to 5 per cent (by weight) of gypsum or natural anhydrite (that is, forms of calcium sulphate) added to control the setting time of the cement. The finished product is referred to as 'portland' cement.

The production of clinker in Australia responds to market conditions. Competition with imported products has become a significant issue for domestic production, especially in recent years. Between 2009–10 and 2014–15, five clinker production facilities ceased operations. Year on year fluctuations in emissions from this category are strongly correlated to fluctuations in cement production. Improvements in industry practices such as the recycling of cement kiln dust have resulted in small reductions in emissions per unit of production.

There are three clinker producers in Australia and their facilities report on their activity and emissions through the National Greenhouse and Energy Reporting (NGER) scheme.

Efforts are underway to reduce emissions from cement clinker production by using supplementary cementious materials ('SCM') such as unburnt limestone, ground blast furnace slag and fly ash to lower the amount of clinker used per unit of concrete produced (CIF 2022).

Free lime (CaO) released during the curing of concrete from the hydration of clinker materials can potentially and very slowly (years to centuries) re-absorb atmospheric CO_2 through a process called carbonation. In line with the IPCC 2006 Guidelines (Volume 3, Chapter 2, Section 2.2.1.4), Australia does not estimate an emissions sink for this category as it is not considered practical or good practice without further work on a methodology. The IPCC 2019 Refinement (IPCC 2019) does not provide any additional information on this category.

Lime Production (2.A.2)

Lime is an important chemical having major uses in metallurgy (steel, copper, gold, aluminium and silver), other industrial applications (water softening, pH control, sewage sludge stabilisation), and construction (soil stabilisation, asphalt additive and masonry lime).

The producers of commercial lime in Australia report their activity and emissions through the NGER scheme. One facility produced lime in-house until 2008–09.

Emissions of CO_2 from the production of lime vary year to year according to the quantities of commercial and in-house lime produced. The quantities of lime produced are dependent on the demand for lime within the Australian economy- in particular in the resources sector, as evident by decreases notable in 1998–99 and 1999–2000 caused by the fall in demand for minerals processing particularly in the gold sector and in 2008–09, associated with global economic downturn.

Glass production (2.A.3)

Due to confidentiality restrictions, CO_2 emissions associated with the production of glass are included in Other Process uses of carbonates (2.A.4).

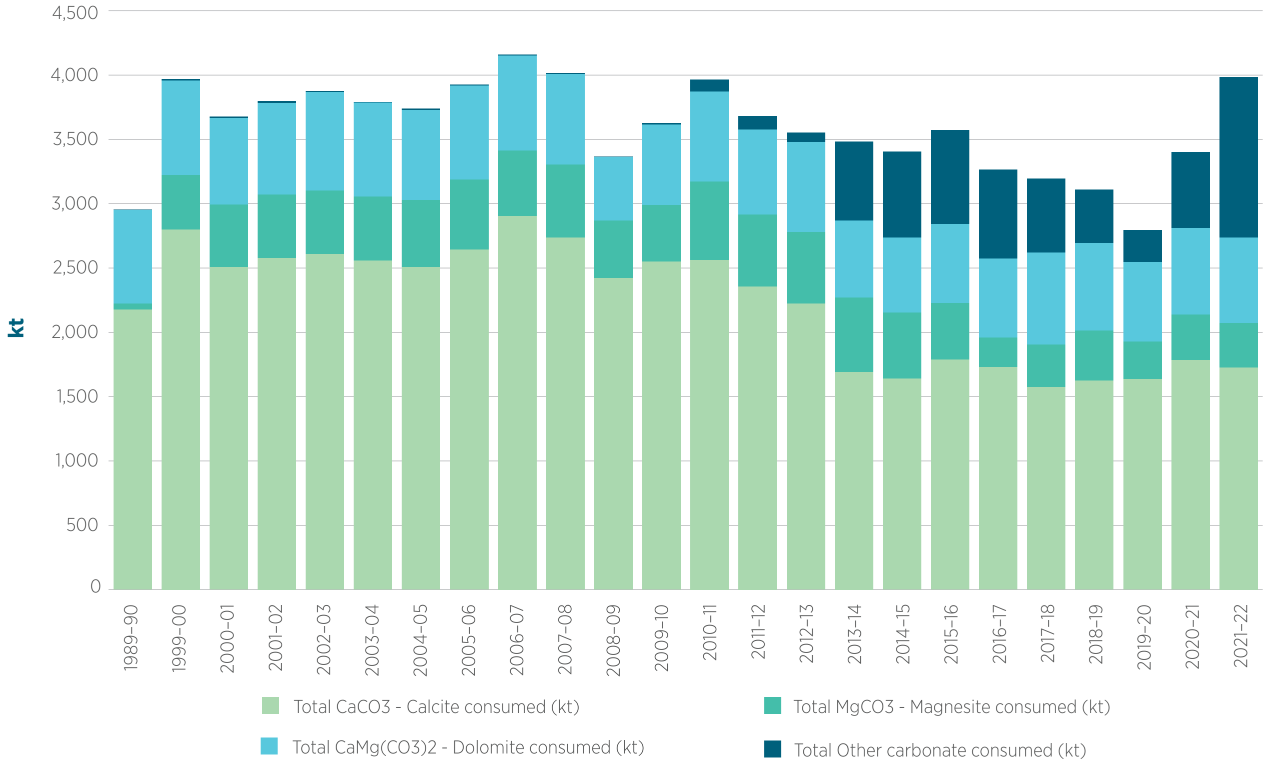
Other process uses of carbonates (2.A.4)

Apart from use in cement and lime production, limestone ($CaCO_3$), magnesite ($MgCO_3$) and dolomite ($CaCO_3$. $MgCO_3$) are basic raw materials that have commercial applications in a number of industries including metallurgy (for example, iron and steel), glass manufacture, ceramics and clay bricks, agriculture, construction, magnesia production and environmental pollution control. To improve the completeness of the inventory, emissions from other carbonates known to be supplied to the Australian economy have also been included. These are sodium bicarbonate, potassium carbonate, barium carbonate, lithium carbonate and strontium carbonate.

All CO_2 emissions associated with the consumption of carbonates, with the exception of the emissions reported under cement (2.A.1) and lime (2.A.2) production, are accounted for under Other Process Uses of Carbonates. This includes emissions from the use of limestone by the iron and steel, ferroalloys, magnesia, zinc, glass, ceramics and clay brick production. To protect confidentiality, other emissions from the production of soda ash (2.B.7) have also been aggregated in the reporting of this category.

The trend in emissions is heavily influenced by the consumption of limestone (calcite) which is consumed in greater quantities than any other carbonate. The year on year growth in carbonate consumption has varied from positive to negative throughout the time series as changes in activity in the broad range of consuming industries occur.

Figure 4.6 Other process uses of carbonates (2.A.4): Carbonate consumption by type, Australia, 1989–90 to 2021–22, kt



Companies using carbonates in their production processes report on their activity and emissions through the NGER scheme.

4.2.2 Methodological issues

Cement Production (2.A.1)

Calcium carbonate ($CaCO_3$) from calcium rich raw materials such as limestone, chalk and natural cement rock is heated at temperatures of approximately 1500°C in cement kilns to form lime (CaO) and CO_2 in a process known as calcination.

$CaCO_3$ + heat ® CaO + CO_2

Emissions from clinker production are estimated using a tier 2 method.

$$E_{cl} = [EF_{cl} . A_{cl} + EF_{cl} . F_{ckd} . A_{ckd} + EF_{toc} . (A_{cl} + A_{ckd})] . 10^{-6}$$

CO_2 emissions from clinker manufacture (E_{cl}) are estimated by the application of a country-specific emission factor EF_{cl}, in kilograms of CO_2 released per tonne of clinker produced, to the annual national clinker production A_{cl}.

The country-specific EF is the product of the fraction of lime used in the clinker and a constant reflecting the mass of CO_2 released per unit of lime produced. This factor was derived using the World Business Council for Sustainable Development (WBCSD 2005) methodology. Assuming CaO and MgO proportions of 0.66 and 0.015 respectively, based on Ryan and Samarin 1992, leads to an EF of 534 kg CO_2 per tonne of clinker.

In addition to the emissions associated with the lime used in the clinker, the methodology accounts for emissions associated with the calcination of cement kiln dust (A_{ckd}) and the quantity of total organic carbon (TOC) expressed as a proportion of total clinker produced. F_{ckd} is the degree of calcination of cement kiln dust (ranging from 0 per cent to 100 per cent) and is assumed to be 100 per cent in Australia such that F_{ckd} = 1 (following WBCSD 2005). A_{ckd} is the quantity of cement kiln dust (CKD) produced annually. The EF for TOC (EF_{toc}) is taken from WBCSD 2005 (equivalent to 10kg CO_2 per tonne of clinker).

Choice of emission factor

Under the provisions of the *National Greenhouse and Energy Reporting (Measurement) Determination 2008*, facilities are able to determine facility-specific EFs based on the CaO and MgO contents of their cement clinker according to the following equation:

$$F_{CaO} \times 0.785 + F_{Mgo} \times 1.092$$

Where F_{CaO} is the estimated fraction of cement clinker that is calcium oxide derived from carbonate sources and produced from the operation of the facility

F_{MgO} is the estimated fraction of cement clinker that is magnesium oxide derived from carbonate sources and produced from the operation of the facility

0.785 is the molecular weight ratio of carbon dioxide to calcium oxide

1.092 is the molecular weight ratio of carbon dioxide to magnesium oxide

From 2015–16, two cement production facilities have reported facility-specific EFs based on facility-specific measurement of the CaO and MgO contents of their produced clinker. The remaining facilities continue to use the country-specific factor as this factor best represents their particular product specifications. The country-specific EF is used for all facilities from 1989–90 to 2014–15 as adopted by all cement producers under the NGER scheme prior to 2015–16.

Activity data

Data for cement production for individual facilities were obtained from the NGER scheme for 2008–09 onwards and the reporting mechanisms of the former Emissions Intensive, Trade Exposed Industries assistance program (EITEI – subsequently known as the Jobs and Competitiveness Program) for 2006–07 and 2007–08. Data for the period 1989–90 to 2005–06 were obtained by industry survey undertaken by the Cement Industry Federation (CIF). In all cases, all producers of cement have been captured throughout the time-series.

Lime production (2.A.2)

CO_2 is produced when either high calcium lime (CaO) or dolomitic lime (CaO-MgO) are manufactured by the calcination of calcium rich raw materials (limestone or dolomite) in a kiln.

$$CaCO_3 \text{ (limestone)} + \text{heat} \rightarrow CaO \text{ (high calcium lime)} + CO_2$$
$$CaCO_3.MgCO_3 \text{ (dolomite)} + \text{heat} \rightarrow CaO.MgO \text{ (dolomitic lime)} + 2\ CO_2$$

Emissions from lime production are estimated using a tier 2 method.

Total CO_2 emissions E_q associated with lime production A_q are estimated as the sum of emissions by facility according to:

$$E_l = \Sigma A_l \, . \, EF_l$$

The EF for lime produced is estimated for each facility from a consideration of the molecular weights (56 for CaO, 44 for CO_2) and the composition of the lime products.

Choice of emission factor

Information important to the derivation of lime production emission factors has been obtained under the former EITIEs program and the NGER scheme from 2006–07 onwards, where available.

Where lime producers have information on the specifications of their product, they are able to derive facility-specific emission factors on the basis of pure calcium carbonate (CaO) and magnesium carbonate (MgO) content of their product. The pure carbonate emission factors used to derive facility-specific emission factors are as follows:

- 0.785 t CO_2 x the fraction of pure CaO in the lime
- 1.092 t CO_2 x the fraction of pure MgO in the lime

The following equation is applied to derive a facility-specific emission factor:

$$EF = 0.785 \text{ t } CO_2 \text{ x the fraction of pure CaO in the lime} + 1.092 \text{ t } CO_2 \text{ x the fraction of pure MgO in the lime}$$

Where lime producers manufacture lime with a high MgO content, their facility-specific emission factor will be higher than the default.

From 2006–07 onwards, facility-specific emission factor information related to commercial lime production became available. The weighted average of these emission factors for all facilities producing commercial lime (including those who did not provide facility-specific emission factors) was 0.751 t CO_2/t lime produced in 2006–07 – based on the relative contributions to total production of all commercial lime producers. This weighted value applied only to manufacturers of commercial lime and is higher than the commercial lime country-specific EF because it reflects the non-standard specifications of producers with commercial lime with a high MgO content. To date, no facility level information on in-house lime production has been available.

Where facility-specific lime product composition information is not available, Australia provides country-specific emission factors for the use of lime manufacturers reporting under the NGER scheme. These are based upon assumed fractional purities of commercial and inhouse lime and are calculated according to the equation:

$$EF = F \times (44.01/56.08)$$

Where F is the fractional purity of lime produced
44.01 is the molecular weight of CO2
56.08 is the molecular weight of CaO

The country-specific emission factors are calculated as follows:

- 0.675 t CO_2 / t commercial lime produced, based on a fractional purity of lime of 0.86
- 0.730 t CO_2 /t in-house lime produced, based on a fractional purity of lime of 0.93

As outlined above, facilities that do have product composition information, have reported facility-specific emission factors. The average emission factor for all facilities weighted on the basis of relative levels of production is 0.751 t CO_2/t lime.

The following timeline sets out the application of each of the emission factors:

	1989–90	2005–06	2006–07	2020–21
Commercial lime	Weighted average		Facility-specific EFs	
	EF 0.751 t CO_2/ t lime		Default country-specific EF 0.675 t CO_2/t lime	
In-house lime	Default country-specific EF 0.73 t CO_2/t lime			

The fluctuation in the implied emission factor year on year reflects the relative proportions of commercial and in-house lime production as well as the relative proportions of production of individual lime producers from 2006–07 onwards where facility level emission factors are used.

For in-house lime, as no producers have supplied composition information, the country-specific emission factor is applied for all years where in-house lime production occurs.

Data on lime production (including data on the amount of lime produced in-house) have been collected under the NGER scheme for 2008–09 onwards and the reporting mechanisms of the former EITEI Program for 2006–07 and 2007–08. Data for the period 1989–90 to 2005–06 were obtained by industry census undertaken by the National Lime Association up to 1999–00 and various consultants from 2000–01 to 2005–06 (For example, GHD 2009c). The census and NGER scheme collection mechanisms have enabled complete coverage of lime producers throughout the time-series. Activity data is reported in table A5.4.1.1.

Other process uses of carbonates (2.A.4)

A tier 2 method is utilised to estimate emissions from other process uses of carbonates. The mass of CO_2 emitted per unit of limestone EFIS, dolomite EF_d and other carbonates use EF_o is estimated from a consideration of the purity of the raw materials and the stoichiometry of the chemical processes (44 for CO_2; 100 for limestone; 184 for dolomite, 84 for magnesite, 106 for soda ash and 114 for the remaining carbonates). Only the amount of carbonate material used in an application which generates CO_2 is used in the estimation of CO_2 emitted.

Total CO_2 emissions, E, are estimated by summing over each facility the quantity of limestone, A_{ls}, dolomite, A_d, and other carbonate use, A_o, multiplied by their respective fractional purities and emission factors:

$$E = A_{ls} . F_{ls} . EF_{ls} + A_d . F_d . EF_d + A_o . F_o . EF_o$$

The fractional purities are country specific and include limestone, F_{ls}, 0.90, dolomite F_d, 0.95, and for all other carbonates, 1.00. The emission factors are derived from stoichiometry and are 0.396 t CO_2/t limestone, 0.522 t CO_2/t magnesium carbonate, and 0.453 t CO_2/t dolomite.

Choice of Emission Factor

No facility-specific data on emission factors were obtained under the NGER scheme. Country-specific CO_2 fractional purities and stoichiometric EFs were applied for all facilities and for all years. Limestone and dolomite consumption data have been collected under the NGER scheme from 2008–09 and the reporting mechanisms of former EITEIs Program for 2006–07 and 2007–08 (EITEI 2007 and 2008). Data for the period 1989–90 to 2005–06 were obtained by a combination of industry survey (for example GHD 2009c) (GHD 2009) and back casting of production based on NGER scheme data.

Emissions from the manufacture of clay bricks

Emissions from carbonate consumption associated with the manufacture of clay bricks are based upon the quantities of clay bricks produced annually as recorded by the Australian Bureau of Statistics (ABS 1991a, 2000 and 2012) and a country-specific emission factor derived from data provided by the peak industry body representing Australian clay brick and paver manufacturers, Think Brick. The ABS discontinued their reporting of clay brick production in 2012 and from that point onwards, brick production has been derived using ABS construction activity as a driver (ABS 2022) (ABS 2022).

Soda Ash Consumption (2.A.7, reported under 2.A.4)

A tier 2 method is utilised for the Australian inventory. CO_2 emissions are associated with the use of soda ash where it is assumed that for each mole of soda ash use, one mole of CO_2 is emitted. The mass of CO_2 emitted from the use of soda ash E_{sau} may be estimated from a consideration of the consumption data A_{sau} and the stoichiometry of the chemical process (where 44.01 is the molecular weight of CO_2 and 105.99 is the molecular weight of $Na2CO_3$).

$$\mathbf{E_{sau} = 0.415\ kg/tonne\ Na_2CO_3\ .\ \Sigma A_{sau}}$$

Data on soda ash consumption were collected under the NGER scheme for 2008–09 onwards and the reporting mechanisms of the former EITEIs Program for 2006–07 and 2007–08. Data for soda ash consumption for the period 1989–90 to 2005–06 were obtained by industry survey (Energreen 2009) and data on soda ash imports taken from ABS 2015. Activity data is reported in Table A5.4.1.3.

4.2.3 Uncertaintiy assessment and time-series consistency

The tier 1 uncertainty analysis in Annex II provides estimates of uncertainty according to IPCC source category and gas.

Activity data obtained under the NGER scheme (2008–09 onwards) was compared with activity data obtained from the former EITEI Program for each facility and with data obtained from GHD and Energreen consulting to ensure the consistent classification of sources and consistency of data.

For lime production, time series consistency is maintained through the use of a weighted average EF of 0.751 t CO_2/t lime produced for the years when individual facility data are not available (1989–90 to 2005–06). It is assumed for the years 1989–90 to 2005–06 that lime producers continued to produce lime in the same relative proportions as observed in 2006–07 when facility-level data first became available.

For other uses of carbonates, where facilities were newly identified from NGER scheme data (2008–09 onwards) as emitting facilities, activity data was interpolated to the facility's commencement date – assuming that consumption of limestone and dolomite in previous years was equal to the consumption of limestone and dolomite in 2008–09 for the each of the new facilities.

Where facility-specific EFs were identified from NGER scheme data (2008–09 onwards) for particular facilities, in category 2.A.2 and 2.A.4, the observed EFs were interpolated using a national weighted average EF for all years 1989–90 to 2005–06.

4.2.4 Category-specific QA/QC and verification

This source category is covered by the general QA/QC of the greenhouse gas inventory in Annex 4. Additional source specific quality control checks were undertaken to assess completeness and international comparability.

In order to maintain continuity in the compilation of *industrial processes and product use* emissions estimates, the Department engaged the external consultant previously used to collect activity data and EF information to undertake a quality control assessment of the full time series of activity data, EFs and emissions estimates. This work is of particular importance in industrial processes where confidentiality of historical activity data poses some challenges for the assessment of time series consistency.

Reconciliation between sources of carbonate supply and use in the Australian economy are undertaken to ensure completeness (see Table 4.2). This reconciliation includes limestone used in soda ash production as well as consideration of dolomite, soda ash use, magnesite and other carbonates (barium, lithium, potassium, strontium and sodium bicarbonate).

Table 4.2 Reconciliation of limestone, dolomite, soda ash, magnesite and other carbonates supply and use in the Australian economy, 2021–22

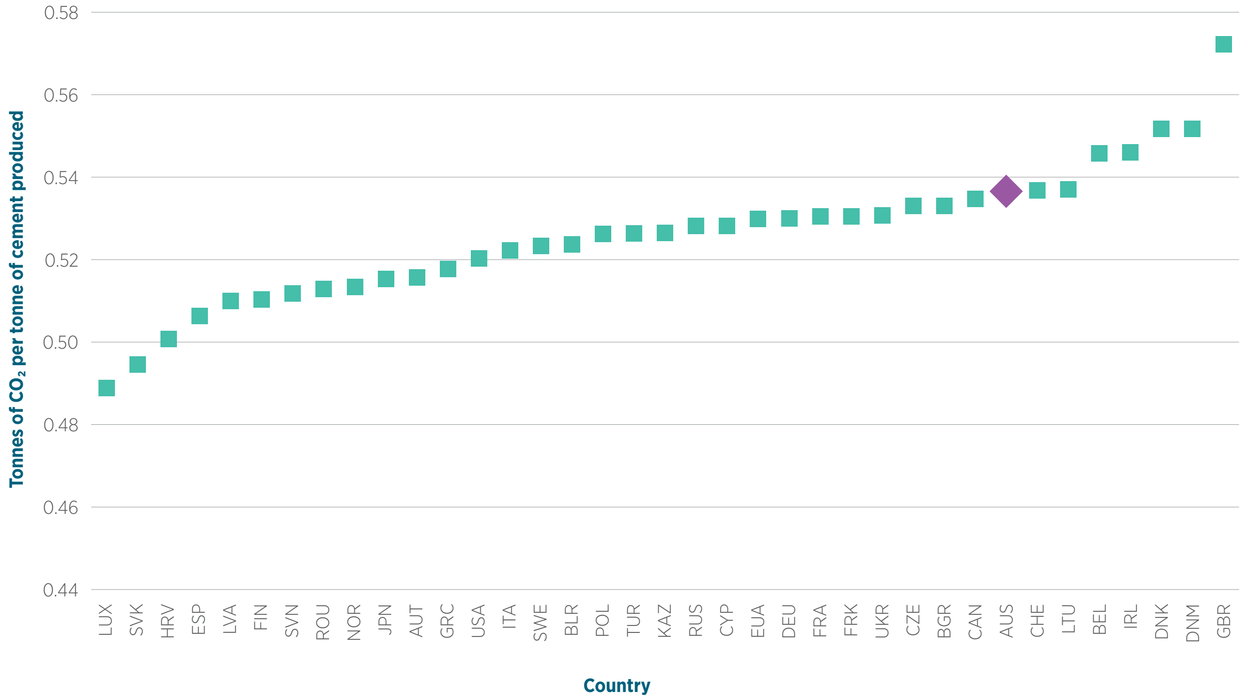
		Raw material (d) (kt)	Emissions (Gg CO_2)	Carbon (kt)
Use				
2.A.1	Cement production (b)	6,383	2,818	769
2.A.2	Lime production	2,013	905	247
2.A.3	Glass Production	163	73	20
2.A.4	Other process uses of carbonates	3,038	1,676	457
2.B.7	Soda Ash Production			
3.C.2	Agricultural Liming	3,312	1,318	360
Total Use		**18,128**		
Supply				
Implied production		17,221		
Imports		916		
Exports		9		
Total supply		**18,128**		

(a) Cement emissions excluding those from the calcination of magnesium carbonates.

(b) Includes tonnes of limestone, dolomite, soda ash, magnesite and other carbonates.

Comparisons of IEFs and activity data with international data sources are conducted systematically for the Australian inventory.

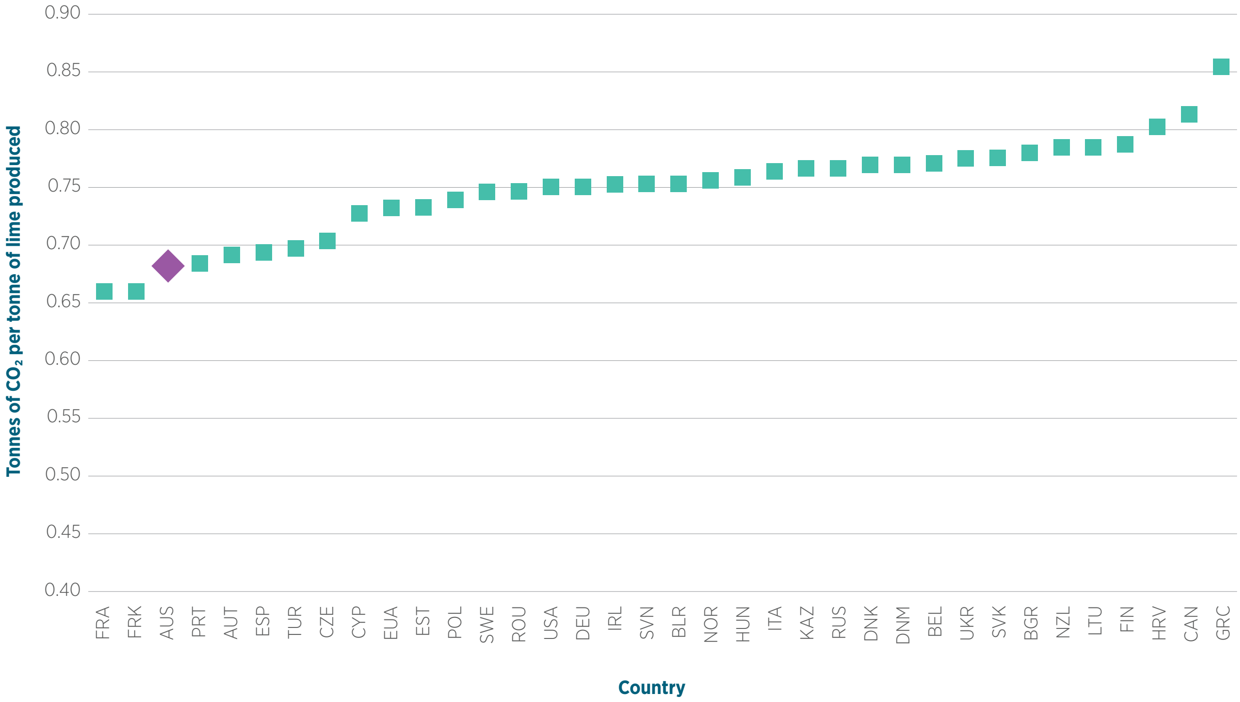
Figure 4.7 Cement production implied emission factors for Annex I countries (2023 submission) and Australia (2024 submission), tonnes of CO_2 per tonne of cement produced



Australia's IEF for cement production at the national level has fallen from 0.558 t CO_2/tonne of cement produced in 1994–95 to 0.537 t CO_2/tonne of cement produced in 2021–22. The IEF fluctuates year on year according to the relative contributions of product from each facility with their own particular product specifications.

The IEF for cement clinker production for Australia (above) is within the range reported by other Annex I parties. Australia's IEF is higher than the IPCC 2006 tier 1 default EF of 0.52 t CO_2/t cement clinker produced. This is due to the relative proportions of CaO and MgO in Australia's cement clinker and the incorporation of emissions from CKD recirculation in Australia's IEF.

Figure 4.8 **Lime production implied emission factors for Annex I countries (2023 submission) and Australia (2024 submission), tonnes of CO_2 per tonne of lime produced**



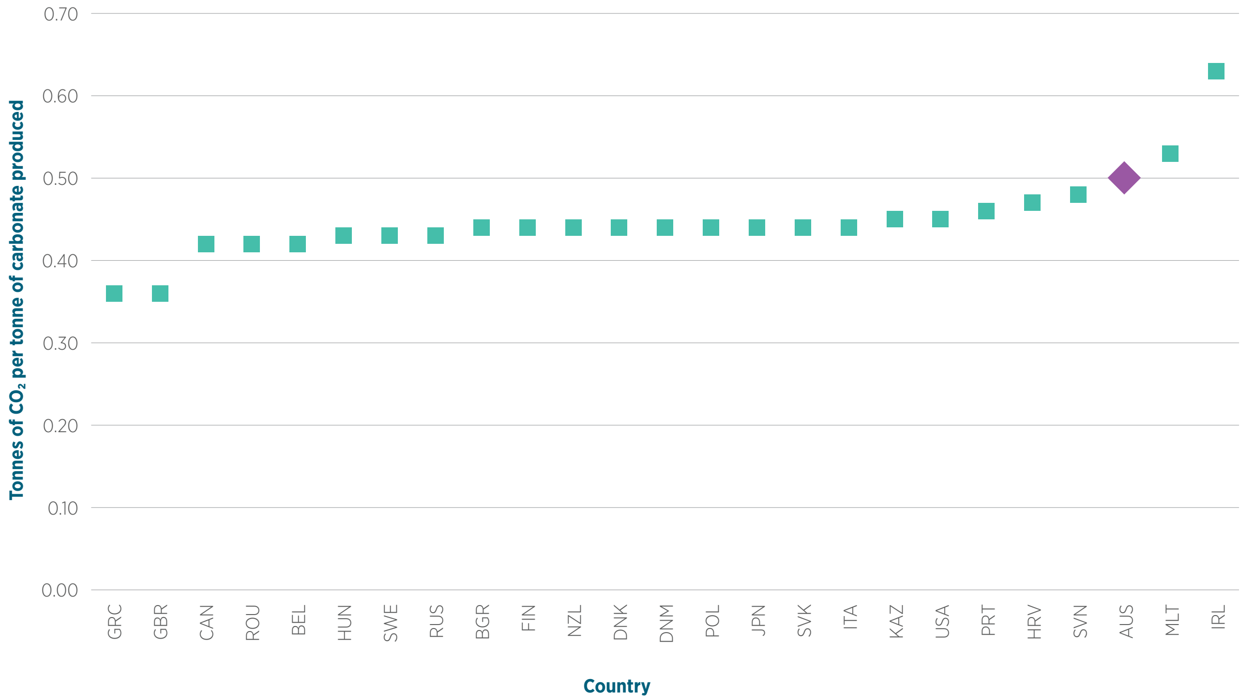
Note: In the figure above, outliers have been excluded for Japan (0.428), the Netherlands (0.437) and Great Britain (0.446).

Australia's IEF for lime production at the national level has fluctuated year-on-year between 0.68 t CO_2/tonne of lime produced and 0.82 t CO_2/tonne of lime produced according to the relative contributions of product from each facility with their own particular product specifications. This reflects the use of different types of carbonates as well as the relative proportions of commercial and in-house lime produced and lime kiln dust recirculation. The IEF reflects relatively low levels of LKD calcination reported under the NGER scheme.

Statistical analysis indicates that the IEF for lime production for Australia (above) is not significantly different to the factors reported by other Annex I parties. Australia's IEF is lower than the *IPCC2006* tier 1 default EF of 0.75 t CO_2/ tonne high calcium quicklime produced. This is due to a lower fractional purity compared with the IPCC (0.86 compared with 0.95) and the incorporation of a portion of dolomitic lime production in the default EF. In years where dolomitic lime production is reported, Australia's IEF is similar or higher than the IPCC default EF.

The IEF for *Other Process Uses of Carbonates* (2.A.4) for Australia is also reported with the distribution of IEF values for other Annex I countries. Results are shown in Figure 4.10.

Figure 4.9 Other Process Uses of Carbonates implied emission factors for Annex I countries (2023 submission) and Australia (2024 submission), tonnes of CO_2 per tonne of carbonate



Note: In the figure above, outliers have been excluded for Iceland (0.089), Lithuania (0.130), and Norway (0.876).

Australia's carbonates IEF ranges between 0.410 t CO_2/t carbonate consumed and 0.499 t CO_2/t carbonate consumed. With the availability of facility level data, the national IEF fluctuates according to changes in the relative proportions of each carbonate consumed by individual facilities from year on year.

Statistical analysis indicates that the IEF for carbonates use for Australia (above) is not significantly different to the factors reported by other Annex I parties. Australia's IEF is within the range of IPCC default EFs 0.380 t CO_2/t carbonate and 0.521 t CO_2/t carbonate. The 2006 IPCC Guidelines suggest the use of a fractional purity of 1 in the absence of country-specific information. In Australia's case, fractional purities of 0.9 for limestone and 0.95 for dolomite are used.

International comparison of mineral products activity data is also undertaken. Reported cement production is consistent with cement production for Australia reported by the United Nations given the high level of use of supplementary cementitious materials (fly ash and granulated blast furnace slag) in Australian cement.

4.2.5 Category-specific recalculations

Recalculations are shown in Table 4.3 and are due to:

A. Revisions to ABS Construction Statistics

Revised information on construction activity received from the ABS, impacting emissions from ceramics production between 2011 and 2021.

B. Revisions to carbonate consumption data

Revised carbonate consumption data in the production of ceramics has resulted in a revision to emissions estimates for 2021.

Table 4.3 Mineral industry (2.A), recalculation of total CO_2–e emissions (Gg), 1989–90 to 2020–21

	2023 Submission	2024 Submission	Change		Reasons for Recalculation (Gg CO_2–e)	
Year	Gg CO_2–e	Gg CO_2–e	Gg CO_2–e	%	A	B
1989–90	5,489.6	5,489.6	-	0.0	-	-
1994–95	5,826.3	5,826.3	-	0.0	-	-
1999–00	6,231.9	6,231.9	-	0.0	-	-
2004–05	6,478.8	6,478.8	-	0.0	-	-
2005–06	6,669.0	6,669.0	-	0.0	-	-
2006–07	6,985.5	6,985.5	-	0.0	-	-
2007–08	6,898.4	6,898.4	-	0.0	-	-
2008–09	6,408.1	6,408.1	-	0.0	-	-
2009–10	6,304.0	6,304.0	-	0.0	-	-
2010–11	6,454.0	6,454.0	-0.0	0.0	-0.0	-
2011–12	6,411.5	6,411.5	-0.0	0.0	-0.0	-
2012–13	6,105.3	6,105.3	-0.0	0.0	-0.0	-
2013–14	6,004.5	6,004.4	-0.0	0.0	-0.0	-
2014–15	5,878.6	5,878.5	-0.0	0.0	-0.0	-
2015–16	5,691.7	5,691.6	-0.1	0.0	-0.1	-
2016–17	5,599.6	5,599.5	-0.1	0.0	-0.1	-
2017–18	5,522.1	5,521.9	-0.2	0.0	-0.2	-
2018–19	5,589.2	5,588.9	-0.3	0.0	-0.3	-
2019–20	5,230.7	5,230.5	-0.3	0.0	-0.3	-0.0
2020–21	5,584.9	5,614.0	29.1	0.5	30.5	-1.4

4.2.6 Category-specific planned improvements

The methodology and emission factors used for the estimation of emissions from *mineral products* will be kept under review.

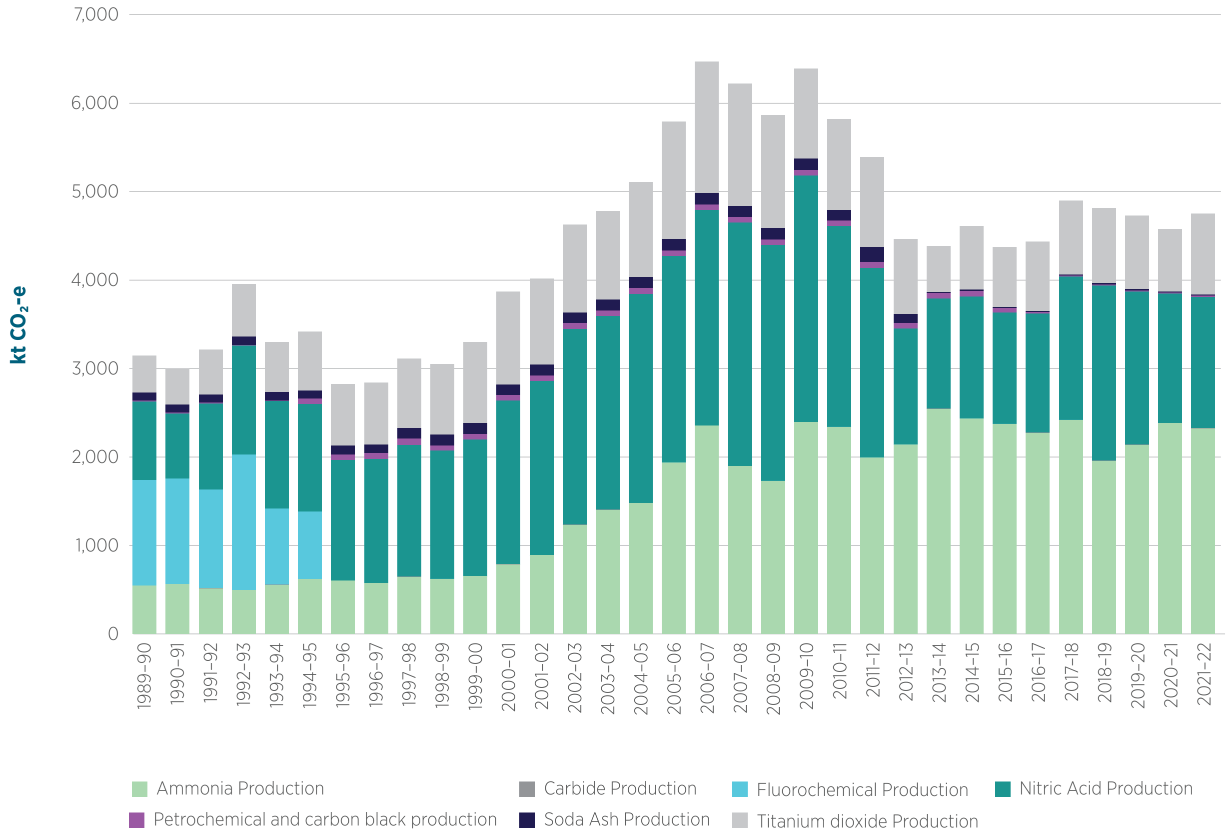
Australia has been monitoring the progress of empirical research into various forms of mineral carbonation such as that associated with cement. Australia will explore the possibility of including allowance for this chemical process in future inventory submissions.

4.3 Chemical Industry (CRT category 2.B)

4.3.1 Category description

Key categories for Australia in the chemicals sector are CO_2 from ammonia production, N_2O from nitric acid production, and HFCs from fluorochemical production. Emissions associated with the chemical industry are shown in Figure 4.10.

Figure 4.10 Emissions from the chemical industry, Australia, 1989–90 to 2021–22, kt CO_2–e



Ammonia production (2.B.1)

The overall process of producing ammonia involves a series of stages to remove impurities such as sulphur, carbon monoxide, carbon dioxide and water from the natural gas feedstock and the generation and reaction of hydrogen and nitrogen. The multi stage process involved in ammonia production (from natural gas feedstock) results in the industrial process emissions of CO_2, NMVOC, and CO in addition to ammonia and sulphur compounds.

Carbon dioxide emissions from ammonia reflect the use of natural gas for both energy and feedstock uses. In Australia's inventory, only emissions from the use of natural gas as a feedstock are reported in the *industrial processes and product use* sector. An appropriate deduction has been made in natural gas consumption in the *stationary energy* sector to remove the possibility of double-counting.

Ammonia is produced in seven plants operated by six producers in Australia. All companies provided natural gas consumption and CO_2 recovery data (where appropriate) for this Inventory under the NGER scheme.

Nitric acid production (2.B.2)

The manufacture of nitric acid (HNO3) generates N_2O as a by-product of the high temperature catalytic oxidation of ammonia (NH_3). Nitric acid is used as a raw material mainly in the manufacture of nitrogenous agricultural fertiliser.

Nitric acid is produced by six producers which report under the NGER scheme.

Due to confidentiality obligations, emissions for the nitric acid category are reported as 'included elsewhere', aggregated with emissions from the use of N_2O in anaesthesia and aerosols, and reported under *2.B.6 confidential chemical industry emissions.*

Adipic acid production (2.B.3)

Adipic acid is used in the manufacture of synthetic fibres, coatings, plastics, urethane foams, elastomers, and synthetic lubricants. There is no adipic acid production occurring in Australia and therefore no emissions are reported for this category.

Caprolactuam, glyoxal and glyoxylic acid production (2.B.4)

Caprolactuam, glyoxal, and glyoxylic acid are important sources of N_2O emissions in countries where they are produced. Caprolactuam is consumed as the monomer for nylon-6 fibres and plastics used notably in carpet manufacturing. Glyoxal is used as a crosslinking agent for vinyl acetate/acrylic resins, disinfectants, as a gelatine hardening agent, textile finishing agent, and as a wet-resistance additive to paper. Glyoxylic acid is used for the production of synthetic aromas, agrochemicals, and pharmaceutical intermediates. There is no Caprolactuam, Glyoxal and Glyoxix Acid production occurring in Australia and therefore no emissions are reported for this category.

Carbide production (2.B.5)

Silicon carbide and calcium carbide are not produced in Australia. Minor quantities of acetylene are produced from imported calcium carbide and used in welding applications. Activity data and emissions were previously reported under the NGER scheme by one company, and are therefore confidential. Emissions for this category are reported as 'included elsewhere' and the estimates have been aggregated with emissions from *soda ash production* for reporting in *2.B. 10 confidential chemical industry emissions.*

Other – Titanium dioxide production (2.B.6)

Rutile (titanium dioxide) is naturally occurring in Australia. Synthetic rutile can be produced from naturally occurring ilmenite using coal reductant. The rutile is then refined using a petroleum coke reductant to produce titanium dioxide (TiO_2).

Titanium dioxide is a white pigment which is used in paint manufacture, paper, plastics, rubber, ceramics, fabrics, floor covering, printing ink, and other miscellaneous uses). Titanium dioxide products are referred to generically as titanium dioxide unless there is a need to make a distinction between the products.

The coal and petroleum coke used as reductants in the synthetic rutile and TiO_2 production processes have been removed from the stationary energy sector to eliminate the possibility of a double-count with this reporting category.

Soda ash production (2.B.7)

The majority of soda ash was produced in Australia by one company located in South Australia using the Solvay process. This facility ceased production in 2012–13 and was converted for import and distribution. The majority of soda ash consumed in Australia is now imported primarily from the United States of America. There remains one company in Australia producing soda ash for its own in house use.

Production of soda ash remained relatively constant while imports of soda ash have experienced large fluctuations and an overall increase in quantities.

Petrochemical and carbon black production (2.B.8)

The manufacture of organic chemicals results in process emissions of NMVOC. Other gases such as CO_2, CH_4, N_2O, NO_x and CO may also be generated depending on the manufacturing process.

Time series of emissions of CH_4 and NMVOCs are included in the inventory for methanol, butadiene, carbon black, ethyl benzene, ethylene, ethylene oxide, formaldehyde, HDPE, LDPE, LLDPE, propylene, polypropylene, polystyrene, styrene, polyvinyl chloride, and styrene butadiene rubber. Disaggregated production and emissions data for these sources are confidential. Emissions estimates are aggregated for polymers and other chemicals as a whole. Approximately 15 companies producing a large range of polymers and other chemicals in Australia reported through a company census conducted by a Energreen Consulting on behalf of the department up to 2008. From 2008 onwards, emissions have been estimated on the assumption that plant capacities have not changed.

CO_2 emissions from ethylene oxide production are reported in 2.H Food and Drink, where by-product CO_2 is used and emitted.

Fluorochemical production (2.B.9)

From 1990 to 1995, a single company – Pacific Chemicals Industries produced HCFC-22. Fugitive emissions of HFC-23 from this production have been included in the inventory for all relevant years.

4.3.2 Methodological issues

Ammonia production (2.B.1)

A tier 2/3 method is utilised for the Australian inventory. Ammonia is manufactured by the catalytic steam reforming of natural gas. Hydrogen from the reformed natural gas and nitrogen from air are compressed at reduced temperatures to form ammonia:

$$3H_2 + N_2 \rightarrow 2NH_3$$

The manufacture of ammonia from the catalytic steam reforming of natural gas is documented to result in emissions of CO_2, NMVOC and CO. While the CO_2 equivalent emissions associated with the use of natural gas are accounted for, data on emissions of NMVOC and CO are not currently available. It is assumed that carbon in natural gas feedstock is converted entirely to CO_2.

The general method for deriving emissions relates a country-specific emission factor EF, (reported in Table A5.3.1.1) to plant specific natural gas consumption data Ai:

$$E_a = \Sigma A_i \,.\, EF_i. - R$$

Where: A_i is plant specific natural gas feedstock consumption by feedstock type (i)
EF_i is the plant-specific emission factor for natural gas feedstock type (i)
R is CO_2 captured and sold for use in the food and drink industry and urea production.

The CO_2 recovered is deducted from CO_2 emissions from ammonia production and included in reporting under *2.H.2 Food and Drink* and *3.H Urea Application.* The quantity of CO_2 recovered for use is derived from data reported under the NGER scheme. Ammonia producers are required to report the quantity of CO_2 recovered and used in urea production and it is assumed that CO_2 recovered and not used in urea production is sold to the food and drink industry.

Choice of emission factor

A facility-specific EF for the consumption of natural gas for four facilities reported under the NGER scheme were used for 2008–09 onwards where available.

For the remaining three facilities, no facility-specific EF information was available. Therefore the country-specific EF for the consumption of natural gas as listed in Table A5.3.1.1 of the NIR was used.

Activity data

Data on fuel consumption, ammonia production and CO_2 capture were obtained under the NGER scheme for 2008–09 onwards. Data for consumption of fuels were inferred from data on production for the period 1989–90 to 2007–08 provided by EnerGreen 2009 assuming constant consumption to production factors in order to ensure time series consistency. Complete coverage of all ammonia producers has been maintained through the data collection mechanisms utilised throughout the time-series as listed above. Production data is shown in Table A5.4.1.4.

Nitric acid production (2.B.2)

A tier 3 method is utilised for the Australian inventory. Nitric acid production involves three distinct chemical reactions. These are summarised as follows:

$$4\,NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$$
$$2NO + O_2 \rightarrow 2NO_2$$
$$3NO_2 + H_2O \rightarrow 2HNO_3 + NO$$

Nitric oxide (NO), an intermediate product in the manufacture of nitric acid, readily decomposes to N_2O and nitrogen dioxide (NO2) at high pressures for temperatures in the range of 30 to 50°C.

The emissions of N_2O, En, from the manufacture of nitric acid production An is calculated according to:

$$E_n = A_n \,.EF_n$$

Choice of emission factor

The EFs for nitric acid production are facility-specific and obtained under the NGER scheme for 2008–09 onwards. Two nitric acid production plants apply NGER scheme method 4, which prescribes periodic or continuous measurement. Other facilities applied NGER scheme method 2, which prescribes periodic updated EFs. Individual plant-specific emission factors reported under the NGER scheme are not provided due to confidentiality constraints.

For earlier years, incomplete data on facility-specific EFs were available from Energreen 2009. Where facility-specific factors were not available, no information about the factors applicable to the remaining facilities were inferred from the Energreen data on the assumption that factors applicable to each facility are technology-specific and independent of each other. In these cases, IPCC good practice default factors were applied in accordance with information available on the applicable technologies (Energreen 2008 and 2009). Time series consistency is maintained by the interpolation of the available facility-specific EFs to the most recent year for which data were available.

Activity data

Data on nitric acid production for individual facilities were collected under the NGER scheme from 2008–09 onwards. Data for nitric acid production for the period 1989–90 to 2007–08 were provided by Energreen 2009.

NGER scheme methods provide reporters methods for reporting plant specific variables such as emission factors. Consistent with IPCC 2006, NGER scheme methods are able to account for operational conditions during a reporting year such as temporary losses of N_2O destruction capability. Production and emissions from nitric acid production are reported in Table A5.4.1.5.

Carbide production (2.B.5)

While calcium carbide is not produced in Australia, acetylene is produced from imported calcium carbide. The main source of emissions reported in this category arises from the use of acetylene with the combustion of acetylene producing CO_2 emissions.

The quantity of acetylene use is based on company data supplied to a consultant representing the department up to 2009 (Energreen 2009). From 2009 onwards, population data are used as the input to emissions estimation.

A tier 2 method is used. Emissions from 1989–90 to 2008–09 are estimated based on consultancy work reported. Emissions in subsequent years are estimated using a per capita rate derived from production volumes reported in that work.

Other – Titanium dioxide production (2.B.6)

A tier 2 method is utilised for the Australian inventory. The processes that are used in the production of TiO_2 in Australia that lead to process greenhouse gas emissions are synthetic rutile production using the Becher process, and rutile TiO_2 production via the chloride route.

The Becher process reduces the iron oxide in ilmenite to metallic iron and then reoxidises it to iron oxide, and in the process separates out the titanium dioxide as synthetic rutile of about 91 per cent to 93 per cent purity. Rutile TiO_2 is produced through the carbothermal chlorination of rutile ore or synthetic rutile to produce titanium tetrachloride (TiCl4) and oxidation of the TiCl4 vapours to TiO_2 according to the following reactions (Kirk-Othmer, 1999; p.2018):

$$2TiO_2 + 4Cl_2 + 3C \rightarrow 2TiCl_4 + 2CO + CO_2$$

$$TiCl_4 + O_2 \rightarrow TiO_2 + 2Cl_2$$

Based on stoichiometry and assuming complete conversion of the input C to CO_2 through further conversion of CO in excess air, the CO_2 EF cannot be less than 0.826 tonnes of CO_2 per tonne of TiO_2 (based on 1.5 moles of CO_2 per mole of TiO_2).

Emissions from rutile and TiO_2 respectively may be calculated by:

$$CO_2 \text{ Emissions} = \Sigma F_i \times A_i$$

Where EF_i is the EF for fuel type (i) and A_i is the quantity of fuel type (i) consumed as a reductant.

Choice of emission factor

No facility-specific information on EFs from the NGER scheme has been used in this inventory. Country-specific EFs are applied to the quantities of black coal and petroleum coke consumed in the synthetic rutile and titanium dioxide production processes.

Activity data

Data on synthetic rutile and TiO_2 production, black coal and petroleum coke consumption were obtained under the NGER scheme from the three manufacturers, Illuka, Tronox and Cristal. For the inventory years 2006–07 and 2007–08, activity data collected under the former EITEIs Program has been used.

Data for consumption of coal and petroleum coke were derived from data on production for the period 1989–90 to 2005–06 provided by Energreen 2009 and constant consumption to production factors in order to ensure time series consistency.

Soda ash production (2.B.7)

A tier 2 method is utilised for the Australian inventory. To protect confidentiality, these emissions are aggregated with emissions from *acetylene* under 2.B.10.

In the Solvay process, sodium chloride brine, limestone, coke and ammonia are the raw materials in a series of reactions leading to the production of soda ash, sodium bicarbonate and waste products containing calcium carbonate. Ammonia, however, is recycled and only a small amount is lost. The quantity of coke used as a reductant is deducted from the energy sector as it is a non-energy use of coke and ensures there is no double-counting. Both this use of coke as well as limestone consumed in the manufacture of soda ash are accounted for under this category.

The series of reactions involved in the Solvay process may be simply expressed as:

$$CaCO_3 + 2NaCl \rightarrow Na_2CO_3 + CaCl_2$$

The CO_2 generated in pyrolysis processes is captured, and directed to Solvay precipitating towers for consumption in a mixture of brine (aqueous NaCl) and ammonia. The Solvay process itself is in theory stoichiometrically neutral in relation to CO_2 gas (that is, generation equals uptake), however, in practice a greater amount of CO_2 is generated than can be absorbed in order to optimise the production process.

To estimate the excess CO_2 generated during production the carbon in the products and waste materials is deducted from the carbon in the raw materials leaving the excess carbon which is assumed to be entirely converted to CO_2 gas.

$$E_s = [\ \Sigma_f\ (CC_f\ .\ A_f) + \Sigma_i\ (CC_i \ x\ A_i)\ {}_{-}\Sigma_p\ (CC_p\ x\ A_p).\ -\ \Sigma_w\ (CC_w\ x\ A_w)\ ]\ x\ 3.664$$

Where E_s is the emissions of CO_2 from the production of soda ash and sodium bicarbonate CC_f is the carbon content of the fuel consumed A_f is the mass of fuel consumed (coke)

CC_f is the carbon content of the carbonate (f) consumed

A_f is the mass of carbonate (f) consumed

CC_i is the carbon content of the fuel input (i)

A_i is quantity of fuel type (i) consumed in the production of soda ash

CC_p is the carbon content of a product (p)

A_p is the mass of product (p) (soda ash and sodium bicarbonate)

CC_w is the carbon content of the waste products

A_w is the mass of waste product (brine mud)

In the first step of the Solvay process limestone is calcined to form lime which is then mixed with water to produce slaked lime for the ammonia recovery step. Any limestone that is not calcined is removed as waste (backstone and grits) from the process and this is deducted from the mass of limestone consumed in the emissions estimate.

A relatively small amount of waste material containing carbon in the form of calcium carbonate is also deducted from the carbon in the raw materials. The calcium carbonate waste is produced during a brine purification process where calcium and magnesium salts are removed from the brine feedstock. The purification of the brine is achieved through a reaction of soda ash and sodium hydroxide with the calcium and magnesium salts in the brine forming the solids, calcium carbonate and magnesium hydroxide. Calcium carbonate is also formed in the manufacture of the sodium hydroxide used in these reactions.

Soda ash is taken from the product stream and diverted to the brine purification process where it reacts with the calcium salts (calcium sulphate) to form calcium carbonate and sodium sulphate:

$$Na_2CO_3 + Ca(OH)_2 \rightarrow 2\ NaOH + CaCO_3$$

Sodium hydroxide is manufactured using soda ash (also diverted from the product stream) and slaked lime with calcium carbonate as a waste by-product:

$$MgSO_4 + 2\ NaOH \rightarrow Mg(OH)_2 + Na_2SO_4$$

The sodium hydroxide manufactured is then fed into the brine purification process where it reacts with the magnesium salts (magnesium sulphate) to form magnesium hydroxide and sodium sulphate.

$$MgSO_4 + 2\ NaOH \rightarrow Mg(OH)_2 + Na_2SO_4$$

In this way the CO_2 absorbed into the soda ash product is then diverted for use in the brine purification process and the manufacture of sodium hydroxide is converted into calcium carbonate. The carbon in the calcium carbonate formed in these reactions is deducted from the raw materials in the calculation of the emissions estimate. The soda ash product used in the brine purification process and manufacture of sodium hydroxide is essentially a non-emissive use of soda ash and the amount used is not included in the total soda ash produced for sale.

Choice of emission factor

The EFs for limestone consumption and coke consumption are facility-specific and obtained under the NGER scheme for 2008–09 onwards and under the former EITEIs Program for 2006–07 and 2007–08. As there is only one producer, complete coverage for the sector was achieved.

Activity data

Data on limestone and coke consumption for the purpose of soda ash production were collected under the NGER scheme for 2008–09 onwards and the reporting mechanisms of the former EITEIs Program for 2006–07 and 2007–08.

Data for limestone and coke consumption for the period 1989–90 to 2005–06 were derived from data for soda ash production obtained by industry survey (EnerGreen 2009). Time series consistency was maintained by the application of constant factors of limestone and coke consumption per unit of soda ash production estimated from data available for the period 2006–07 to 2008–09.

Petrochemical and carbon black production (2.B.8)

A tier 2 method is utilised for the Australian inventory, incorporating emission factors derived from plant specific data (EnerGreen 2009). Emissions from miscellaneous organic chemical manufacture are dependent on the level of activity and extent of emission control and estimated according to equation:

$$E_{ij} = (A_j \times EF_{ij})/10^{-6}$$

Where E_{ij} is the process emission (Gg per year) of gas i from industrial subsector j

A_j is the amount of activity (production or consumption) of material in industrial sector j (tonnes per year)

EF_{ij} is the EF associated with gas i per unit of activity in industrial sector j (kg per tonne) – see Table 4.4.

For methanol, Australia was not able to identify a CO_2 EF unique to the technology type previously used in Australia, and does not have feedstock consumption data available to support a mass balance equation. As an alternative, it was identified the CH_4 IEF for Methanol production in the USA is similar to Australia (2.3 kg/t vs 2.0 kg/t for Australia) – as this implies a comparable production technology in used, Australia derived CO_2 emissions using the USA CO_2 IEF of 670 kg/t.

Table 4.4 Emission factors for organic chemicals

Subsector	CO_2 (kg/tonne)	CH_4 (kg/tonne)	NMVOC (kg/tonne)
Acetylene [(a)]	3 384 kg CO_2 per tonne C_2H_2 used		
Butadiene			1.5
Carbon black		0.11	0.5
Ethyl benzene			0.03
Ethylene		0.03	0.25–1.5
Ethylene oxide			0.069
Formaldehyde			9.2
HDPE			1.5
LDPE and LLDPE			1.5
Methanol [(b)]	670 [(c)]	0.002	
Propylene			1.5
Polypropylene			1.5
Polystyrene [(b)]			0.1–5.4
Styrene [(b)]		4	18
Styrene butadiene rubber		1.5	1.5
Polyvinyl chloride		8.5	8.5

Source (EnerGreen 2008 and 2009). (a) Based on stoichiometry. (b) IPCC 1997. (c) USEPA 2021.

Fluorochemical production (2.B.9)

An emission factor of 0.04t of HFC-23 per tonne of HCFC-22 has been used for the estimation of emissions from HCFC-22 production.

4.3.3 Uncertainty assessment and time-series consistency

The tier 1 uncertainty analysis in Annex II provides estimates of uncertainty according to IPCC source category and gas.

Activity data obtained under the NGER scheme was compared with activity data obtained from the former EITEIs Program for each facility and with data obtained from GHD and Energreen consulting to ensure the consistent classification of sources and consistency of data.

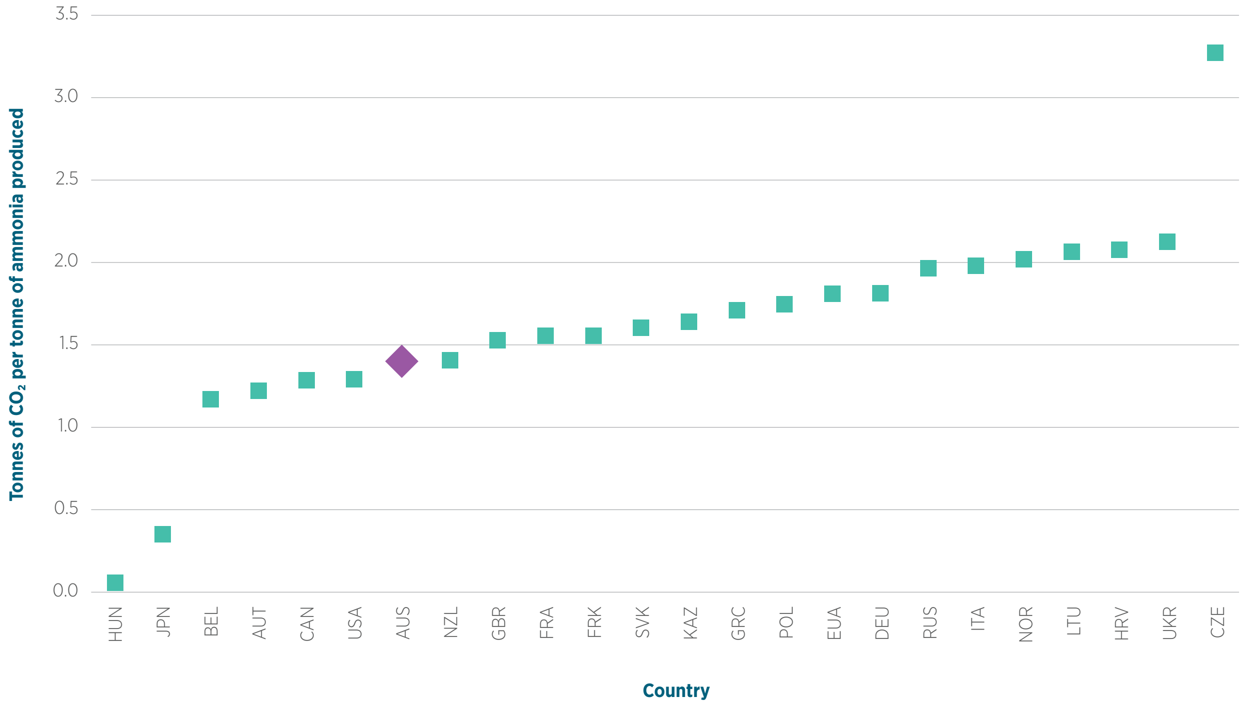
Where facility-specific EFs were identified from the NGER scheme data for particular facilities, in category 2.B.2, the reported EFs for 2006–07, 2007–08 and 2008–09 were interpolated for each facility to the most recent year for which data were available.

4.3.4 Category-specific QA/QC and verification

This source category is covered by the general QA/QC of the greenhouse gas inventory in Annex 1. Additional source specific quality control checks were undertaken to assess international comparability.

The IEF per unit of production for Australia's inventory was compared with the IEFs for other Annex I parties in the cases of ammonia (Figure 4.11) and nitric acid (Figure 4.12) production. The factors for Australia were found to be not significantly different to the factors reported by other Annex I parties.

Figure 4.11 Ammonia implied emission factors for Annex I countries (2023 submission) and Australia (2024 submission), tonnes of CO_2 per tonne of ammonia produced

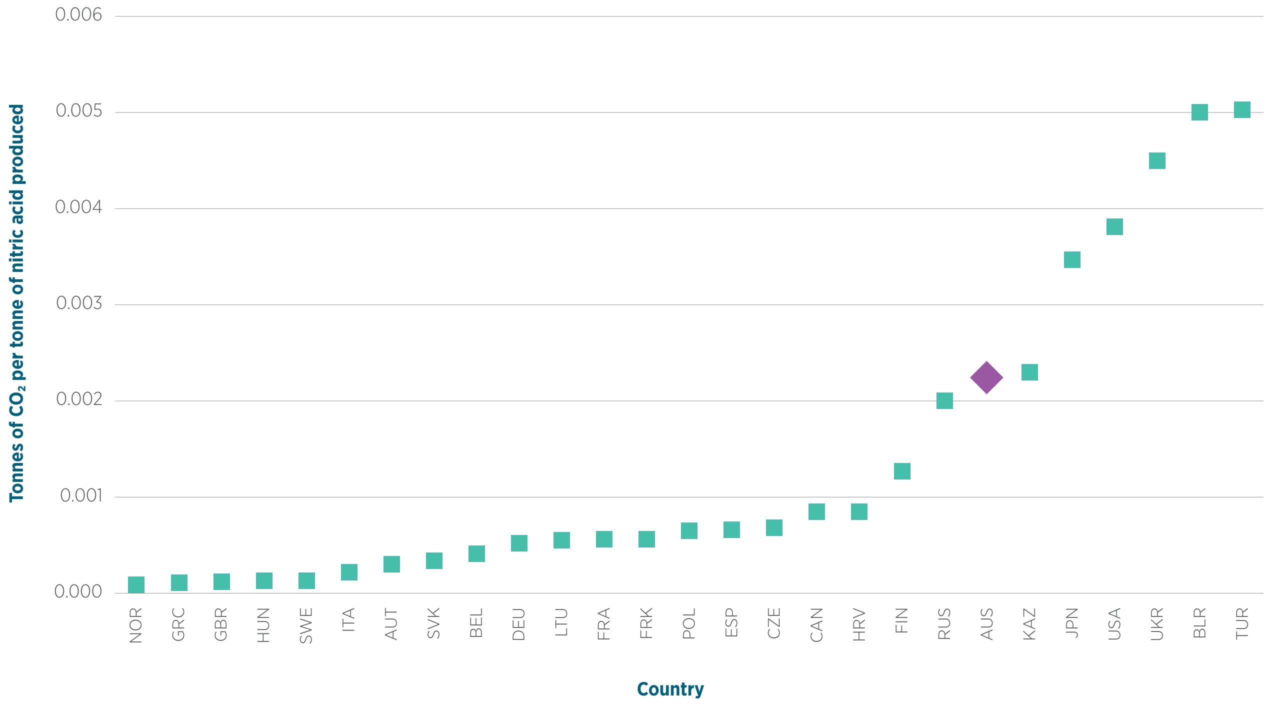


The IEF for ammonia production for Australia has fluctuated year-on-year between 1.073 t CO_2 generated per tonne of ammonia produced and 1.552 t CO_2 generated per tonne of ammonia produced according to fluctuations in ammonia production levels of individual facilities.

In general, Australia's IEF is generally lower than the default values listed in the *2006 IPCC Guidelines* of 1.666–3.273 t CO_2/t ammonia. The *2006 IPCC Guidelines* (IPCC 2006) lists a range of default "total fuel requirements" (including natural gas consumed for energy purposes as well as chemical feedstock) by production process ranging between 29.7 GJ fuel/t NH_3 and 42.5 GJ fuel/t NH_3. Under the NGER scheme, Australian ammonia facilities must report feedstock and fuel use separately and it is only the feedstock quantity that is used in the estimation of CO_2 emissions. Australia's feedstock fuel requirements range between 23.10 and 30.16 GJ fuel/t NH_3 produced.

This specific IP / non-IP split in activity data explains the difference between Australia's IEF and the IPCC defaults. The specific ammonia production technology mix in Australia will also cause differences between parties and the default IPCC values.

Figure 4.12 Nitric acid implied emission factors for Annex I countries (2023 submission) and Australia (2024 submission), tonnes of N_2O per tonne of nitric acid produced



The IEF for nitric acid production for Australia ranges between 0.002 t N_2O per tonne of nitric acid produced and 0.010 t N_2O per tonne of nitric acid produced. The IEF fluctuates year on year according to fluctuations in nitric acid production levels at individual facilities. Emissions at individual facilities are highly technology-specific with three main types of production plants and differing levels of abatement technology in place.

In 2011, the Department engaged a consultant to review N_2O emissions control in the nitric acid industry (EnerGreen Consulting 2011). This review found that a number of facilities were either trialling N_2O emissions reduction technology or monitoring developments domestically and internationally with a view to retrofitting existing plants or integrating abatement technology into future expansions. Plant-level EFs have been declining since the 1990s and more recent reductions have come about as a result of the introduction of continuous monitoring of N_2O emissions and an associated improvement in management of process catalysts.

4.3.5 Category-specific recalculations

Recalculations are shown in Table 4.5 and relate to minor corrections of estimates associated with acetylene use between 2009–10 and 2018–19.

Recalculations are due to minor historical corrections to population data used to estimate emissions of CO_2 from carbide production.

Table 4.5 Chemicals (2.B), recalculation of total CO_2-e emissions (Gg), 1989–90 to 2020–21

	2023 Submission	2024 Submission	Change	Change
Year	Gg CO_2-e	Gg CO_2-e	Gg CO_2-e	%
1989–90	3,145.4	3,145.4	-	0.0
1994–95	3,417.9	3,417.9	-	0.0
1999–00	3,301.5	3,301.5	-	0.0
2004–05	5,109.3	5,109.3	-	0.0
2005–06	5,791.4	5,791.4	-	0.0
2006–07	6,468.2	6,468.2	-	0.0
2007–08	6,225.2	6,225.2	-	0.0
2008–09	5,868.0	5,868.0	-	0.0
2009–10	6,389.3	6,389.3	-0.0	0.0
2010–11	5,820.8	5,820.8	-0.0	0.0
2011–12	5,389.8	5,389.8	0.0	0.0
2012–13	4,463.5	4,463.5	-0.0	0.0
2013–14	4,387.4	4,387.4	0.0	0.0
2014–15	4,609.6	4,609.6	0.0	0.0
2015–16	4,371.1	4,371.1	-0.0	0.0
2016–17	4,434.5	4,434.5	-0.0	0.0
2017–18	4,897.5	4,897.5	-0.0	0.0
2018–19	4,813.9	4,813.9	0.0	0.0
2019–20	4,730.7	4,730.7	-	0.0
2020–21	4,575.3	4,575.3	-	0.0

4.3.6 Planned improvements

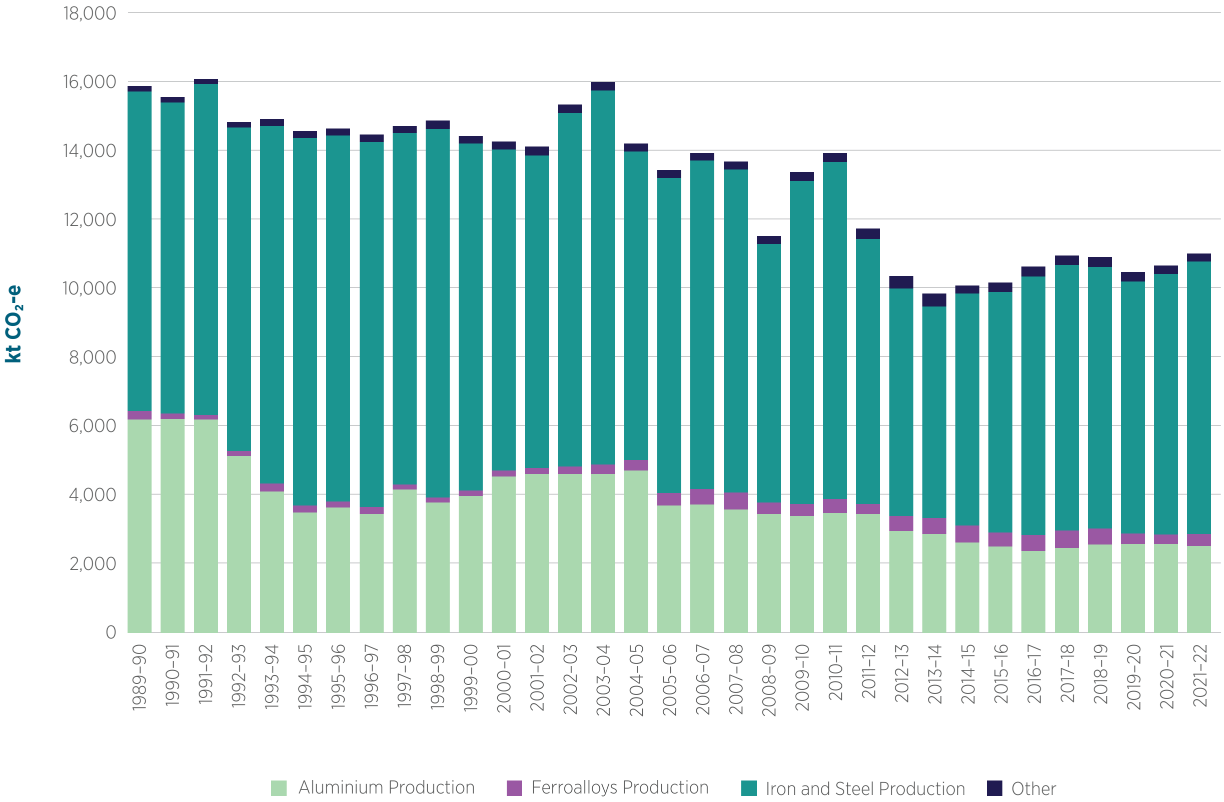
Technology to manufacture hydrogen via electrolysis with renewable electricity is expected to be implemented in Australia on a broad scale. We will establish process to ensure that NGER scheme reporting on ammonia production from these renewable sources are appropriately identified and to track its implementation. This will ensure that emission trends from ammonia production continue to be representative of Australia's circumstances.

4.4 Metal Industry

4.4.1 Category description

Key categories in the Australian metals sector are iron and steel and aluminium production.

Figure 4.13 Emissions from the metal industry, Australia, 1989–90 to 2021–22, kt CO_2–e



Iron and steel production (2.C.1)

Emission sources relate to the in-house production of metallurgical coke, and fugitive gas leaks associated with the distribution of coke oven gas and other products within industrial premises

Metallurgical coke is an essential material in iron and steel production where it serves a number of major functions including the provision of a porous support for furnace ingredients, as a combustion ingredient producing the reducing atmosphere required for ore refinement and as a chemical reductant. Since 2002–03, pulverised coal has also been used in Australian iron and steel production to improve the performance of the blast furnace. Emissions from the use of coke and pulverised coal as a reductant are reported in this category.

Emissions from the production of coke and from the consumption of natural gas are reported in the Energy sector. An assessment of NGER scheme energy data confirms there is currently no consumption of blast furnace gas by any facilities external to the iron and steel facilities. Accordingly, no re-allocation of CO_2 emissions associated with that activity to the Energy sector is required. This is kept under review for changes in practice. Carbonate use in iron and steel production is accounted for under 2.A.2.

There are two major producers of iron and steel in Australia which report through the NGER scheme. Integrated iron and steel production occurs primarily in New South Wales and South Australia. A hot briquetted iron (HBI) plant that used natural gas as a reductant in Western Australia between 1999–00 and 2004–05 is also included in the estimates from *2.C.1 iron and steel production.* In addition to the production of iron and steel from integrated iron and steel facilities, there are also three iron and steel producing facilities where electric arc furnaces are in operation.

Due to confidentiality, emission from *iron and steel production* are reported as “included elsewhere” (IE) and estimates are aggregated with emissions from *ferroalloys production* and *other metals production* for reporting under *2.C.7 other.*

There has been a general declining trend in the Iron and Steel implied emission factor due to the increased use of pulverised coal injection in lieu of coke. A down-turn in emissions from this category during 2004–05 occurred due to the blast-furnace re-lining activities at the Whyalla steel works. A notable decline of emissions from iron and steel production occurred in 2011–12 with approximately 20 per cent reduction on 2010–11. This decrease in emissions reflected the closure of the No.6 blast furnace at the Port Kembla steelworks in October 2011.

Ferroalloys production (2.C.2)

Emissions from the consumption of fossil fuels when used as reductants, or when used to produce carbon anodes on-site, or as carbon anodes are estimated under this category. There is one company producing ferroalloys in Australia consuming black coal, coking coal, coke oven coke, petroleum coke and limestone in the process. These emissions are reported under *2.C.7 Other Metals* to protect confidentiality of data.

Aluminium production (2.C.3)

Australia is the worlds largest producer of bauxite, used in aluminium production, and a significant global producer of alumina and aluminium (AAC 2021). Emissions from the production of aluminium are driven by production levels and the associated consumption of coal tar, petroleum coke and other inputs to the anode production process. Additional perfluorocarbon emissions resulting from process upsets are also reported under this category.

Aluminium is produced by the electrolysis of alumina in a series of complex electrode reactions. The overall reaction results in aluminium being produced at the cathode and carbon dioxide at the anode:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

The electrolysis process is conducted in carbon-lined steel pots containing high purity carbon anodes. The cell electrolyte consists of a molten bath of cryolite (Na3AlF6) to which varying proportions of aluminium fluoride, calcium fluoride or lithium fluoride may be added to lower the melting point, decrease the density of the electrolyte and improve energy efficiency.

Carbon dioxide is primarily formed by the chemical reaction of oxygen (produced in the electrolysis process) with the carbon anode. During the electrolysis of alumina to aluminium, some of the CO_2 formed at the anode may be reduced to CO by a secondary reaction involving particles of aluminium or sodium.

Grjotheim and Welch (1980) report that for a typical 150kAmp pre-baked cell, the anode gas consists of 70–85 per cent CO_2 with the balance (15–30 per cent) as CO. Measurements conducted by the Aluminium Development Council (ADC 1995) at several Australian smelters indicate that approximately 10 per cent of the anode gas (by weight) consists of CO. On contact with air, the majority of the CO in anode gas is burnt to CO_2 immediately above the electrolyte.

The perfluorinated carbon compounds (PFC), tetrafluoromethane (CF4) and hexafluoroethane (C2F6) are powerful greenhouse gases which are generated during the so-called anode effect in the production of aluminium. The anode effect is characterised by an increase in cell voltage as a result of the cryolite bath becoming deficient in alumina.

There are four companies operating aluminium smelters in Australia which report through the NGER scheme.

The strong downward trend in emissions per tonne of aluminium produced since the 1990s has occurred as a result of improvements in process control and the resultant reduction in PFC emissions. Any fluctuations in implied emissions factors occurring in more recent years are the result of small fluctuations in the number of anode effects in the production process occurring due to electricity supply disruptions and potline maintenance. The fall in the PFC implied emission factor between 2004–05 and 2006–07 occurred as a result of a smelter upgrade at Hydro Kurri Kurri (conversion of Potline No 1 from side-work to centre-work) and an enhanced emissions performance at the Tomago smelter (AAC 2007).

In Australia, bauxite is refined to alumina in Western Australia (WA), Queensland (Qld) and the Northern Territory (NT). The in-house production of lime at alumina refineries in Qld and NT represents an industrial process source of CO_2 emissions, which are accounted for under 2.A.2.

Magnesium production (2.C.4)

The inventory includes experimental quantities of SF_6 used between 1995–96 and 1999–00 as a cover gas in magnesium foundries preparatory to the development of a commercial magnesium casting plant (which was not, ultimately, commercially viable).

Lead production (2.C.5), zinc production (2.C.6), other (2.C.7)

In Australia the Lead Production, Zinc Production and Other source categories includes emissions from the production of lead, zinc, copper, nickel, and silver. There are 10 major companies involved in the production of these metals in Australia, which mostly report through the NGER scheme. The major zinc refinery, in Hobart, uses an electrolytic process which is non-emissive. The major lead refinery, at Port Pirie, which also refines a small amount of zinc, uses blast furnace technology.

CO_2 emissions from the use of fossil fuels as reductants, or in the production of carbon anodes on-site, or as carbon anodes in these refineries are reported under this category. An equivalent deduction has been made from fuel consumption in stationary energy to ensure there is no double-count of fuels in the inventory. CO_2 emissions from the consumption of carbonates in the production of other metals are reported under 2.A.4.

Australia's metal ores are predominantly sulphide ores leading to the generation of SO2 as a by-product of metal production. SO2 emissions from metal production are reported under this category.

4.4.2 Methodological issues

Iron and steel production (2.C.1)

A tier 2 method is utilised. The manufacture of iron involves the high temperature reduction of iron-bearing materials in a blast furnace. The blast furnace is essentially a large chemical reactor charged with iron ore, coke and limestone/dolomite to produce hot metal or 'pig iron' which is converted into steel typically by injecting oxygen gas through a charge of scrap and the molten iron. During the process, lime is added to remove impurities and provide a slag of the desired basicity.

The chemical reactions that occur in the blast furnace to produce molten iron (Fe as shown in the equations) may be summarised as follows:

$2C \text{ (coke)} + O_2 \rightarrow 2CO$

$C + H_2O \rightarrow CO + H_2$

$Fe_yO_z + ZCO \rightarrow YFe + ZCO_2$

$Fe_yO_z + ZH_2 \rightarrow YFe + ZH_2O$

$CaCO_3 \text{ (limestone)} \rightarrow CaO + CO_2$

$CaCO_3.MgCO_3 \text{ (dolomite)} \rightarrow CaO.MgO + 2CO_2$

Emissions from integrated iron and steel facilities are reported under the NGER scheme using a carbon balance across the whole of the facility. Due to this approach, disaggregations for 2.C.1.a steel, 2.C.1.b Pig iron, 2.C.1.c Direct reduced iron, 2.C.1.d Sinter, 2.C.1.e Pellet, and 2.C.1 .f Other (coke and pulverised coal consumption) are not available. As described in CRT Table 9, they are aggregated into the total for 2.C.7.b Other (Ferroalloys and other metal production).

Coke

The emissions from the use of coke as a reductant are estimated consistent with those of the Energy sector (Chapter 3.2). A full time series of coke emission factors is provided in Table A5.3.2.21.

The CO_2 EF used to compile the emission estimate for coke consumption (shown in Table 4.6) is derived from a carbon mass balance calculation conducted for the coke oven process. This balance is performed to ensure carbon inputs into the coke oven are balanced with all known outputs. In the case of coke ovens, the input is black coal and outputs are coke oven gas, coal tar and coke.

All outputs are reported in Australia's energy statistics in the form of energy. With emission factors for black coal, coke oven gas and coal tar known, a balance is achieved through the derivation of an appropriate coke emission factor. This balance is performed each year with each new release of the *Australian Energy Statistics* (Annex 5.2).

Table 4.6 Carbon dioxide emission factors for iron and steel

Fuel Type	P Oxidation Factor (%)	F Emission Factor (Gg/PJ)
Coke	100 (a)	109.4
Natural Gas	100	51.4 (c)

Notes:

(a) IPCC (2006) (IPCC 2006) default value.

(b) IPCC (2006) default value.

(c) The CO_2 EF for coke is derived from a carbon balance calculation conducted for the coke oven process.
The natural gas EF is provided by the Australian Gas Association.

Table 4.7 Non-carbon dioxide emission factors for iron and steel

	Emission Factors (Mg/PJ)					
Fuel Type	CH_4	N_2O	CO	NO_x	NMVOC	SO_2
Coke	0.95	0.71	91.25	190.99	0.86	370
Natural Gas	0.95	0.55	69.4	499.45	1.49	2.3

The raw steel produced contains carbon, the ultimate source of which is fossil carbon from the coal input to coke ovens. Since steel is a long-lived product, this is a form of carbon sequestration. The carbon content of steel is reported directly by iron and steel producers under the NGER scheme. The reported carbon contents of steel across all producers is between 0.16 per cent and 0.30 per cent.

Fugitive Emissions

A process EF is established for CH_4 from integrated iron and steel production (0.44 kg CH_4 / tonne of crude steel produced) to reflect mainly sources of fugitive emissions. The estimated CH_4 EF is based on experimental data and engineering calculations conducted at the plant owned by BlueScope Steel by BHP (pers. comm. 2000) for its major Australian integrated iron and steelworks. Process emission sources considered include the in-plant distribution of coke oven gas and natural gas, leakage from coke ovens and the bleeding of unflared blast furnace gas to the atmosphere. By comparison with fugitive emissions from the in-plant distribution of coke oven gas, emissions of CH_4 associated with leakage from coke ovens and the bleeding of unflared gas from blast furnaces are estimated to be of minor significance.

Activity data

Activity data for coke consumption in the production of iron and steel are obtained from the Australian Energy Statistics (Annex 5.2) for inventory years up to 2008–09 and the NGER scheme (Annex 5.1) from 2008–09 onwards. Crude steel production has been sourced directly from companies (Energreen 2008 and 2009) and the NGER scheme). Data on pulverised coal consumed in the blast furnace have been obtained from investor reports published by Bluescope Steel (Bluescope 2014). In 2008–09, NGER scheme crude steel production reporting under the NGER scheme was incomplete and was derived by indexing the crude steel production in 2007–08 to the changes in coke consumption in 2008–09. This is not the case in subsequent years where crude steel production reporting was complete.

Complete coverage of all iron and steel production has been maintained through the data collection mechanisms utilised throughout the time-series as listed above. Production and associated data is provided in Table A5.4.1.6

Ferroalloys production (2.C.2)

Emissions from the consumption of reductants in the production of ferro-alloy metals have been estimated using a tier 2 method. Emissions from the use of reductants in the production of ferroalloys are estimated by the application of country-specific EFs and oxidation factors consistent with those used for the *Energy* sector manufacturing industries (Chapter 3.2.5) to the quantity of each reductant used.

Data on fuel consumed as reductants for the purpose of production of ferro-alloy metals have been collected under the under the NGER scheme from 2008–09 onwards. For the years 1989–90 to 2007–08, this level of fuel consumption has been derived using historical production volumes.

Aluminium production (2.C.3)

CO_2 emitted during the consumption of carbon anodes is reported as if all the carbon is oxidised to CO_2. Emissions from the production of carbon anodes for use in aluminium production are estimated on the basis of the quantities of coal tar, petroleum coke and coke oven coke consumed in the production process and plant-specific EFs. CO_2 emissions are derived using the equation:

$$\mathbf{Eal = A_I \times EC_I \times EF_I}$$

Where A_I is the quantity of fuel type (i) consumed in the production of anodes

EC_I is the energy content of each fuel type (i)

EF_I is the CO_2 EF for each fuel type (i)

Facility specific PFC EFs have been estimated in accordance with accepted international measurement protocols (International Aluminium Institute (2006) , *The Aluminium Sector Greenhouse Gas Protocol , Addendum to the WRI/WBCSD GHG Protocol,* USEPA, International Aluminium Institute (2008), *Protocol for Measurement of Tetrafluoromethane (CF) and Hexafluoroethane* (C2F6) *Emissions from Primary Aluminium Production).*

Choice of emission factor

CO_2 EFs have been applied to the quantities of fuels used in the production of anodes. One NGER scheme reporting facility has derived facility-specific CO_2 EFs for coal tar and petroleum coke. It was assumed that the fuel specifications measured at this facility were equally applicable to all facilities.

The facility-specific fuel consumption EFs for anode production are confidential, however, the implied total CO_2 EF per unit of aluminium produced is shown in Table A5.4.1.7 and confirms that these values are within the historical range of IEFs and not significantly different to the mean of the values reported between 1989–90 and 2009–10.

In the case of emissions of perfluorocarbons, facility-specific EFs at all facilities have been estimated and sourced from the NGER scheme from 2008–09 onwards. National average factors for previous years have been supplied by the Australian Aluminium Council based on collected information on individual facility factors.

Activity data

Data on coke oven coke, petroleum coke and coal tar consumption for the purpose of production of aluminium have been collected under the NGER scheme from 2008–09 onwards. For the years 1989–90 to 2007–08 coal tar and petroleum coke consumption are derived from the carbon in the reported emissions and the typical composition of carbon anodes used in the aluminium production process.

Data on aluminium for the purposes of estimating emissions of PFCs has been obtained under the NGER scheme for 2008–09 onwards and ABARES *Commodity Statistics* (various years) for 1989–90 to 2007–08 (1990–2008).

The carbon anode consumed in aluminium smelting is approximately 3 per cent sulphur by weight. Based on the assumption that 413 kg of carbon from the carbon anode is oxidised (consumed) for each tonne of aluminium produced, this implies that approximately 12.77 kg of sulphur and 25.54 kg of sulphur dioxide are oxidised per tonne of aluminium produced.

Magnesium production (2.C.4)

Sulfur hexafluoride was used in small quantities for experimental work preparatory to the development of a commercial magnesium casting plant between 1996 and 2000. The data on SF_6 use for this experimental foundry was supplied by the CSIRO to an external consultant (Burnbank Consulting 2000) (2000).

Lead production (2.C.5), zinc production (2.C.6), other (2.C.7)

Emissions from the consumption of reductants in the production of lead, zinc and other metals have been estimated using a tier 2 method. Emissions are estimated using country-specific energy contents and CO_2 EFs for relevant fuels or, in certain cases, based on facility-specific EFs.

Ore composition and stoichiometric relationships have been used to derive sulphur dioxide emission estimates for copper, lead, nickel, zinc, and silver. The approach is illustrated using the example of zinc. Zinc occurs either as sulphide ores (ZnS) or carbonate ores ($ZnCO_3$). Australia's zinc production is predominantly from sulphide ores. The objective of the refining process to obtain primary refined zinc is to break the compound ore down by separating the sulphur from the zinc. Based on atomic and molecular weights, 0.980 tonnes of SO_2 will be released per tonne of primary refined zinc. EFs for other metals, based on stoichiometry relationships, are given in Table 4.8.

Table 4.8 Sulphur dioxide emission factors for refined metals

Metal	Tonnes SO_2 per tonne of refined metal
Lead	0.3
Zinc	1.0
Nickel	1.1
Silver	0.3
Copper	2.0

Data on fuel consumed as reductants for the purpose of production of other metals have been collected under the NGER scheme from 2008–09 onwards.

For the years 1989–90 to 2007–08, this level of reductant consumption has been derived using metal production data from the Resources and Energy Quarterly (DISR 2023) . For silver and nickel production, activity data for the pre-NGER scheme period has been derived using metal production statistics from the Resources and Energy Quarterly (DISR 2022), which covers the period up until 2012–13.

4.4.3 Uncertainty assessment and time-series consistency

The tier 1 uncertainty analysis in Annex 2 provides estimates of uncertainty according to IPCC source category and gas.

Activity data obtained under the NGER scheme was compared with activity data obtained from the former Emissions Intensive Trade Exposed Industries (EITEI) Program for each facility and with data obtained from GHD and Energreen consulting to ensure the consistent classification of sources and consistency of data. Where facilities were newly identified from NGER scheme data as emitting facilities for a category, estimates of fuel consumption were interpolated through the time period from the most recent year for which data was available to the year of commencement of the facility based on metal production estimates.

Where facility-specific EFs were identified from NGER scheme data for particular facilities, the reported EFs for 2006–07, 2007–08 and 2008–09 were interpolated for each facility between 2005–06 and the most recent year for which data were available.

4.4.4 Category-specific QA/QC and verification

This source category is covered by the general QA/QC of the greenhouse gas inventory in Annex 4. Additional source specific quality control checks were undertaken to assess international comparability.

Iron and steel (2.C.A)

The consumption of coke as a reductant which is used as the basis of emissions from iron and steel can be compared between the primary data source under the NGER scheme and the *Australian Energy Statistics* (DCCEEW 2023). A secondary source of trend comparison is the production of crude steel.

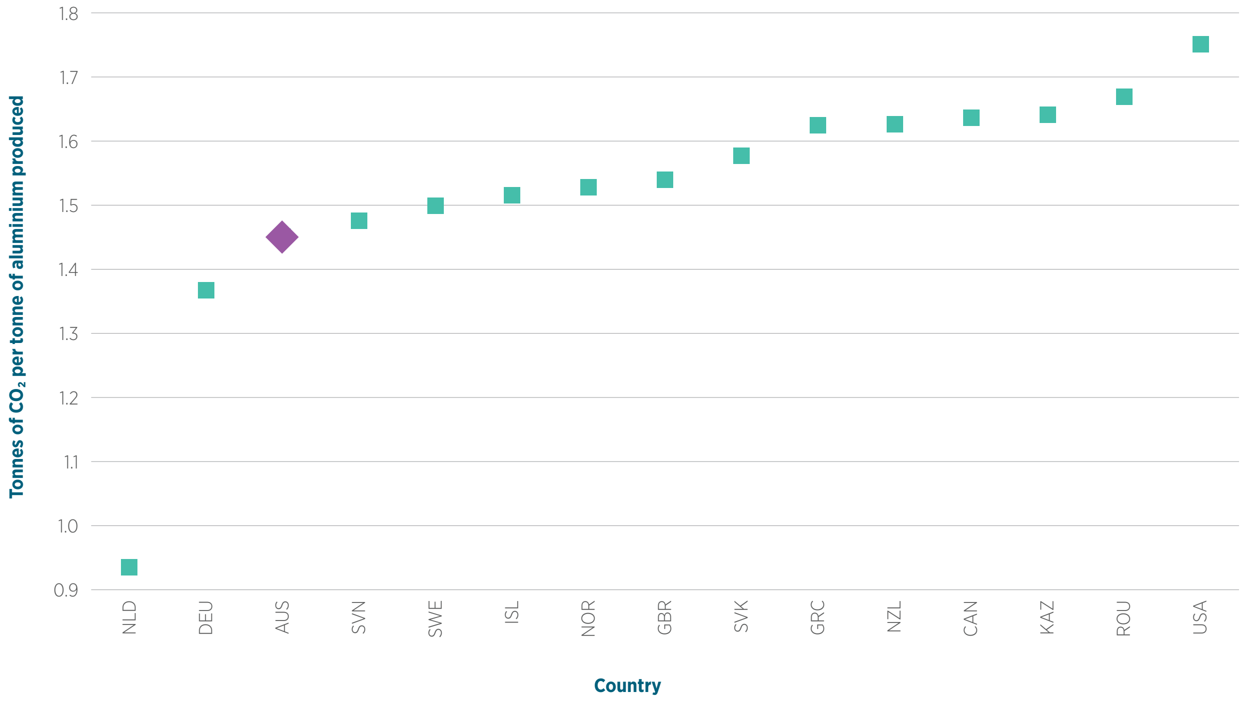
Aluminium (2.C.3)

Emissions of PFCs by the Australian aluminium industry are a key category under both the level and trends analyses. Consequently, additional analysis has been performed to provide a comparison of Australian emission trends with those worldwide. The results of the comparison show that the trend in emissions per unit of production in Australia is very close to that observed worldwide. The decline in PFC emissions per unit of aluminium production in Australia since the 1990s has mirrored the decline internationally (94 per cent), whereas the International Aluminium Institute (2020) reports a decline of 90 per cent between 1990 and 2019 worldwide. Emissions per unit of production reported by Australia are lower than the global averages, reflecting relatively modern plant and efficient operation, although this difference has narrowed slightly over time.

Monitoring of PFC concentrations occurs at the Cape Grim Baseline Air Pollution Station in Tasmania. Analysis of the observed atmospheric data has been undertaken by the CSIRO and compared to the emissions estimates in the inventory. Estimates of CF_4 and C_2F_6 emissions based on the measured data are in reasonable agreement with inventory estimates for 2020–21 (CSIRO 2023) (2023).

The quantity of CO_2 per tonne of aluminium produced has been compared with that from other Annex I parties reporting emissions from this source. The results of this comparison are shown in Figure 4.14.

Figure 4.14 Aluminium production implied emission factors for Annex I countries (2023 submissions) and Australia (2024 submission), tonnes of CO_2 per tonne of aluminium produced



The CO_2 IEF for aluminium production for Australia ranges between 1.40 t CO_2/t aluminium produced and 1.78 t CO_2/ t aluminium produced. IEFs fluctuate between observed years according to the quantities of carbon-based fuels used to produce anodes. Statistical analysis indicates that the IEF for aluminium production for Australia (in the shaded column above) is not significantly different to the factors reported by other Annex I parties.

4.4.5 Category-specific recalculations

A revision to AD associated with the consumption of petroleum coke in the production of carbon anodes at one facility has resulted in a revision to CO_2 emissions estimates from the production of aluminium in 2021.

Table 4.9 Metals (2.C), recalculation of total CO_2-e emissions (Gg), 1989–90 to 2020–21

	2023 Submission	2024 Submission	Change	Change
Year	Gg CO_2-e	Gg CO_2-e	Gg CO_2-e	%
1989–90	15,887.0	15,887.0	-	0.0
1994–95	14,577.6	14,577.6	-	0.0
1999–00	14,436.9	14,436.9	-	0.0
2004–05	14,220.8	14,220.8	-	0.0
2005–06	13,452.0	13,452.0	-	0.0
2006–07	13,944.7	13,944.7	-	0.0
2007–08	13,695.3	13,695.3	-	0.0
2008–09	11,535.2	11,535.2	-	0.0
2009–10	13,397.6	13,397.6	-	0.0
2010–11	13,949.0	13,949.0	-	0.0
2011–12	11,749.2	11,749.2	-	0.0
2012–13	10,371.8	10,371.8	-	0.0
2013–14	9,851.3	9,851.3	-	0.0
2014–15	10,092.0	10,092.0	-	0.0
2015–16	10,183.9	10,183.9	-	0.0
2016–17	10,638.1	10,638.1	-	0.0
2017–18	10,957.4	10,957.4	-	0.0
2018–19	10,915.5	10,915.5	-	0.0
2019–20	10,487.2	10,487.2	-	0.0
2020–21	10,875.8	10,673.7	- 202.1	-1.9

4.4.6 Category-specific planned improvements

All activity data, methodologies and emission factors are kept under review.

4.5 Non-Energy Products from Fuels and Solvent Use (CRT category 2.D)

4.5.1 Category description

Lubricant Use (2.D.1)

The use of lubricants in engines is primarily for their lubricating properties and associated emissions are therefore considered as non-combustion emissions to be reported in the IPPU Sector. However, in the case of 2– stroke engines, where the lubricant is mixed with another fuel and thus on purpose co-combusted in the engine, the emissions should be estimated and reported as part of the combustion emissions in the Energy Sector (IPCC 2006).

Parafin Wax Use (2.D.2)

No consumption of Paraffin Wax is reported due to only trivial amounts being consumed in Australia – emissions are not estimated. There are no activity data to support the preparation of a robust emissions estimate. However, based on the overall average of Annex-1 paraffin use per capita and implied CO_2 EF, it is estimated that emissions comprise around 0.7Gg CO_2–e or 0.0001% of total national emissions.

Other (2.D.3)

Surface coating operations involve the application of paint, varnish, lacquer or paint primer for decorative or protective purposes. Thinning solvents are normally used to dilute surface coating formulations or for cleaning purposes. Surface cleaning or degreasing operations involve the removal of materials such as oils, grease, waxes and moisture from surfaces. Chemical products manufacturing and processing covers paint and ink manufacturing. General solvent use and consumer cleaning by the domestic and commercial sectors covers a large range of products including Domestic and Commercial Aerosol Products; Other Domestic and Commercial Products; and Consumer Cleaning Products.

Cutback bitumen is the most common form of primer used in Australia to protect roads from excessive wear. Cutback bitumen primers and primer binders are manufactured from refined bitumen which are 'cutback' (i.e. blended) with petroleum solvents. NMVOC emissions occur during the mixing of bitumen batches, stockpiling, application and curing of the road surface.

4.5.2 Methodological issues

Lubricant Use (2.D.1)

Lubricants, together with bitumen and solvents, are non-fuel products of crude oil, which are included in the Australian Energy Statistics (Annex 5.2). It is assumed that 60 per cent of lubricants are not oxidised during engine operation, i.e. not actually combusted (Australian Institute of Petroleum, pers. comm. 1996). Therefore the stated consumption of lubricants and greases is reduced by 60 per cent before emissions are estimated. Emissions of gases other than CO_2 are included with the emissions arising from fuel combustion in the engine type concerned in the relevant sector. Some lubricants may be incinerated subsequent to use, and any emissions from incineration are included in the Waste sector.

Other (2.D.3)

In accordance with IPCC 2006, per capita EFs from the *EMEP/EEA air pollutant emission inventory guidebook 2016* (EMEP/EEA 2016) have been adopted for estimating NMVOC emissions from Other Domestic/Commercial products and Consumer Cleaning Products. The mean population for the financial year is multiplied by the EF and the result is expressed in gigagrams (Gg). EFs are expressed in terms of per capita use per year.

EFs for general solvent use and consumer cleaning products are presented in Table 4.9.

Table 4.10 Emission factors for general solvent use and consumer cleaning products

Product	Emission Factor kg NMVOC/capita/yr
Domestic/Commercial Aerosol Products [(a)]	
Household (cleaning) products	0.201
Care car products	0.161
Cosmetics and toiletries	0.355
Sub Total	**0.717**
Other Domestic/Commercial Products [(b)]	
DIY/buildings	0.522
Car care products	0.303
Cosmetics and toiletries	0.733
Pharmaceutical products	0.048
Pesticides	0.076
Sub Total	**1.682**
Household Cleaning Products [(b)]	
Non-aerosol	0.252
Other products	0.054
Sub Total	**0.306**
Total	**2.40**

Source: (a) Aerosol Association of Australia (pers. comm., 1994) . (b) *EMEP/EEA* (2016).

According to Treadrea (1995), for a system in equilibrium where the quantity of NMVOC used is constant each year and the average temperature conditions do not vary significantly from year to year, the quantity of flux and cutter lost to the atmosphere will be approximated by the quantity used each year.

It is assumed that the quantity of fluxed bitumen is negligible; the fraction of total bitumen consumption used in cutback bitumen is approximately 42 per cent (Australian Asphalt Pavement Association, pers. comm., 1995); and, the quantity of cutter added to the bitumen used in cutback bitumen is equal to 5.4 per cent (Treadrea P. 1995). Bitumen data are sourced from *Australian Energy Statistics* (Annex 5.2).

4.5.3 Uncertainty assessment and time-series consistency

The tier 1 uncertainty analysis in Annex 2 provides estimates of uncertainty according to IPCC source category and gas. Time series consistency is ensured by use of consistent models, model parameters and datasets for the calculations of emissions estimates.

4.5.4 Category-specific QA/QC and verification

This source category is covered by the general QA/QC of the greenhouse gas inventory in Annex 4.

4.5.5 Category-specific recalculations

There are no recalculations in Non-Energy Products from Fuels and Solvent Use in this submission

4.5.6 Category-specific planned improvements

All activity data, methodologies and EFs are kept under review.

4.6 Electronics Industry (CRT category 2.E)

Whilst there is some small scale manufacture of electronics in Australia, in accordance with UNFCCC inventory reporting guidelines (decision 24/CP.19), emissions associated with the use of fluorinated compounds in the electronics industry are considered negligible and are not estimated.

Australia has identified a small amount of specialty electronic components manufacturing, consuming around 20kg of NF_3 which is destroyed in the process.

It is also understood that negligible amounts of electronics cooling fluids containing NF_3 are consumed in Australia, confined to consumer use in personal computers and hobby applications, and for which no IPCC guidance on emission estimation could be identified.

4.7 Product Uses as Substitutes for Ozone Depleting Substances (CRT category 2.F)

4.7.1 Category description

This subsector comprises emissions of synthetic gases from the use of hydrofluorocarbons (HFCs) in refrigeration and air conditioning (2.F.1), foam blowing (2.F.2), fire extinguishers (2.F.3), aerosols/metered dose inhalers (2.F.4) and solvents (2.F.5).

HFC refrigerants were first used in Australia in 1994 and have been increasing in use since that time as ozone depleting refrigerants are phased out under the Montreal Protocol. A phase-down of bulk imports of HFCs commenced on 1 January 2018.

4.7.2 Methodological issues

The methodology used for compiling emissions estimates relates emissions to the stock and vintage of hydrofluorocarbon (HFC) gases in various equipment end-use categories. Where equipment stock data are available (in the case of domestic refrigeration and air conditioning, motor vehicle air conditioning and metered dose inhalers), information on the vintage and lifetimes of the capital stock of appliances have been used to estimate emissions on a bottom up basis. Where these stock data are not available, a top-down approach has been used.

The method relies primarily on inputs of data on HFC imports (an estimate of potential emissions – there is no local production of HFCs in Australia) reported under the *Ozone Protection and Synthetic Greenhouse Gas Management Act, 2003.* As part of the licensing conditions specified in the Act, quantities of gas imported in bulk and in pre-charged equipment are reported and these data are used for emissions estimation.

The methodology uses specified equations to estimate HFC emissions for each equipment type for three separate processes:

1. initial losses that occur at the initial charging of the equipment;
2. emissions from leakages during the life of the equipment; and
3. the emissions from the disposal of the equipment.

Initial losses occur when an amount of bulk imported gas (Mb_{ijkt}) is allocated to a specific equipment type j. Emissions during the life of the equipment depend, in the first year, on the amount of imported bulk gas allocated to the equipment type j and the amount of gas in imports of precharged equipment of type j ($Mpc_{i|kt}$) and, for every year thereafter, on the opening stock of gas in the equipment type ($S_{i|kt-1}$) plus any replenishments of gas (R) in the equipment type that may have occurred in that year. Emissions at disposal depend upon the closing stock of gas of vintage k in year t ($S_{i|kt}$), the proportion of the equipment stock retiring in each year (a|kt) and the quantity of gas recovered for destruction (D_{ijkt}).

The methodology is summarised by the following equations:

$$E_{ijkt} = Mb_{ijkt} * IL_{ijkt} + (S_{ijkt1} + Mb_{ijkt} + Mpc_{ijkt} + R_{ijkt}) * (EF_{ij}) + (\alpha K_{jkt} * S_{ijkt} - D_{ijkt})$$

$$S_{ijkt} = S_{ijkt1} + Mb_{ijkt} + Mpc_{ijkt} + R_{ijkt} - E_{ijkt} - D_{ijkt}$$

$$R_{ijkt} = \Sigma_{t-1,\, t-z} E_{ijkt}$$

$$D_{ijktbase} = \alpha K_{jkt} * S_{ijkt} * DF_{ijk}$$

$$D_{ijkt} = D_{ijktbase} / \Sigma_j \Sigma_k D_{ijktbase} * DTOT_t$$

and

$$E_t = \Sigma_i \Sigma_j \Sigma_k E_{ijkt}$$

Where E_t is the sum of emissions of all gases of type i from all equipment types j and vintages k in year t

E_{ijkt} is the emissions of gas i from equipment type j and vintage k in year t

S_{ijkt-1} is the opening stock of gas i from equipment type j and vintage k in year t

S_{ijkt} is the closing stock of gas i from equipment type j and vintage k in year t

Mb_{ijkt} is the quantity of bulk import of gas i allocated to equipment type j for vintage k if k = year t

Mpc_{ijkt} is the quantity of gas i in imports of pre-charged equipment type j for vintage k if k= year t

R_{ijkt} is the amount of replenishment of the stock of gas i for equipment type j and vintage k in year t

EF_{ijkt} is leakage rate of gas i from equipment type j and vintage k in year t (in the first year of operation, EF is divided by 2 – assuming equipment is in operation for an average of 6 months)

IL_{ijkt} is the initial loss rate of gas i from equipment type j and vintage k in year t

αK_{jk} is the proportion of the capital stock of equipment type j and vintage k retired in year t

$\Sigma_{t-1,t-z} E_{ijkt}$ is the sum of initial and annual emissions from t-z to t where t is the current year and z is the number of years between replenishments

D_{ijkt} is the amount of gas i destroyed from equipment type j and vintage k in year t

DF_{ijkt} is the base destruction factor for gas i destroyed from equipment type j and vintage k in year t

$D_{ijktbase}$ is estimated base amount of gas i destroyed from equipment type j and vintage k in year t

$DTOT_t$ is the actual total gas destroyed reported by Refrigerant Reclaim Australia

The initial loss rate (IL_{ijkt}) and annual loss rates (EF_{jkt}) applied to each vintage of each equipment type are country-specific factors, supported by the use of IPCC (2006) defaults (the mid-point of specified ranges) where country-specific information is not available.

Replenishment and disposal

Commercial equipment is assumed to be replenished to full charge every two years.

Light vehicle air conditioners are assumed to be replenished to full charge once after 6 years of operation.

Sensitivity testing of the impact of these assumptions on emissions is provided under in appendices to this chapter. Lifetime emissions are not affected by these assumptions, while the time profile of emissions is considered to be not significantly sensitive to these assumptions.

Average equipment lifetimes are based on country-specific expert assessment for refrigeration and air-conditioning equipment, and on IPCC default values for other equipment classes. A constant proportion of the equipment stock (akt) is assumed to be disposed over a period of time centred on the midpoint of the average equipment lifetime.

The charge remaining in equipment at retirement is assumed to be emitted to the atmosphere, subject to reclaim and destruction data reported by Refrigerant Reclaim Australia (RRA), the operator of the sole product stewardship scheme for refrigerants in Australia. The total amount of HFC gas recovered for destruction by RRA data is allocated between different equipment classes in assumed proportions informed by IPCC default recovery factors. The key assumptions are shown in Table A5.4.1.9.

Bulk gas activity data allocation

Bulk imported HFC gas allocations to equipment types are undertaken in 3 ways depending on what information is available about equipment stocks and production levels. These are identified below as methods 1 to 4. Methods for each end use category are also identified in Table A5.4.1.9.

Bulk gas demand is first estimated for classes of equipment where data on equipment stocks is available, then the residual bulk gas is allocated to the remainder of equipment types.

Method 1 covers the allocation of bulk gas to light vehicle air conditioning. Vehicle stocks by vintage in each inventory year are available from data underpinning the estimation of emissions from road transport. The following equation is used:

$$G_{demmv} = G_{dpmv} + G_{drmv}$$

$$G_{dpmv} = (New_{mv} - Imp_{mv}) \times Chg_{mv}$$

Where G_{demmv} is total gas demand for production and replenishment for motor vehicle air conditioners

G_{dpmv} is gas demand for domestic production for motor vehicle air conditioners

G_{dpmv} is the gas demand for replenishment for motor vehicle air conditioners – assumed to be total replacement of lost gas in the 5th year of operation

New_{mv} is new additions to the motor vehicle stock – based on motor vehicle census data used for the estimation of emissions for the transport sector

Imp_{mv} is imports of pre-charged motor vehicle air conditioners

Chg_{mv} is the unit charge of motor vehicle air conditioners

Method 2 covers the allocation of bulk gas to domestic refrigeration and air conditioning. Total stocks of domestic refrigerators and air conditioners are estimated based on data available from the Australian Bureau of Statistics. To achieve mass balance, the method includes a 'stock in storage' factor, where a proportion of imported units are held over for installation in a following year. The following equation is used:

$$G_{demdrac} = G_{dpdrac} + G_{drdrac}$$

$$G_{dpdrac} = (Exp_{drac} - Imp_{domrac} + Ret_{drac} + \Delta S_{drac}) \times Shr_{hfc} \times Chg_{drac}$$

Where $G_{demdrac}$ is total gas demand for production and replenishment for domestic refrigerators and air conditioners

G_{dpdrac} is gas demand for domestic production for domestic refrigerators and air conditioners

G_{drdrac} is the gas demand for replenishment for domestic refrigerators and air conditioners – no replenishment assumed

Exp_{drac} is the exports of domestic refrigerators and air conditioners

Ret_{drac} is the retirements of domestic refrigerators and air conditioners – based on assumptions about the operational life of each equipment type

ΔS_{drac} is the change in stock of domestic refrigerators and air conditioners calculated according to:

CS_{drac} – OS_{drac}

Where CS_{drac} is the closing stock of domestic refrigerators and air conditioners

OS_{drac} is the opening stock of domestic refrigerators and air conditioners

Imp_{drac} is the imports of domestic refrigerators and air conditioners adjusted for stock in storage = $Imppce_{drac} \times P_{inst}$

Where $Imp_{pcedrac}$ is total imports of pre-charged domestic refrigerators and air conditioners

P_{inst} is the proportion of pre-charged domestic refrigerators and air conditioners $_{inst}$alled in the year of import

Shr_{hfc} is the share of domestic production using HFCs

CHG_{drac} is the unit charge of domestic refrigerators and air conditioners

Bulk gas demand is summed for method 1 and 2 equipment types as follows:

$$G_{demtotal} = G_{demmv} + G_{demdrac}$$

Where $G_{demtotal}$ is total demand for gas for production and replenishment for motor vehicle air conditioners and domestic refrigeration and air conditioners

G_{demmv} is total gas demand for production and replenishment for motor vehicle air conditioners

$G_{demdrac}$ is total gas demand for production and replenishment for domestic refrigerators and air conditioners

After bulk gas demand for method 1 and 2 equipment types is allocated, the residual gas is allocated to method 3 and 4 equipment types.

Method 3 covers commercial refrigeration and air conditioning, and metered dose inhalers. Method 4, is a simplified version of Method 3 which does not account for equipment level data and covers foams, aerosols and fire protection equipment. There is no equipment stock information available for these equipment types. Gas is allocated to these equipment types according to the following equation:

$$G_{res} = G_{bulk} - G_{demtotal}$$
$$G_{resi} = G_{res} \times Shr_{resi}$$

Where G_{res} is the residual gas available to commercial refrigeration and air-conditioning, metered dose inhalers, foams, aerosols and fire protection equipment

G_{bulk} is total bulk gas imported available to all equipment

G_{demmv} is total gas demand for production and replenishment for motor vehicle air conditioners

$G_{demdrac}$ is total gas demand for production and replenishment for domestic refrigerators and air conditioners

G_{resi} is the residual gas available to equipment type (i)

Shr_{resi} is the share of residual gas used in equipment type (i) – this value is based upon end use data

The amount of bulk gas estimated to be used in filling of newly manufactured products in method 3 and 4 may vary substantially between years, as it depends on the quantity of bulk imports remaining after demand for filling method 1 and 2 products and replenishments across all product categories is satisfied.

Activity data: HFC gas imported into Australia

Data on imports of HFC gases are reported under licensing arrangements operating under the *Ozone Protection and Synthetic Greenhouse Gas Management Act, 2003.*

Imports of bulk gas are allocated initially to individual end uses on the basis of a consideration of the amount of gas required for domestic production and replenishment/servicing and retrofitting for the sources which are estimated on a bottom-up basis (gas demand in domestic refrigeration, packaged, split and refrigerated portable air-conditioning and light vehicle air conditioning). After this initial gas demand is satisfied, the residual bulk gas is allocated to the remaining end use categories in proportion to the information on use as reported by licensees under the Act. The sensitivity of these allocations on emissions estimates has been tested and the results are reported in the QA/QC section. The results show that lifetime emissions are not affected by these assumptions; the time profile of emissions – whilst impacted – is not considered sensitive to these assumptions.

Quantities of gas imported in bulk and contained in pre-charged equipment by end-use category for the current reporting year are shown in Table A5.4.1.10.

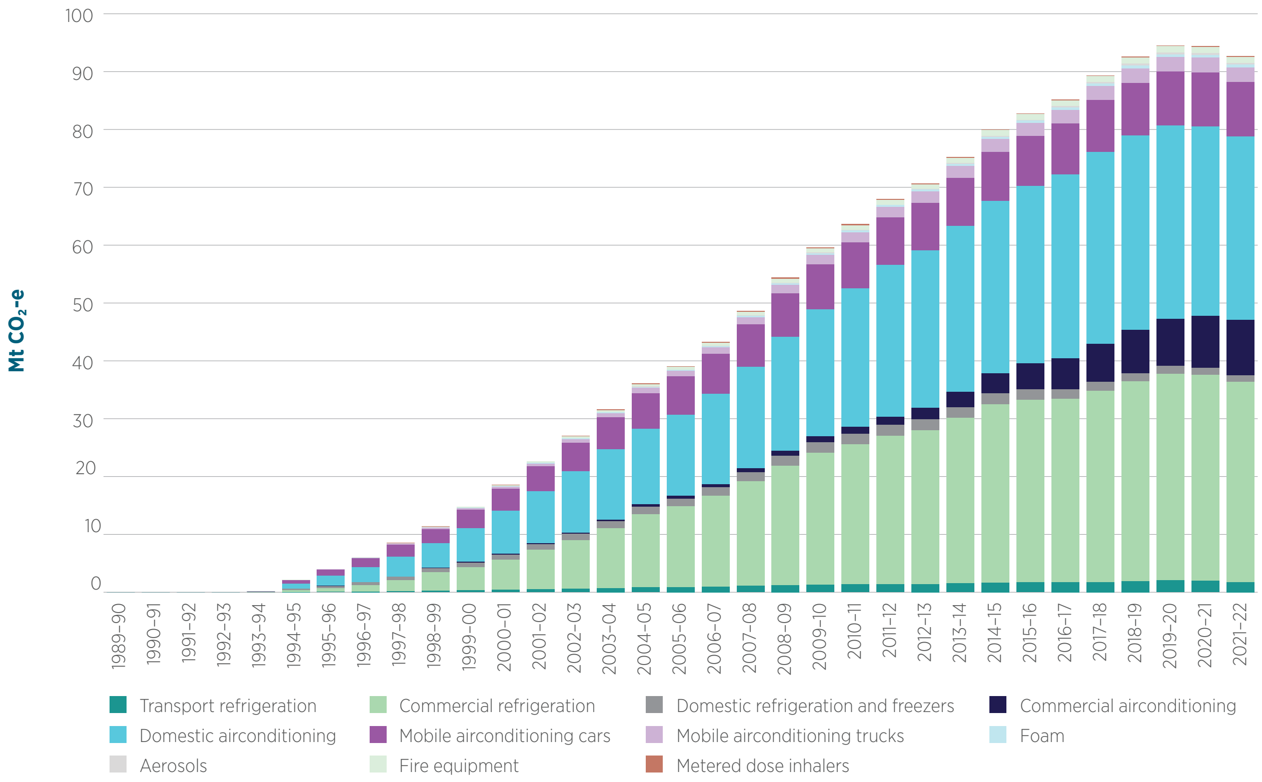
Collection of data on HFC imports under the *Act* commenced in the 2004–05 financial year. There are no data available on the import of HFCs for years prior to this. It is therefore necessary to backcast import data to enable an estimate of the bank of gas and associated emissions. For each of the end-use categories, information on the transition from the use of CFC refrigerants to HFC refrigerants provided in Burnbank (2002) was used to determine a time series of HFC imports up to 2004–05 when actual import data are available.

Overview of the stocks of gas in operating equipment

Figure 4.15 shows the growth in the stock of synthetic gas in operating equipment, with stock summary data shown in Table A5.4.1.11.

The chart shows significant growth in gas contained in commercial refrigeration systems, motor vehicle air conditioners and split system air conditioners. The general growth in the stock of gas over the time series reflects the transition from CFC to HFC refrigerant use associated with the Montreal Protocol controls on CFC use. In addition to the transitional trend, the growth in commercial refrigeration systems reflects similar growth in Australia's economy, whilst the growth in motor vehicle air conditioning and residential split systems reflects declines in relative prices of imported residential air conditioning systems as well as a transition in the vehicle fleet to more modern air conditioned vehicles.

Figure 4.15 Growth in the bank of HF gas in operating equipment (Mt CO_2–e)



Refrigeration and air conditioning (2.F.1)

The refrigeration and air-conditioning sector accounts for the majority of HFC consumption in Australia. Emissions from any piece of equipment include both the amount of chemical leaked during initial charging of equipment and the amount emitted during service life. Emissions also occur at equipment disposal. The disposal emission equation assumes that a certain percentage of the chemical charge will be emitted to the atmosphere when that vintage is discarded. Disposal emissions are thus a function of the quantity of chemical contained in the retiring equipment and the proportion of chemical released at disposal. The rate at which equipment is retired is based on IPCC default average service-lives for the various types of equipment.

Domestic Refrigeration and freezers

A bottom-up capital stock model was used to determine a time series for the stock of gas contained in domestic refrigeration and freezers. The estimates are based on data on the number of households and the numbers of domestic fridge freezers found in each household in Australia (ABS 2008a and ABS 2008b) and pre-charged equipment import data collected under the *Ozone Protection and Synthetic Greenhouse Gas Management Act.* Stock estimates in recent years are based on Expert Group projections and reflect a transition to the use of hydrocarbon refrigerants in place of HFCs.

Average charges per unit for domestic refrigerators are based on the pre-charged equipment data collected under the *Act.* Service life emissions are derived using Expert Group (2018).

Domestic production of household refrigerators no longer takes place in Australia with the last producer closing Australian operations in August 2009. The number of newly manufactured products filled with HFC gas is inferred as the balance of opening and closing stock numbers, imports/exports and retirements. The estimated amount of gas filled may vary substantially between years; where the above balance is negative, this amount is assumed to be zero.

It is assumed that no replenishment of gas losses from domestic refrigerators takes place as the units contain small well-sealed charges of gas. Unit disposals are based on an average lifetime of 15 years with the first units in each vintage retiring after 5 years. Stocks of domestic refrigerators and halocarbon gas are shown in Table A5.4.1.12.

Domestic air conditioning

Stationary air conditioning comprises refrigerated portable, split and packaged systems. Emissions from this sub category are estimated on a bottom-up basis using equipment population estimates based on numbers of households and white-goods data provided by the (ABS) (2008), and pre-charged equipment import data. Tables A5.4.1.13, A5.4.1.14 and A5.4.1.15 show the capital stocks and HFC stocks from the three types of air conditioning equipment.

Leakage rates are based on country-specific expert assessment. Quantities of residual gas disposed in each vintage are based on the IPCC average equipment life of 15 years. The first disposals of gas are assumed to occur after 6 years of operation.

Mobile air-conditioning (Passenger Cars)

Emissions from the use of air conditioners in passenger cars and light commercial vehicles (vehicles under 3.5 tonnes gross vehicle mass) are also estimated on a bottom-up basis. Data on the stock of motor vehicles obtained from the ABS *Motor Vehicle Census* (ABS) (2020) have been used to construct a capital stock model. The stock of light vehicles and of HFC gas contained in motor vehicle air-conditioners are reported in Table A5.4.1.16. It is assumed that all new units manufactured from 1994–95 onwards contain HFC-134a.

The stock of gas has been compiled using the ABS data on light vehicle stocks, import data on number of units imported and average charge, and assumptions about proportions of each vintage with air-conditioning for early years in the time series. Assumptions needed on the percentage of pre-1995 vehicles retrofitted with HFC-134a units to estimate an addition to the stock of gas were taken from Burnbank (2002).

The number of newly manufactured vehicles filled with HFC gas is estimated as the balance of increases in vehicle stocks, less the number of vehicles imported in that year. When the number of imported vehicles exceeds the increase in new vehicle stocks, it is assumed that no domestic filling of gas into newly manufactured vehicles occurs.

Analysis has shown that the charge in pre-filled units does not significantly differ between model years in the fleet, indicating that despite a general trend of increasing vehicle sizes, there is not an increase in air-conditioning equipment charge due to being offset by more efficient equipment.

Equipment disposals are based on the IPCC default average life-span of 12 years with the first units of each vintage retiring after 5 years of operation.

Mobile air conditioning (heavy vehicles), transport refrigeration and commercial refrigeration and air conditioning

Heavy vehicles are defined as vehicles of over 3.5 tonnes gross mass. Transport refrigeration comprises vehicle and self-powered refrigeration units used in commercial vehicles. Commercial refrigeration comprises stand-alone, medium and large and industrial refrigeration units and is the most significant user of synthetic gases in Australia. Commercial air conditioning covers the use of chiller units used in commercial buildings.

The quantities of imported gas are allocated on the basis of pre-charged equipment as reported under the *Ozone Protection and Synthetic Greenhouse Gas Management Act* and a proportion of bulk gas adjusted for gas demand in domestic refrigeration and air conditioning and mobile air conditioning. Once the gas required for loss replenishment needs is satisfied, the remaining bulk gas is allocated to charging new locally produced units.

Country specific leakage rates are applied to each gas vintage. Quantities of residual gas disposed in each vintage are based on the IPCC average equipment life values and the assumption that gas losses are replenished after every 2 years of a unit’s life. The first disposals of gas occur after 5 years of operation. Imports of gas and stocks in the operating equipment are shown in Tables A5.4.1.17 to A5.4.1.20.

Foam Blowing Agents (2.F.2)

The quantities of imported gas are allocated to foam on the basis of a proportion of bulk gas adjusted for gas demand in domestic refrigeration and air conditioning and mobile air conditioning.

IPCC default leakage rates are applied to each gas vintage. Quantities of residual gas disposed in each vintage are based on the IPCC average equipment life of 20.5 years. The first disposals of gas occur after 5 years of operation. There is no recovery or replenishment assumed in foams.

Foams are given emission profiles depending on the foam type (open cell or closed cell). Open cell foams are assumed to be 100 per cent emissive in the year of manufacture. Closed cell foams are assumed to emit a portion of their total HFC content upon manufacture, a portion at a constant rate over the lifetime of the foam, and a portion at disposal. Emissions from both open and closed cell foams are estimated as one source using the vintage stock model with an average initial charge and annual operation leakage rate. Imports of gas and stocks are shown in Table A5.4.1.21.

Fire Protection (2.F.3)

The quantities of imported gas are allocated to fire extinguishers on the basis of pre-charged equipment imports and a proportion of bulk gas adjusted for gas demand in domestic refrigeration and air conditioning and mobile air conditioning. Once the gas required for loss replenishment needs is satisfied, the remaining bulk gas is allocated to charging new locally produced units.

IPCC default leakage rates are applied to each gas vintage. Quantities of residual gas disposed in each vintage are based on the IPCC average equipment life of 10 years and the assumption that gas losses are replenished after every 2 years of a unit's life. The first disposals of gas occur after 5 years of operation. Imports of gas and stocks are shown in Table A5.4.1.22.

The Australian Fire Protection Association (FPA) has been consulted on the potential use of PFCs in fire extinguishers. They have confirmed that the ozone depleting or synthetic greenhouse fire fighting gases most common in Australia are: FE 227 (HFC 227ea), FM 200 (HFC 227ea), NAF-S-III (HCFC Blend A) and NAF-P-III (HCFC Blend C). The use of other gases is considered quite rare. On this basis, PFC use in fire extinguishers is reported as not occurring.

Aerosols (including metered dose inhalers) and Solvents (2.F.4 and 2.F.5)

Emissions from these sectors come from two sources: product use and fugitive emissions associated with product manufacture. Emissions from solvent and aerosol product use can be assumed to be 100 per cent of the charge size (100 per cent of consumption over the life of the product).

The quantities of bulk gas imported into Australia and allocated for use in aerosols and solvents is based on the proportion of reported end use adjusted for gas requirements in domestic refrigerator and air conditioning and mobile air conditioning. No replenishment is assumed to occur. Therefore all gas imported in bulk goes into charging domestically produced stock.

The complete charge of gas from an aerosol application is assumed to be lost at a base rate of 50 per cent per year.

There is no domestic production of metered dose inhalers (MDIs) in Australia. Imports of metered dose inhalers containing HFCs are not covered by the *Ozone Protection and Synthetic Greenhouse Gas Management Act* (2003). Consequently, emissions of HFCs from the use of metered dose inhalers are estimated on a bottom up basis. Estimates of the imports of gas contained in metered dose inhalers is based on information supplied by the Department of Sustainability, Environment, Water, Population and Communities (SEWPaC) on the number of MDIs imported into Australia in 2008–09 and a per capita based estimation of imports up to that year. Assumptions about the penetration of HFC propellants in imported MDIs are based on information from Burnbank (2002). On average, each imported unit is pre-charged with 14 grams of HFC-134a based on information supplied from SEWPaC.

Emissions from MDIs are estimated according to the same assumptions used for aerosols and solvents.

The growth in imports and the bank of HFC in this category is shown in Tables A5.4.1.23 and A5.4.1.24.

4.7.3 Uncertainty assessment and time-series consistency

The uncertainty of emissions in this category is estimated to be 27%.

Data on imports of HFC gas became available under the *Ozone Protection and Synthetic Greenhouse Gas Management Act* from 2004–05 onwards. Import quantities for prior years were extrapolated based on Burnbank 2002.

4.7.4 Category-specific QA/QC and verification

Mass-balance quality control

Data are obtained from companies under licensing arrangements established under the *Ozone Protection and Synthetic Greenhouse Gas Management Act* (2003) and has been subject to verification against known published sources (the Australian Bureau of Statistics data on imports of HFC-134a). A mass balance analysis has been completed to ensure that:

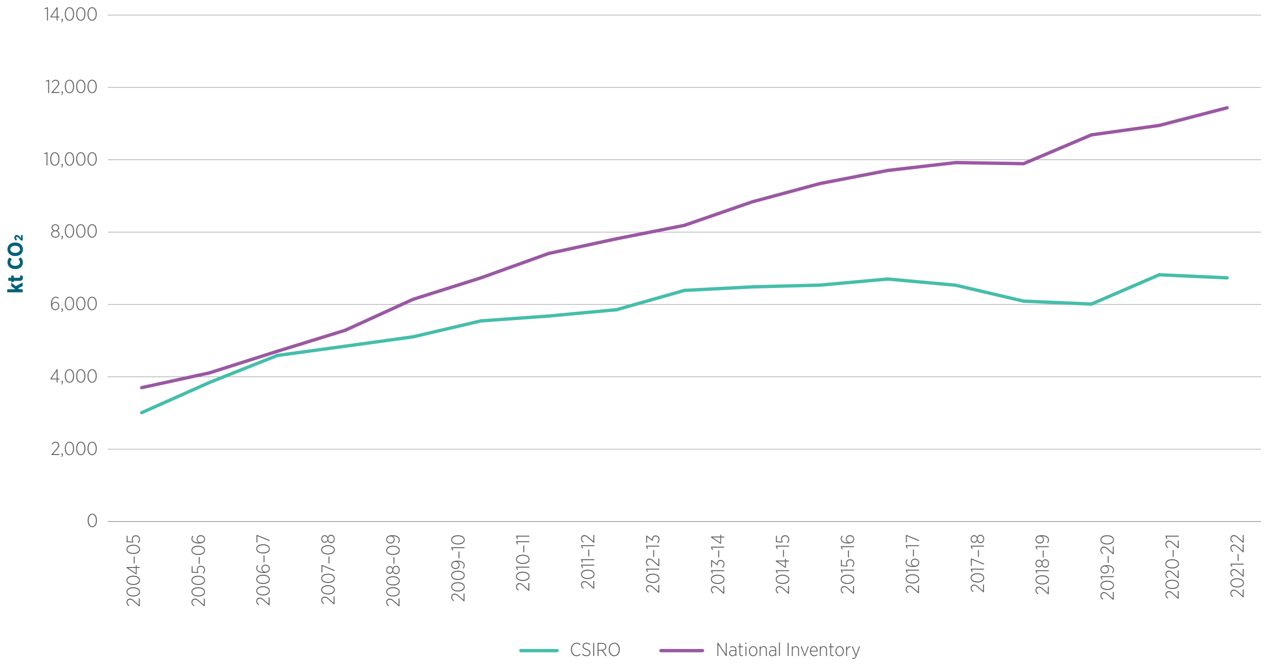
- all imported gas in bulk and pre-charged equipment is assigned to an appropriate end-use category, and
- stock changes and emissions and gas destruction were fully tracked and accounted for.

The results of these allocation and stock balances are presented in Tables A5.4.1.25 and A5.4.1.26.

External verification through atmospheric testing

Monitoring of atmospheric HFC concentrations has been undertaken by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) at the Cape Grim Baseline Air Pollution Station in Tasmania since the mid 1990's. The verification process undertaken independently by CSIRO lags the official inventory submission by one year. CSIRO uses inverse modelling techniques to derive an estimate of national HFC emissions based on atmospheric measurements of HFC concentrations. The comparison of estimates based on Cape Grim measurements with inventory estimates are shown below. The average variance between the two estimates is 37 per cent.

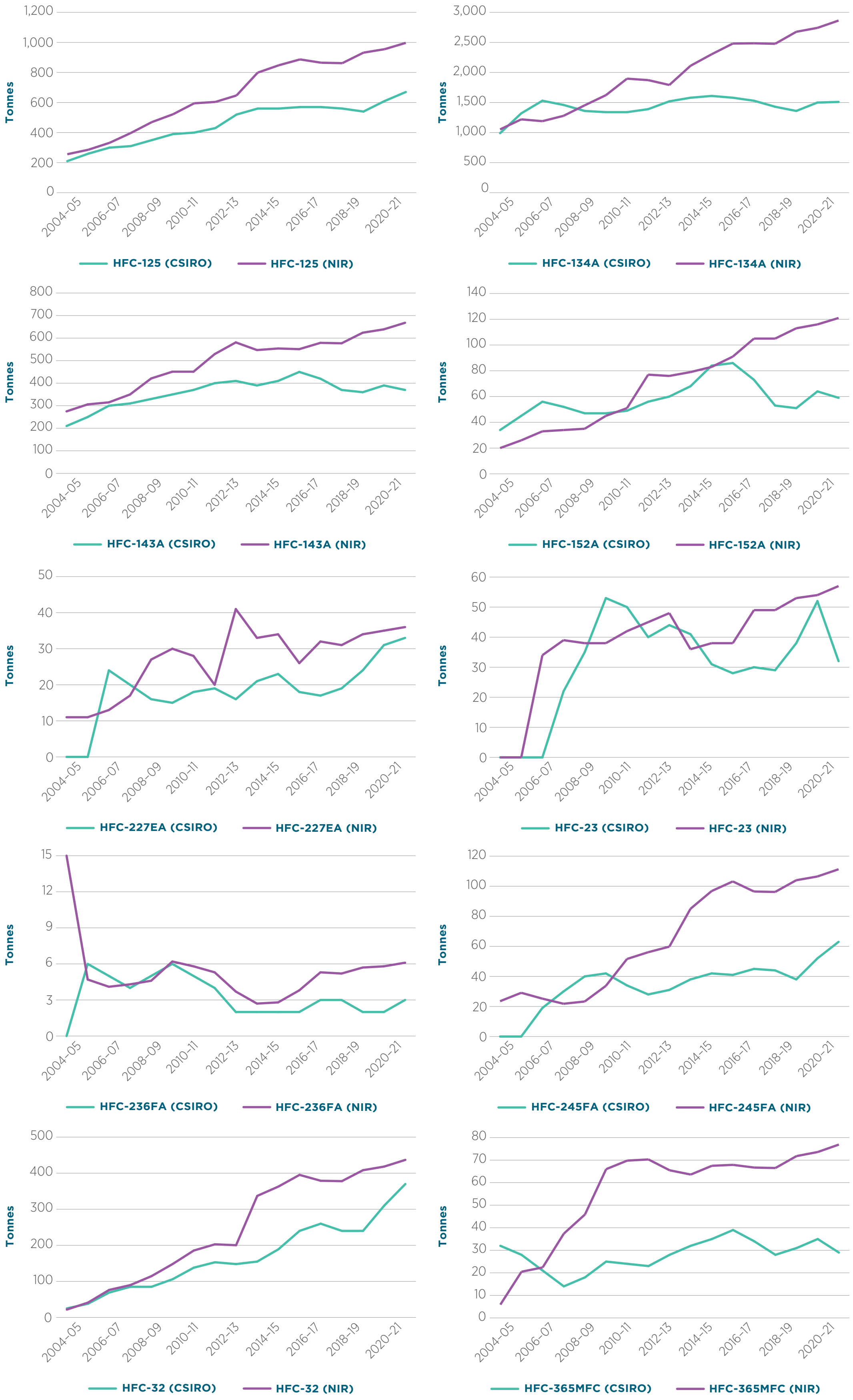
Figure 4.16 Comparison of Inventory HFC emission estimates with estimates derived from Cape Grim measurement data



The 2006 IPCC Guidelines (IPCC 2006) (p 6.21) identify fluorinated gases as being among the most suitable for which inverse modelling could provide verification of emissions estimates. As inverse modelling can be prone to natural source interference, F-gases are well suited to this approach as they have no natural sources. The remote location of the Cape Grim monitoring station also reduces the likelihood of measurement error from international sources. Additionally, there are no sinks for F-gases and therefore changes in concentrations reflect changes in emissions.

Gas species fluctuations observed at Cape Grim are also used to calibrate gas speciation in the HFC emissions model. Comparisons of CSIRO and NIR estimates of individual HFC gas species are shown below.

Figure 4.17 Comparison of HFC emissions by species (t)



4.7.5 Category-specific recalculations

Recalculations are shown in Table 4.11 and are due to a revision in activity data concerning light vehicle stocks.

Table 4.11 Product Uses as Substitutes for Ozone Depleting Substances (2.F): recalculation of total CO_2–e emissions (Gg)

	2023 Submission	2024 Submission	Change	
	Gg CO_2–e	Gg CO_2–e	Gg CO_2–e	%
1989–90	-	-	-	-
1994–95	100.4	100.4	-	0.0
1999–00	1,150.5	1,150.5	-	0.0
2004–05	3,699.5	3,699.5	-	0.0
2005–06	4,108.7	4,108.7	-	0.0
2006–07	4,706.4	4,706.4	-	0.0
2007–08	5,286.3	5,286.3	-	0.0
2008–09	6,141.5	6,141.5	-	0.0
2009–10	6,735.3	6,735.3	-	0.0
2010–11	7,409.8	7,409.8	-	0.0
2011–12	7,816.4	7,816.4	-	0.0
2012–13	8,187.3	8,187.3	-	0.0
2013–14	8,837.4	8,837.4	-	0.0
2014–15	9,343.5	9,343.5	-	0.0
2015–16	9,705.2	9,705.2	-	0.0
2016–17	9,922.3	9,922.3	-	0.0
2017–18	9,891.6	9,891.6	-	0.0
2018–19	10,688.5	10,688.5	-	0.0
2019–20	10,949.2	10,949.2	-	0.0
2020–21	11,405.4	11,437.5	32.0	0.3

4.7.6 Category-specific planned improvements

The Department keeps methods and activity data under review. Enquiries were made with industry participants in developing this submission to assess the extent of recycling of HFC gas in Australia. This investigation did not indicate that significant recycling is currently occurring; this issue will be monitored to assess whether significant reuse of HFC gas in Australia becomes an activity to consider.

4.8 Other product manufacture and use (CRT category 2.G)

4.8.1 Category description

Sulphur hexafluoride (SF_6) is used in electricity supply and distribution (2.G.1) and miscellaneous uses including eye surgery, tracer gas studies, magnesium casting, plumbing services, tyre manufacture and industrial machinery equipment (2.G.2).

Emissions of N_2O from aerosol products and anaesthesia (2.G.3) are estimated, but are confidential and are included in the Nitric acid production emissions (2.B.2).

4.8.2 Methodological issues

Electrical Equipment (2.G.1)

Australia has implemented the IPCC tier 2a method to estimate emissions of SF_6 from the electricity supply and distribution network.

Total Emissions = Manufacturing Emissions + Installation Emissions + Use Emissions + Disposal Emissions

Country specific emission factor (use of equipment)

With the availability of facility-level leakage rates from 2009–10 onwards obtained from over 300 facilities under the NGER scheme, Australia has developed a base country-specific EF consistent with the IPCC tier 3b method (IPCC GPG 3.56). This base factor is then calibrated each year from 2009–10 onwards in line with atmospheric SF_6 concentrations measured at the CSIRO Cape Grim monitoring station.

For the 2008–09 reporting year amendments were made to the *National Greenhouse and Energy Reporting (Measurement) Determination 2008,* which requires utilities and other entities to estimate their emissions from their own data using mass-balance and 'top-up' approaches. Under these approaches, surveyed entities 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 in the principle method. The approaches are consistent with those set out in the *Electricity Networks Association Industry Guideline for* SF_6 *Management,* ENA Doc 022–2008 (2008).

In the reporting year 2009–10, 15 companies, with stocks of 5.2 Mt of SF_6 as CO_2–e , elected to utilise one of the new EF methods to estimate losses, including the two largest users of SF_6 in Australia. The weighted average emission rate derived from these 15 NGER scheme reports was estimated at 0.0078 tonnes of SF_6 per tonne of stock of SF_6 per year. In 2010–11, the average emission rate derived from these 15 NGER scheme reporters (with stocks of 5.2 Mt in 2010–11) was estimated at 0.01 tonnes of SF_6 per tonne of stock of SF_6 per year. The fluctuation in leakage rates between the two reporting years is attributed to differing service intervals and equipment retirement and replacement schedules. This fluctuation was smoothed by taking a weighted average of the two years leakage rates to derive a leakage rate of 0.0089 tonnes of SF_6 per tonne of stock of SF_6 per year.

The reported EF obtained from facilities under the NGER scheme incorporates emissions from the operation of equipment and also emissions from disposal. A separate estimate of emissions from disposal is not available. Nonetheless, emissions from disposal are included with the EF from operation or use of the equipment – refer to *Energy Networks Australia, ENA Industry Guidelines for* SF_6 *Management,* ENA Doc 022–2008. (2008)

Calibration of annual leakage rate with atmospheric observations

Annual loss rates of SF_6 from 2009–10 onwards are adjusted in line with changes in atmospheric concentrations measured at the Cape Grim monitoring station in Tasmania (CSIRO) (2023). CSIRO uses inverse modelling techniques to derive an estimate of national SF_6 emissions based on atmospheric measurements of SF_6 concentrations. The base annual leakage factor is indexed to the changes in a national implied emission factor given by the CSIRO national estimate divided by the national stock of SF_6. SF_6 is considered to be an ideal gas to use inverse modelling techniques to derive national estimates, as there are no sinks for SF_6 and therefore changes in concentrations reflect changes in emissions. The calibration of leakage rates with atmospheric observation data allows the trend in atmospheric observations to be replicated in the inventory.

Annual leakage rates applied for each inventory year from 2009–10 onwards are shown below. As national emission estimates derived from atmospheric observations show a degree of volatility, a 3–year average has been used to derive the adjusted annual leakage rate for each inventory year.

Table 4.12 Annual SF_6 leakage rates derived from CSIRO estimates

Inventory year	CSIRO national SF_6 emissions estimate (t SF_6)	Annual leakage rate (t SF_6/t stock)
2009–10	31	0.0083
2010–11	26	0.0072
2011–12	21	0.0062
2012–13	21	0.0054
2013–14	18	0.0049
2014–15	17	0.0048
2015–16	22	0.0052
2016–17	25	0.0050
2017–18	17	0.0048
2018–19	16	0.0034
2019–20	16	0.0037
2020–21	25	0.0039
2021–22	28	0.0039

Source: CSIRO 2023.

This factor has been applied to the total stock of SF_6 gas in the electricity supply and distribution network.

Historical stock of SF_6 held by electrical equipment users

Historical stocks of gas have been derived based on a consideration of equipment stock changes between 1971–72 and 2007–08, prior to the introduction of the NGER scheme. Critical to this process is a consideration of equipment lifetimes in Australia.

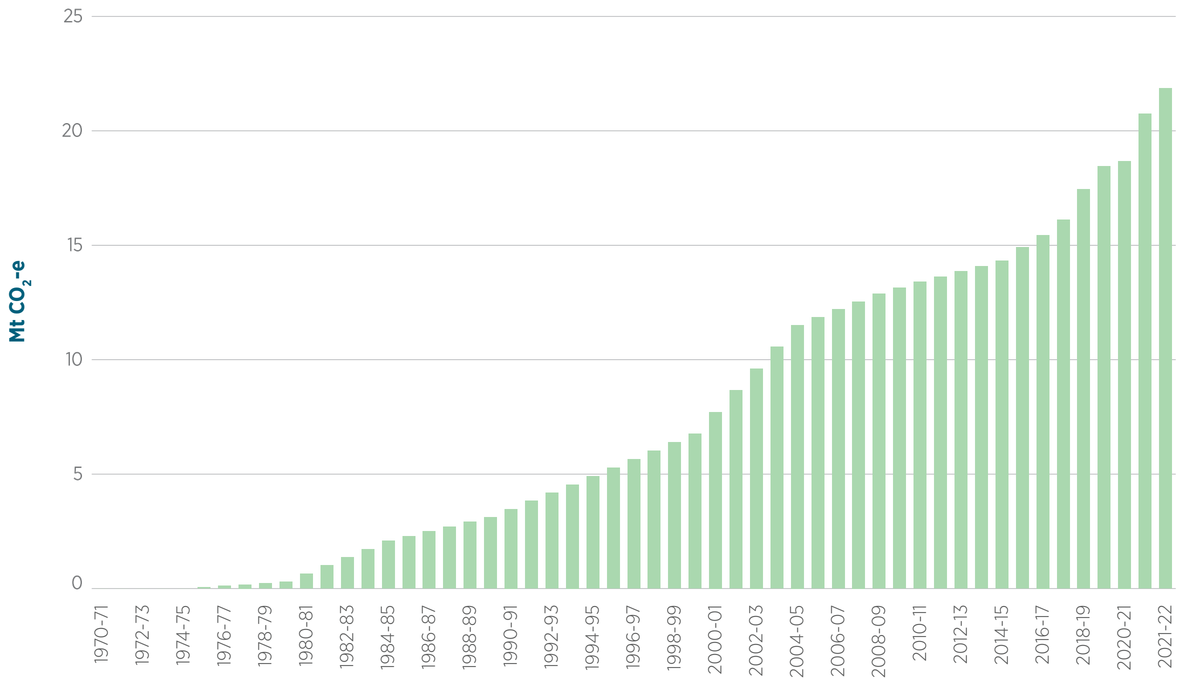
There is no comprehensive data available on the retirement of equipment using SF_6 in Australia. However, evidence on the retirements of circuit breaker stock that utilise SF was obtained from data published by Transgrid, the major network in the largest State of New South Wales, in the Transgrid, Network Management Plan 2011 (February 2011). The characteristics of Trangrid's operations were considered likely to be similar to those of other large utilities in Australia and mainly reflect the operation of high voltage transmission lines. Confirmation of the general age profile of Transgrid's circuit breaker assets was provided in the Transgrid *Network Management Plan 2011* (Transgrid 2011). This report also indicated that the first time SF_6 was used in equipment in Australia was in the period 1975–79.

Analysis of the change in the age profile of the stock of circuit breakers using SF_6 based on changes in the asset register between 2001–02 and 2009–10 provided a basis for an estimated retirement rate of around 0.4 per cent of the stock each year since 2002–03 (i.e. after equipment reached approximately 28 years). Transgrid also identified plans to phase out certain classes of circuit breakers using SF_6 over the next decade. Based on Transgrid's announced plans, the retirement rate was expected to increase to around 1 per cent of stock by 2018–19.

The 2006 IPCC Guidelines (2006) indicate that equipment lifetimes containing SF_6 are 'more than 30 to 40 years' Providing a default factor of >35 years, the range of likely outcomes reported by the 2006 IPCC Guidelines (page 8.21) is -10 per cent – +40 per cent – i.e. retirement is most likely to occur within the range of 31 years to 49 years.

The time profile of the stock of Transgrid's circuit breakers can be used to derive an estimate of the stock of SF_6 held by Transgrid using the application of a constant assumed charge per circuit breaker unit. Estimates of a time series of stock of SF_6 for Australia for 1989–90 to 2007–08 are derived by splicing the stock of SF_6 held by Transgrid to the national stock of SF_6 held in electrical equipment in 2008–09 according to data obtained from the NGER scheme. This approach is consistent with the approaches described in the IPCC Guidelines for extrapolation of data to ensure time series consistency.

Figure 4.18 Estimated stock of SF_6 in Australia (Mt CO_2–e)



Estimation of emissions of SF6 from the manufacture of switchgear and circuit breakers in Australia

In addition to emissions from the operation and disposal of electricity supply and distribution equipment, Australia also estimates emissions associated with the manufacture of electricity supply and distribution equipment.

Many major international suppliers of electrical equipment operate in Australia – ABB, Siemens, Mitsubishi etc. Currently no data are collected under the NGER scheme from the manufacturers of electrical equipment in Australia about their use of SF_6 or their emissions of SF_6. In addition, no information is available at this time to indicate the quantities of gas imported to fill new equipment in Australia prior to sale relative to the quantities of gas imported in pre-charged equipment.

To prepare an estimate of emissions from this source requires an assumption in relation to the proportion of pre-charged imported equipment relative to equipment charged with gas domestically using imported gas. For these estimates it is assumed that half of all equipment used in Australia was either manufactured in Australia or that, if imported, the equipment was charged with SF_6 in Australia. To proxy this outcome, the amount of SF_6 required for charging of new equipment in Australia was assumed to be equal to half of the sum of the change in stock of SF_6 in use recorded during the year and estimated emissions from use in stock.

The 2006 IPCC Guidelines does not report a default emission rate for global manufacturing. It does report factors taken from studies in Europe, which put leakage rates between 7 per cent for sealed pressure units and 8.5 per cent for closed pressure units. Much higher rates are assumed for Japan (29 per cent).

On the other hand, New Zealand reported a leakage rate associated with charging of units during manufacturing in 2009 of 0.79 per cent. The major manufacturer of this equipment in New Zealand, ABB, is also a significant supplier in Australia and, as Australian and New Zealand economies are highly integrated and reflect related political and cultural histories, it could be appropriate to consider the country-specific data from New Zealand. Given the range of factors available, Australia has assumed that the IPCC rates identified for European closed pressure units, which lie around the mid-point of the range, are applicable in Australia from 1995–96 onwards and the pre-96 GPG factor of 15 per cent prior to 1995–96.

Emission factors

The 2006 IPCC guidelines notes that it is not good practice to apply recently calculated EFs to leakages from earlier periods. In the absence of country specific information, Australia developed a time series of EFs for use of electrical equipment derived from the following assumptions:

a. application of the IPCC GPG global default factor for 1989–90 to 1994–95 of 5 per cent (IPCC GPG 3.58);
b. application of IPCC GPG global default factor for the year 1999–00 of 2 per cent (IPCC GPG 3.58);
c. country-specific factor for 2008–09 onwards – 0.89 per cent adjusted according to inverse modelled estimates in CSIRO 2019;
d. interpolation of EFs between the above point estimates;
e. the above emission rates include disposal emissions.

In the absence of country specific information, Australia has developed a time series of EFs for manufacture or on-site filling of imported electrical equipment derived from the following assumptions:

a. application of the IPCC GPG global default factor for 1989–90 to 1994–95 of 15 per cent (IPCC GPG 3.58);
b. application of IPCC GPG global default factor for the year 1999–00 of 8.5 per cent per cent (IPCC 2006 Table 8.3);

The decline in leakage rates over time reflects improved awareness and training of personnel in the handling of SF_6 as reflected in industry initiatives both globally, through CIGRE, or nationally – for example as reflected in the development of an Australian Standard AS2791/1996 , *Use and handling of* SF_6 *in high voltage switchgear and control gear* (1996) and industry guidelines as in the Energy Networks of Australia, *Industry Guideline for* SF_6 *Management* (2008).

Stocks and emissions of SF_6 emissions from electrical equipment are presented below.

Table 4.13 Stocks and emissions of SF_6 from electrical equipment

	Stock of SF_6 in electrical equipment				Manufacturing of electrical equipment			
	National stock		Emission factor	Emissions	Quantity	Leakage rate	Emissions	Total Emissions
Year	t CO_2-e	per cent growth	t/t	t CO_2-e	t CO_2-e	t/t	t CO_2-e	t
2004–05	11,859,325	2.97%	1.39%	164,281	253,046	8.50%	21,509	8.15
2005–06	12,201,135	2.88%	1.26%	154,014	247,912	8.50%	21,073	7.68
2006–07	12,542,945	2.80%	1.14%	142,907	242,359	8.50%	20,600	7.17
2007–08	12,884,755	2.73%	1.02%	130,960	236,385	8.50%	9,455	6.16
2008–09	13,152,259	2.08%	0.89%	117,508	192,506	8.50%	16,363	5.87
2009–10	13,400,529	1.89%	0.83%	111,377	179,823	8.50%	15,285	5.56
2010–11	13,629,772	1.71%	0.72%	98,786	164,015	8.50%	13,941	4.94
2011–12	13,859,014	1.68%	0.62%	86,041	157,642	8.50%	13,400	4.36
2012–13	14,088,257	1.65%	0.54%	75,886	152,565	8.50%	12,968	3.90
2013–14	14,317,500	1.63%	0.49%	70,343	149,793	8.50%	12,732	3.64
2014–15	14,905,043	4.10%	0.48%	71,974	329,758	8.50%	28,029	4.39
2015–16	15,449,759	3.65%	0.52%	80,331	312,524	8.50%	26,565	4.69
2016–17	16,123,360	4.36%	0.50%	80,455	377,028	8.50%	32,047	4.93
2017–18	17,440,957	8.17%	0.48%	83,474	700,536	8.50%	59,546	6.27
2018–19	18,454,360	5.81%	0.34%	62,912	538,158	8.50%	45,743	4.77
2019–20	18,683,967	1.24%	0.37%	69,139	149,373	8.50%	12,697	3.59
2020–21	20,124,027	11.01%	0.39%	81,047	1,069,475	8.50%	90,905	7.54
2021–22	21,210,833	5.40%	0.39%	85,424	602,799	8.50%	51,238	5.99

Other uses of SF_6 (2.G.2)

An estimate of SF_6 emissions from other applications including eye surgery, tracer gas studies, magnesium casting, plumbing services, tyre manufacture and industrial machinery equipment has been made on the basis of a per capita emissions value derived from the National Inventory of New Zealand. An average per capita emission rate of 0.8 kg of SF_6 per person per year has been applied to Australia's total population to derive a time series of emissions from this source.

For consideration of the potential for SF_6 used in military aircraft, enquiries with the Royal Australian Air Force have confirmed that no SF_6 gas is used in Australian aircraft radar systems.

N_2O from product uses (2.G.3)

Emissions of N_2O from aerosol products and anaesthesia are based on production data provided by the industrial gas manufacturers (BOC and Air Liquide) up to the year 2007–08. From 2007–08 onwards, N_2O consumption is indexed to population growth. These data and the resultant emissions estimates are confidential and are included in the Nitric acid production emissions (2.B.2).

In 2002–03, one of the two N_2O producing plants in Australia ceased production and imports of N_2O commenced. For 2002–03 onwards, N_2O emissions from product uses include those from the use of imported gas in addition to domestic production.

4.8.3 Uncertainty assessment and time-series consistency

Inventory uncertainty for SF_6 emissions is estimated at ±30 per cent which is comparable with uncertainty estimated for the modelled emissions by CSIRO. Further information on uncertainties is included in Annex 2.

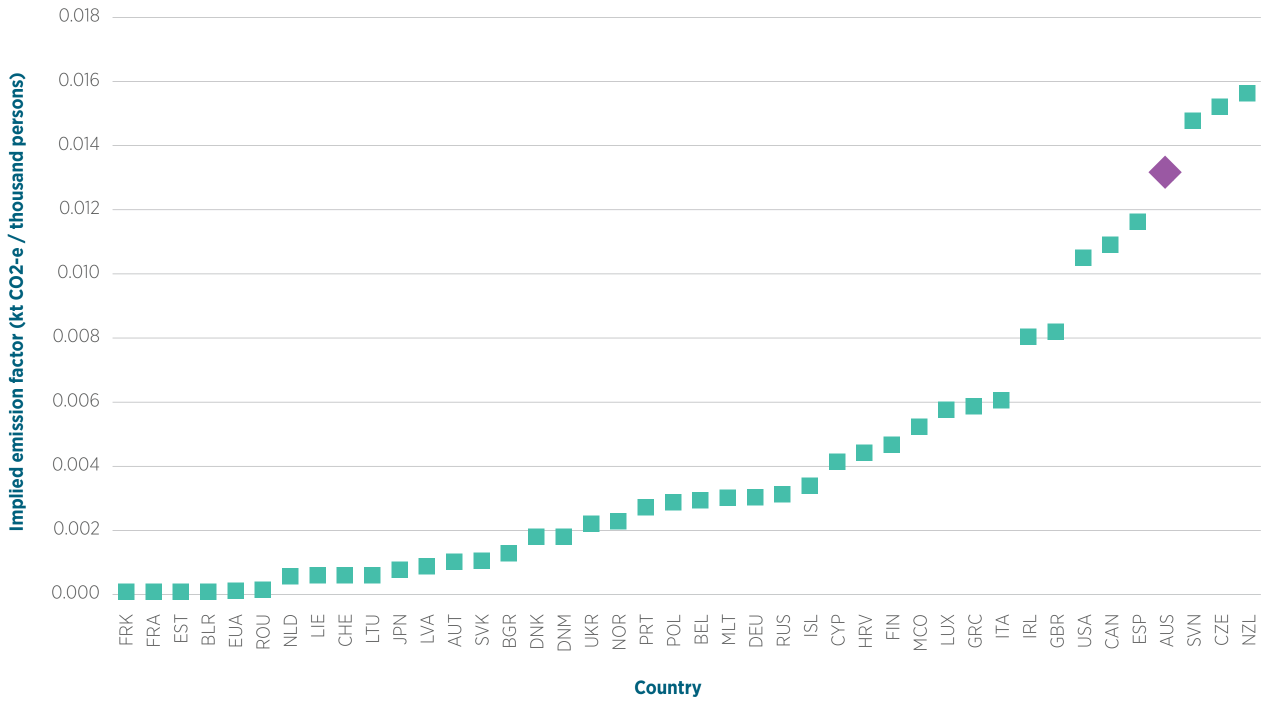
Time-series consistency for SF_6 is maintained through the application of splicing techniques to derive a national-representative series of SF_6 stocks in equipment (see Figure 4.19), with an interpolated series of EFs derived from the 2006 IPCC Guidelines (2006)

4.8.4 Category-specific QA/QC and verification N_2O from product uses (2.G.3)

With limited information available on the production and import of N_2O gas for use in Australia, a per capita factor has been derived from historical data on production and import. This factor is estimated as 0.013 kt CO_2–e /'000 persons. A comparison with other Annex-1 reporting parties shows this per capita factor to be within the range of derived per capita factors (0.00–0.02 kt CO_2–e /'000 persons).

Figure 4.19 demonstrates it is towards the upper end of the range of per capita factor and therefore likely to lead to a conservative estimate of emissions from N_2O use.

Figure 4.19 **N_2O use implied per capita emission factors or Annex I countries (2023 submission) and Australia (2024 submission), kt of CO_2–e per thousand persons**



This category is also covered by the general QA/QC of the greenhouse gas inventory in Chapter 1.

Electrical Equipment (2.G.1)

Australia applies two tests to consider the reasonableness of its estimates of SF_6 emissions from the electricity supply and distribution industry:

Comparison of the country specific emission factor with the IPCC default.

The IPCC GPG provides a global default factor of 2 per cent (IPCC GPG 3.57). Australia has applied this factor for 1994–95, while noting that the IPCC itself is somewhat cautious about the validity of these estimates presenting an uncertainty range of ±30 per cent indicating an IPCC range of 1.33 per cent – 2.6 per cent.

The *2006 IPCC Guidelines* (2006), page 8.17, provides that it is good practice to select factors from countries with similar equipment designs and handling practices. In Australia, and based on the purchasing patterns of Transgrid, the dominant source of equipment are European manufacturers, although with an increasing supply from Japanese manufacturers.

Table 4.14 2006 IPCC Guidelines default factors for Europe and Japan

	Default	Uncertainty	Range (higher)	Range (lower)
	Tonnes of SF_6 emissions per tonne (nameplate)	%	Tonnes of SF_6 emissions per tonne (nameplate)	Tonnes of SF_6 emissions per tonne (nameplate)
euro closed pressure	0.026	±30	0.0338	0.0182
Japan closed pressure	0.007	±30	0.0091	0.0049
euro sealed pressure	0.002	±20	0.0024	0.0016
Japan sealed pressure	0.007	±30	0.0091	0.0049

The IPCC notes that the defaults are those documented for 1995 – before any special industry actions for emission reduction were implemented (IPCC 2006, page 8.15). This makes validity of comparison for any year after 1995 difficult.

However, it can be noted that the base national factor estimated for Australia for 2009–10 (0.0089) – which is an average factor applied across the full range of equipment types in use in Australia (and typically sourced from Europe or Japan) – falls within the range presented in the 2006 IPCC *Guidelines* (0.0016 to 0.0338) – that should be applied for the year 1994–95 (and before any emission reduction actions were undertaken by industry).

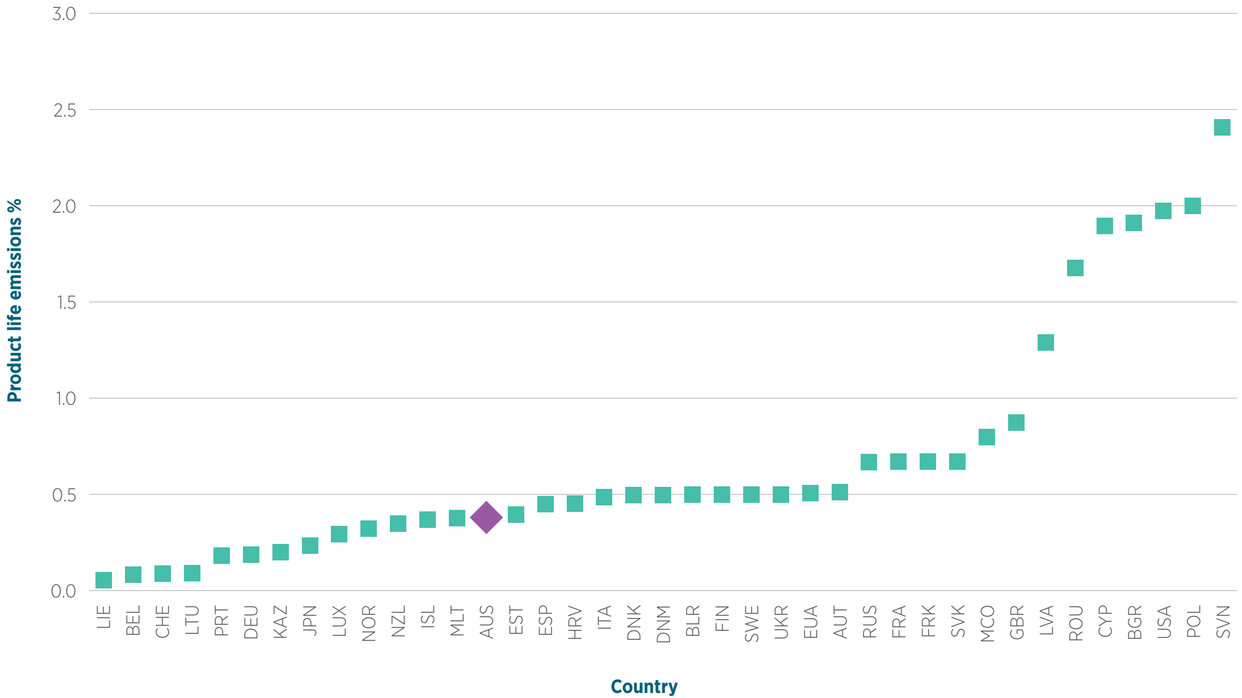
Since 1994–95, Australia has had active programs in place to reduce emissions from this source typified by the industry action documented in Electricity Networks Association, *Electricity Networks Association Industry Guideline for* SF_6 Management, ENA Doc 022–2008 (2008).

Consequently, Australia's assessment is that the country specific base EF, 0.0089 tonnes of SF_6 emission per tonne of SF_6 stock, is consistent with the information presented by the IPCC.

Comparison of the country specific emission factor with the factors of similar countries.

The estimated country specific EF for Australia was compared with factors applied in other Annex-1 parties. Australia's EF is consistent with the factors used in most Annex I parties.

Figure 4.20 Product life emission factors for Annex I countries (2023 submission) and Australia (2024 submission), per cent



Data available for Transgrid on equipment retirements are also consistent with the retirement information of other Annex I parties of similar circumstances and recent history. Of the group of major Annex I parties from Western Europe and other OECD countries (20 countries), around seven parties have identified an estimate for emissions from disposal; five indicate that disposal is ‘not occurring’ while the balance do not report.

4.8.5 Category-specific recalculations

Recalculations are shown in Table 4.15 and are due to revised CSIRO emission estimates used to calibrate SF_6 operational leakage rates in electrical equipment.

Table 4.15 SF_6 (2.G), recalculation of total CO_2–e emissions (Gg)

	2023 Submission	2024 Submission	Change	
	Gg CO_2–e	Gg CO_2–e	Gg CO_2–e	%
1989–90	227.3	227.3	-	0.0
1994–95	325.9	325.9	-	0.0
1999–00	216.6	216.6	-	0.0
2004–05	202.2	202.2	-	0.0
2005–06	191.8	191.8	-	0.0
2006–07	180.5	180.5	-	0.0
2007–08	168.3	157.7	-10.6	-6.3
2008–09	151.5	151.5	-	0.0
2009–10	133.8	144.5	10.8	8.0
2010–11	121.8	130.9	9.1	7.5
2011–12	118.5	117.9	-0.6	-0.5
2012–13	111.5	107.7	-3.8	-3.4
2013–14	108.9	102.2	-6.7	-6.2
2014–15	119.7	119.4	-0.4	-0.3

	2023 Submission	2024 Submission	Change	
	Gg CO_2-e	Gg CO_2-e	Gg CO_2-e	%
2015–16	120.7	126.6	5.8	4.8
2016–17	118.9	132.5	13.6	11.4
2017–18	149.7	163.3	13.6	9.1
2018–19	141.1	129.0	-12.1	-8.6
2019–20	108.9	102.3	-6.6	-6.0
2020–21	162.4	192.7	30.4	18.7

4.9 **Other** (CRT category 2.H)

4.9.1 Category Description

The 2.H Other source category includes emissions of CO_2 from the food and beverage industry. The IPCC hierarchy also includes the pulp and paper industry under source category 2.H. While the IPCC guidelines suggest that emissions of CO_2 and CH_4 are possible from the pulp and paper industry, no specific section on these categories is provided. Emissions of CO_2 from use of carbonates from the pulp and paper industry is reported under 2.A.3.

Food and beverage industry (2.H.2)

The supply of CO_2 gas for use in the food and drink industry (2.H.2) is provided from three main sources in Australia. Three ammonia producers sell a proportion of the CO_2 generated as a by-product of the ammonia production process to the food and drink industry. Gas has also been obtained from two natural CO_2 wells located at Caroline in South Australia (commissioned in 1967 and closed in 2017) and Boggy Creek in Victoria (commissioned in 1995). The third source is by product CO_2 from an ethylene oxide plant located in Botany in New South Wales.

In the case of the CO_2 wells and the ethylene oxide plant, some CO_2 sold is also used for medical and other purposes (such as use in fire extinguishers). However, all CO_2 sold by these operators is reported under 2.H.2 *Food and drink.*

A small source of CO_2 emissions also derives from the use of sodium bicarbonate in food production. These emissions are also reported under 2.H. Sodium bicarbonate is a by-product of the production of soda ash.

The manufacture of beer, wine, alcoholic spirits, and bread involve the use of fermentation processes. The IPCC (1997) indicate the fermentation of sugar by industry is not considered to be a net source of CO_2 emissions. Consistent with the 2006 IPCC Guidelines (IPCC 2006), Australia does not estimate CO_2 emissions from this source. NMVOC emissions from food and drink production, however, are included in the inventory. Production data for meat and poultry, beer and wine are obtained from ABS. Production data for sugar are obtained from ABARES Agricultural Commodities (2021).

4.9.2 Methodological issues

Emissions of CO_2 from food and drink are derived based on the assumption that all CO_2 gas used is emitted in the year of production.

CO_2 generated in the production of ammonia and then captured for consumption in the food and drink industry is described in the method for the estimation of emissions from ammonia production (2.B.1). The quantity of CO_2 supplied from the single remaining gas well is derived based on published production capacity.

The quantity of CO_2 supplied from the ethylene oxide plant is derived based on the production capacity of the plant indexed to changes in quantities of soda ash consumption for this plant reported under the NEGR system and a CO_2 EF of 0.45 tonnes of CO_2 per tonne of ethylene oxide produced taken from the Netherlands National Inventory Report. It is assumed that all CO_2 generated is sold for use in food and drink production.

Sodium bicarbonate ($NaHCO_3$) is also produced in the manufacture of soda ash using the Solvay process (see Chapter 4.3.2 (2.B.7)). Uses of sodium bicarbonate in which CO_2 is generated include leavening agents, pharmaceuticals, stock feed buffer and effervescent salts and beverages. EnerGreen Consulting (2009) indicates that the proportion of sodium bicarbonate consumption resulting in emissions of CO_2 is 80 per cent. It is assumed that the sodium bicarbonate thermally decomposes in the following reaction:

$$2NaHCO_3 \rightarrow Na_2CO_3 + H_2O + CO_2$$

The mass of CO_2 emitted from the use of sodium bicarbonate E_{sbu} is estimated using consumption data A_{sbu}, the proportion resulting in emissions and the stoichiometry of the chemical process (where 44.01 is the molecular weight of CO_2 and 84.01 is the molecular weight of $NaHCO_3$).

$$E_{sbu} = 0.8 \text{ x } A_{sbu} \text{ x } 0.262 \text{ kg/tonne } NaHCO_3$$

Emissions of NMVOCs from food and drink production are based on tier 2 methods and IPCC default EFs. Generally the methods involve multiplying the product activity level data (the amount of material produced or consumed) by an associated EF per unit of production or consumption. The NMVOC EFs used are as follows:

Beer	0.035 (kg NMVOC/hl beverage produced);
Red Wine	0.08 (kg NMVOC/hl beverage produced);
White Wine	0.035 (kg NMVOC/hl beverage produced);
Bread	1.66 (kg NMVOC/t food produced);
Sugar	10 (kg NMVOC/t food produced); and
Meat and Poultry	0.3 (kg NMVOC/t food produced).

4.9.3 Uncertainties and time series Consistency

The tier 1 uncertainty analysis in Annex 2 provides estimates of uncertainty according to IPCC source category and gas. Time series consistency is ensured by use of consistent models, model parameters and datasets for the calculations of emissions estimates. Where changes to EFs or methodologies occur, a full time series recalculation is undertaken.

4.9.4 Category-specific QA/QC and verification

This source category is covered by the general QA/QC of the greenhouse gas inventory in Annex 4.

4.9.5 Category-specific recalculations

There are no recalculations in the food and beverages industry in this submission.

4.9.6 Planned improvements

Activity data and EFs will be kept under review.

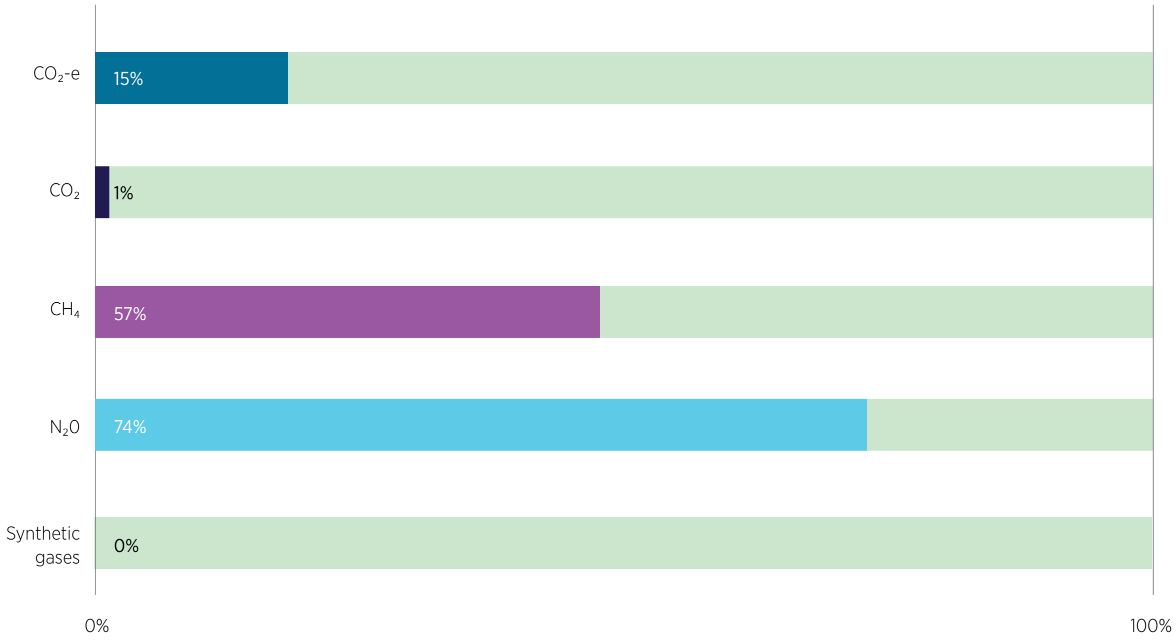
The use of the Netherlands-based factor for ethylene oxide CO_2 emissions will be reviewed for the next submission.

5. Agriculture

5.1 Overview of the sector and background information

The *Agriculture* sector includes emissions from agricultural activities, including livestock and farm management. The sector as a proportion of total emissions (excluding LULUCF) is presented in Figure 5.1.

Figure 5.1 Share of national emissions (excluding LULUCF) for the Agriculture sector by gas, 2021–22



Enteric fermentation was the main source of *Agriculture* emissions, contributing around 71 per cent of the sector's emissions. The next largest source was *agricultural soils,* followed by *manure management. Liming* and *urea application* contribute a small amount of the sector's emissions with *rice cultivation* and *field burning of agricultural residues* contributing the remainder. Changes in emissions by subsector between 2020–21 and 2021–22 are shown in Figure 5.2.

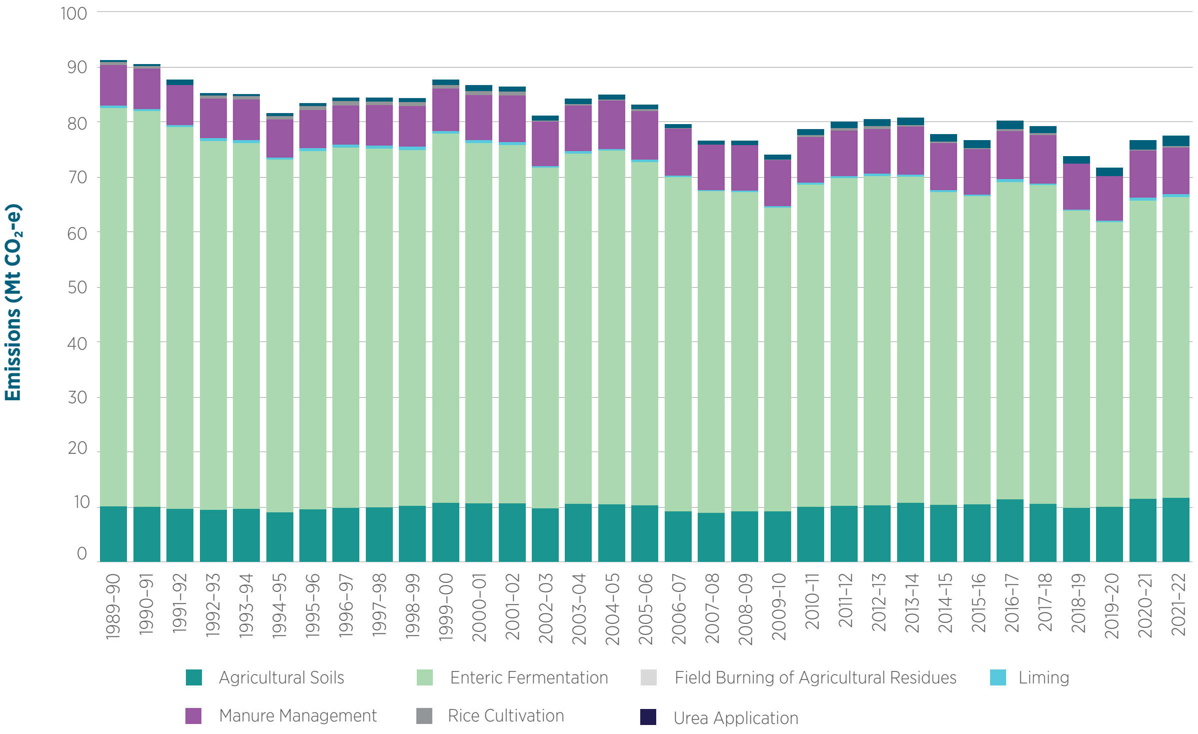
Figure 5.2 Comparison of 2021–22 emissions with past emissions levels from key agriculture subsectors, million tonnes of carbon dioxide equivalent (Mt CO_2-e) and percentage change (%)

		Change in 2021–22 emissions since:		
Agriculture Subsectors	**2021–22 emissions**	**1989–90**	**2004–05**	**2020–21**
3.A Enteric fermentation	**55 Mt**	-18 Mt CO_2-e ▼ -32%	-9.57 Mt CO_2-e ▼ -17%	▲ +1% +0.4 Mt CO_2-e

		Change in 2021–22 emissions since:		
Agriculture Subsectors	**2021–22 emissions**	**1989–90**	**2004–05**	**2020–21**
3.B Manure management	**7 Mt**	▲ +1% +0.1 Mt CO_2-e	-0.51 Mt CO_2-e ▼ -7%	-0.0 Mt CO_2-e ▼ -0%
3.C Rice Cultivation	**0.3 Mt**	-0.2 Mt CO_2-e ▼ -83%	▲ +21% +0.06 Mt CO_2-e	▲ +28% +0.08 Mt CO_2-e
3.D Agricultural Soils	**12 Mt**	▲ +13% +2 Mt CO_2-e	▲ +10% +1.16 Mt CO_2-e	▲ +2% +0.20 Mt CO_2-e
3.E Prescribed burning of savannahs	**IE**	–	–	–
3.E Field Burning of Agricultural Residues	**0.5 Mt**	▲ +11% +0.06 Mt CO_2-e	▲ +30% +0.15 Mt CO_2-e	▲ +6% +0.03 Mt CO_2-e
3.G Liming and 3.H Urea Application	**3.2 Mt**	▲ +82% +2.6 Mt CO_2-e	▲ +39% +1.24 Mt CO_2-e	▲ +4% +0.12 Mt CO_2-e
3.I Other carbon-containing fertilisers and 3.J Other	**NE**	–	–	–

Note: Icons in this figure are sourced from Geotata, adi_sena, Freepik, and Creatype on flaticon.com.

Figure 5.3 CO_2-e emissions from agriculture, by sub-sector, 1990–2022



Livestock industries produce CH_4 and N_2O emissions during feed consumption *(enteric fermentation* (3A)) and from animal waste products *(manure management* (3B)). In Australia, the principal livestock species are cattle and sheep, with breeds chosen for pasture and paddock management systems and, in many cases, in semi-arid or tropical and sub-tropical climatic conditions. As a consequence, typical animal performance tends to vary significantly from those of other Annex I countries. Intensive livestock industries also play an increasing role in Australia, specifically for dairy and beef cattle, poultry and swine.

Enteric fermentation emissions are driven by livestock population numbers, in particular, pasture-raised beef cattle. A decline in emissions in the early 1990s was principally driven by a steep fall in sheep numbers due, in large part, to the collapse of the wool reserve price scheme. The changes in flock and herd numbers reflect changing relative returns to the beef and sheep meat/wool industry and climatic conditions such as drought.

Drought conditions frequently impact Australian livestock numbers, as water availability directly impacts the viability of herds on Australia's rangelands. The national pasture-raised beef cattle herd last peaked in 2012–13 at 25.7 million.

Agricultural soils emissions show gradual upward trend over the long term, which is the result of increasing agricultural fertiliser use and an increase in retention of crop residues. Drought conditions, such as between 2016 and 2019, result in a decrease in crop yields and fertiliser use which explains much of the variation in the time series. These conditions also impact emissions from *manure management.*

Rice cultivation in Australia is highly responsive to water availability. The trend in rice area under cultivation and the resultant emissions can be highly variable from year to year. After a peak in 2001, there has been a sharp decline in rice cultivation as water resources became scarcer. The end of the millennium drought around 2009 saw rice cultivation increase again, although not to the levels observed prior to the onset of the drought.

Periodic increases in CH_4 emissions from rice cultivation observed in more recent years occur as a result of increases in the area of rice cultivation outside of drought periods.

Emissions from *field burning of agricultural residues* show a long-term decrease due to a decline in stubble burning practices in Australia as the practice of stubble retention has become more widespread. Another contributing factor to decreasing emissions is the decline of sugar cane burning as the industry has shifted to green cane harvesting and use of trash blankets.

The *Agriculture* estimates are compiled on a State basis with State emissions totals aggregated into the national account. The inventory is compiled in this way to reduce errors associated with averaging input data across areas with large physical, climatic and management differences.

Australia has a land area of 769 million hectares which covers a wide range of climate zones, soil and vegetation types. These large physical differences lead to significant variability between States in such things as the quality and availability of feed and the performance of animals throughout the year. For example, in northern Australia there are two distinct seasons – wet and dry. During the dry season (winter-spring) the quality and availability of fodder is significantly reduced leading to weight loss in cattle, while in the southern states pasture growth and availability is lower during the colder autumn-winter months. As the climate ranges from tropical to cool, methane conversion factors for manure management systems (MMS) can also vary significantly between the States.

The Australian *Agriculture* methodology consists of both country specific (CS) and IPCC default methodologies and emission factors (EFs) (Table 5.1).

Table 5.1 Summary of methods and emission factors to estimate emissions from Agriculture

Greenhouse Gas Source and Sink Categories Method Applied		**CH_4**		**N_2O**	
		Method Applied	**Emission Factor**	**Method Applied**	**Emission Factor**
A	**Enteric Fermentation**				
1. Cattle	a. Dairy cattle	T3	CS		
	b. Beef cattle – pasture	T3	CS		
	c. Beef cattle – feedlot	T2	CS		
2. Sheep		T3	CS		
3. Swine		T2	CS		
4. Other	a. Poultry (a)	NE	NE		
	b. Alpacas, buffalo, deer, goats, horses, camels, mules/asses, ostriches and emus	T1	D		
B	**Manure management**				
1. Cattle	a. Dairy cattle	T2	CS	T2	CS
	b. Beef cattle – pasture	T2	CS	NA	NA
	c. Beef cattle – feedlot	T3	CS	T3	CS
2. Sheep		T2	CS	NA	NA
3. Swine		T3	CS	T3	CS
4. Other	a. Poultry	T3	D,CS	T3	CS
	b. Alpacas, buffalo, deer, goats, horses, camels, mules/asses, ostriches and emus	T2	D,CS	NA	NA
5. Indirect emissions				T2	D,CS
C	**Rice cultivation**	T1	D		

Greenhouse Gas Source and Sink Categories Method Applied		**CH_4**		**N_2O**	
		Method Applied	**Emission Factor**	**Method Applied**	**Emission Factor**
D	**Agricultural soils**				
1. Direct emissions	a. Inorganic fertilisers			T2	CS
	b. Animal wastes applied to soils			T2	D,CS
	c. Sewage sludge applied to land			T2	CS
	d. Other organic fertilisers (b)			NE	NE
	e. Urine and dung deposited by grazing animals			T2	CS
	f. Crop residues			T2	CS
	g. Mineralisation due to loss of soil C			T2	CS
	h. Cultivation of histosols			T1	D
2. Indirect emissions	a. Atmospheric deposition			T1	CS
	b. Leaching and run-off			T2	CS
E	**Prescribed burning of savannas**	IE	IE	IE	IE
F	**Field burning of agricultural residues**	T2	CS	T2	CS
		CO_2			
G	**Liming**	T2	CS		
H	**Urea application**	T1	D		
I	**Other carbon-containing fertilisers (a)**	NE	NE		

(a) Not estimated as IPCC (IPCC 2006) provides no methods or EF for this source.

(b) Not estimated as the source is considered insignificant (<0.05 per cent of national total) and data is difficult to collect (see Annex 5).

CS = country specific, D = IPCC defaults, T1 = tier 1, T2 = tier 2, T3 = tier 3, NE = not estimated, NA = not applicable, IE = included elsewhere.

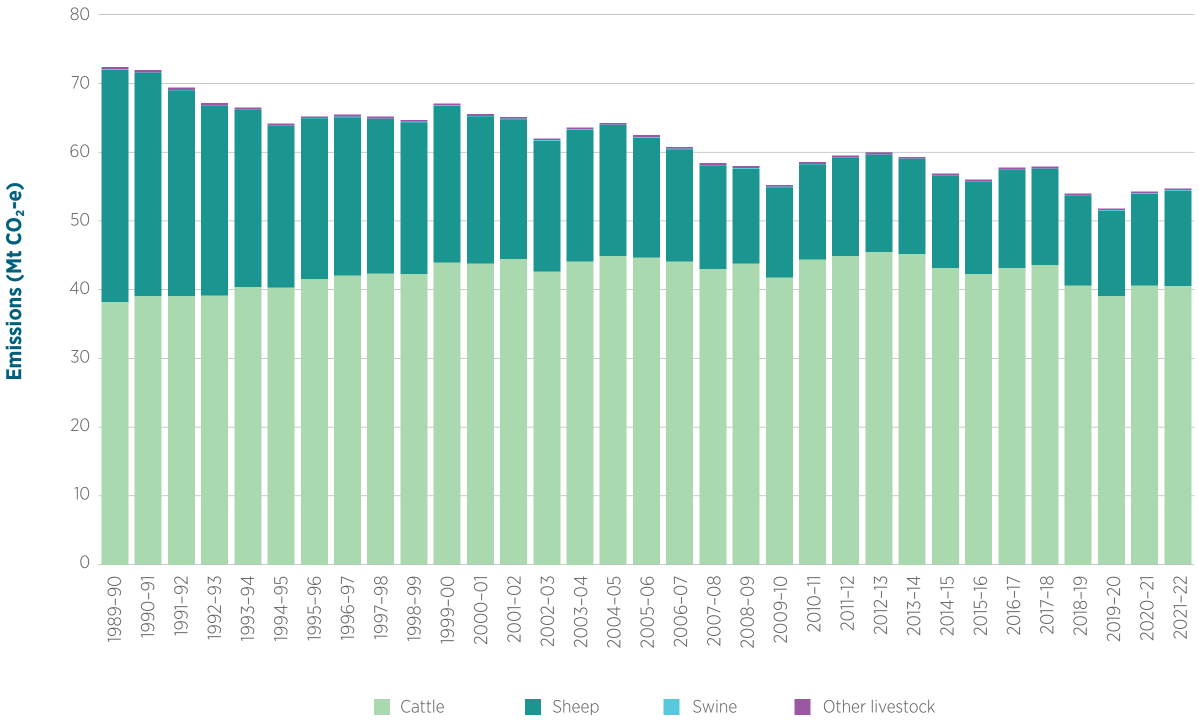
▨ = Key category

5.2 **Enteric Fermentation** (CRT category 3.A)

5.2.1 Category description

Methane is produced by herbivores as a by-product of enteric fermentation, a digestive process by which plant material consumed by an animal is broken down by bacteria in the gut under anaerobic conditions. A portion of the plant material is fermented in the rumen to simple fatty acids, CO_2 and CH_4. The fatty acids are absorbed into the bloodstream, and the gases vented by eructation and exhalation by the animal. Unfermented feed and microbial cells pass to the intestines.

Figure 5.4 Enteric Fermentation emissions by livestock category, Australia, Mt CO_2-e



5.2.2 Methodological issues

For activity data, the inventory relies upon the following data sources for livestock numbers:

- ABS Agricultural Commodities (ABS 2021-22) (annual);
- Australian Lot Feeders Association (ALFA 2022)(quarterly);
- ABS meat chicken production (ABS 2022) & slaughter statistics (ABS 2022)(annual);
- Meat & Livestock Australia farm survey data (ABARES 2022)(annual)

This is supported by the following other sources of production statistics:

- Dairy Australia (annual);
- ABARES Agricultural Commodities (ABARES 1999-2022)(quarterly);
- Australian Wool Testing Authority (AWTA 2022)(monthly)

These data sources allow for enhanced livestock characterisation for cattle, sheep, poultry and swine, and therefore allow the use of IPCC tier 2 methods. For dairy cattle, beef cattle on pasture, sheep and swine, country-specific information is available for emissions factor estimation.

Dairy Cattle (3.A.1.a)

Emissions from dairy and pasture fed beef cattle are estimated based on Charmley et al. (2015) who reported a close relationship between dry matter intake and methane production. The relationship of Charmley et al. (2015) was derived from an analysis of Australian respiration chamber data of dairy and beef (southern and northern) cattle fed diets of >70 per cent forage.

A country-specific method (Minson and McDonald 1987) based on research in Australia is used to estimate intake. Minson and McDonald (1987) derived an equation that estimates feed intake relative to liveweight and liveweight gain of cattle.

The large volumes of milk produced by dairy cattle under modern management regimes requires that the lactating cow consumes considerably more feed than an equivalent non-lactating cow. The increased energy requirements needed to produce this milk is estimated based on the average milk production per head of milking cows (Table A5.5.1.10) and the relationships presented by the Standing Committee on Agriculture (SCA 1990).

Table 5.2 Symbols used in algorithms for dairy cattle

State (i)	Dairy cattle classes (age) (j)
1 = ACT	1 = Milking cows [(a)]
2 = Northern Territory	2 = Heifers > 1 year
3 = NSW	3 = Heifers < 1 year
4 = Queensland	4 = Bulls > 1 year
5 = Tasmania	5 = Bulls < 1 year
6 = South Australia	
7 = Victoria	
8 = Western Australia	

(a) Includes cows used for milk production but not currently lactating.

The equation presented in Minson and McDonald (1987) calculates feed intake of non-lactating cattle from liveweight and liveweight gain data. For lactating cattle the additional intake for milk production (MI_{ij}) is included to give total intake (I_{ij} kg dry matter/head/day):

$$I_{ij} = (1.185 + 0.00454W_{ij} - 0.0000026W_{ij}^2 + 0.315LWG_{ij})^2 \times MR_{lij} + MI_{ij} \quad \text{(3.A.1a\_1)}$$

Where W_{ij} = liveweight (kg) (Table A5.5.1.1)

LWG_{ij} = liveweight gain (kg/day) (Table A5.5.1.2)

MR_l = increase in metabolic rate when producing milk (SCA 1990)

= 1.1 for milking and house cows and 1 for all other classes

The additional intake required for milk production (MI_{ij} kg DM/head/day) is calculated by:

$$MI_{ij} = MP_{ij} \times NE \div k_l / q_{m,\,ij} /18.4 \quad \text{(3.A.1a\_2)}$$

Where MP_{ij} = milk production (kg/head/day) from Dairy Australia State[7] statistics

NE = 3.054 MJ net energy/kg milk (SCA 1990)

k_l = 0.60 efficiency of use of metabolizable energy for milk production (SCA 1990)

$q_{m,\,ij}$ = metabolizability of the diet. This is the ratio of metabolizable energy (ME) to gross energy (GE) in the diet (i.e. ME / GE). Metabolizable energy content is related to digestibility of dry matter (DMD_{ij}). So using the equation of Minson and McDonald (1987), $q_{m\,ij}$ = 0.00795 DMD – 0.0014; (where DMD is expressed as a per cent)

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[7] Litres of milk is multiplied by 1.03 to convert to kg of milk.

The total daily production of methane (M_{ij} kg CH_4/head/day) is given by Charmley et al. (2015) as:

$$M_{ij} = 20.7 \times I_{ij} / 1000 \qquad (3.A.1a\_3)$$

Dairy calves are generally fully weaned to pasture at 12 weeks. Until this time, calves will primarily consume milk or milk replacer, pellets and hay which results in lower emissions. The daily CH_4 production for pre-weaned dairy calves ($MPW_{ENTERIC}$) is given in Table A5.5.1.5. Annual Australian methane production (Gg) for all classes of dairy cattle across all states can then be calculated as:

$$E = \Sigma_i \Sigma_j ((N_{ij=1,2,4} \times M_{ij=1,2,4} \times 365) + (N_{ij=3,5} \times M_{ij=3,5} \times 281) + (N_{ij=3,5} \times MPW_{ENTERIC\ ij=3,5} \times 84)) \times 10^{-6} \qquad (3.A.1a\_4)$$

Where N_{ij} = numbers of dairy cattle in each class for each State and season

M_{ij} = methane production (kg/head/day)

$MPW_{ENTERIC\ ij}$ = methane production for pre-weaned calves (kg/head/day)

Beef Cattle o n pastures (3.A.1.b)

Table 5.3 Symbols used in algorithms for beef cattle on pasture

State (i)	Regions (j)	Season (k)	Beef Cattle Classes (l)	Beef Cattle Subclass (n) [(a)]
1 = ACT		1 = Spring	1 = Bulls < 1 year	1 = Bulls < 1 year
2 = Northern Territory	2a = Alice Springs	2 = Summer	2 = Bulls > 1 year	2 = Bulls > 1 year
	2b = Barkly	3 = Autumn	3 = Cows < 1 year	3 = Cows < 1 year
	2c = Northern	4 = Winter	4 = Cows 1-2 years	4 = Cows 1-2 years
3 = NSW			5 = Cows > 2 years	5a = Cows 2-3 years
4 = Queensland	4a = High		6 = Steers < 1 year	5b = Cows > 3 years
	4b = High/moderate		7 = Steers > 1 year	6 = Steers < 1 year
	4c = Moderate/low			7a = Steers 1-2 years
	4d = Low			7b = Steers 2-3 years
5 = Tasmania				7c = Steers >3 years
6 = South Australia				
7 = Victoria				
8 = Western Australia	8a = South West			
	8b = Pilbara			
	8c = Kimberley			

(a) Beef cattle subclasses (n) only apply to NT and QLD cattle.

The equation presented by Minson and McDonald (1987) calculates feed intake (I kg dry matter/head/day) from liveweight and liveweight gain:

$$I_{ijkln} = (1.185 + 0.00454 W_{ijkln} - 0.0000026\, W_{ijkln}{}^2 + 0.315\, LWG_{ijkln})^2 \times MA_{ijkl=5} \qquad (3.A.1b\_1)$$

Where W_{ijkln} = liveweight in kg (Table A5.5.2.1)

LWG_{ijkln} = live weight gain in kg/head/day (Table A5.5.2.2)

Feed intakes can increase by up to 60 per cent during lactation (ARC 1980) For this study, the intake of all breeding cattle was increased by 30 per cent during the season in which calving occurs and by 10 per cent in the following season, based on relationships presented in (SCA 1990).

The additional intake for milk production ($MA_{i|kl=5}$) is calculated by:

$$MA_{ijkl=5} = (LC_{ijkl=5} \times FA_{ijkl=5}) + ((1-LC_{ijkl=5}) \times 1 \qquad (3.A.1b\_2)$$

Where $LC_{ijkl=5}$ = proportion of Cows >2 lactating

$FA_{ijkl=5}$ = feed adjustment (Table A5.5.2.5)

The total daily production of methane (M_{ijkl} kg CH_4/head/day) is given by Charmley et al. (2015) as:

$$M_{ijkl} = 20.7 \times I_{ijkln} \div 1000 \qquad (3.A.1b\_3)$$

To calculate emissions from beef cattle on pasture it is necessary to first subtract feedlot cattle numbers from the total beef cattle numbers to ensure that feedlot cattle are not double counted. As feedlot cattle spend on average between 70-250 days in feedlots prior to slaughtering, an annual equivalent number is derived using an approach consistent with equation 10.1 in the 2006 IPCC Guidelines (IPCC 2006), and subtracted from beef cattle numbers.

Feedlot cattle are assumed to originate entirely from the steers > 1 year old beef cattle class. Emissions from feedlot cattle are calculated in Section 5.3.2.3.

The approach is represented in the following equation:

$$N_{ijkl} = N_{ijk(\ l=1,\ l=2,\ l=3,\ l=6,\ [(l=7)\ -\ \text{total feedlot numbers}])} \qquad (3.A.1b\_4)$$

Where N_{ijkl} = numbers of non-feedlot beef cattle in each State, region, season and class

$N_{ijk(\ l=1,\ l=2,\ l=3,\ l=6)}$ = number of cattle in State i, region j, season k and class l

$N_{ijk\ (l=7)\ -\ \text{total feedlot numbers}}$ = from Table 5.3, l=7 corresponds with steers >1 year old. In order to calculate total beef cattle numbers in this class, total annual equivalent feedlot numbers must be subtracted from l =7. For WA 99 per cent of feedlot cattle are assumed to be sourced from the South-West region and the balance from the Pilbara and Kimberley.

Annual Australian methane production (Gg) for all classes of beef cattle across all seasons can then be calculated as:

$$E = \Sigma_i\Sigma_j\Sigma_k\Sigma_l\Sigma_n\ (91.25 \times N_{ijkln} \times M_{ijkln}) \times 10^{-6}. \qquad (3.A.1b\_5)$$

Where N_{ijkln} = numbers of beef cattle in each State, region, season and class (head)

M_{ijkln} = methane production (kg/head/day)

91.25 = number of days in each season

Beef cattle in feedlots (3.A.1.c)

Emissions from lot-fed beef cattle are estimated based on Moe and Tyrrell (1979), who related methane production to the intake of three components of the dietary carbohydrate – soluble residue, hemicellulose and cellulose. The relationship was derived from dairy cattle fed diets consisting mostly of high digestibility grains and concentrates, and high quality forages which are consistent with what feedlot cattle in Australia are typically fed.

The simplified tier 2 method from the 2006 IPCC guidelines (IPCC 2006) for estimating intake from growing and finishing cattle is used for feedlot cattle as it has been found to perform well against known feed intake values from commercial feedlots.

Table 5.4 Symbols used in algorithms for feedlot cattle

State (i)	Feedlot cattle classes (duration of stay) (j)
1 = ACT	1 = Domestic (70-80 days)
2 = Northern Territory	2 = Export mid-fed (80-200 days)
3 = NSW	3 = Export long-fed (200+ days)
4 = Queensland	
5 = Tasmania	
6 = South Australia	
7 = Victoria	
8 = Western Australia	

Feed intake (I_j kg dry matter/head/day) of feedlot cattle is estimated using the (IPCC 2006) simplified tier 2 method.

$$I_j = W_j^{0.75} [(0.2444 \times NE_{ma,j} - 0.0111 \times NE_{ma,j}^{\ 2} - 0.472) \div NE_{ma,j}] \quad (3.A.1c\_1)$$

Where W_j = liveweight (kg) (Table A5.5.3.1)
$NE_{ma,j}$ = Dietary net energy concentration (MJ/kg) (Table A5.5.3.2)

The equation developed by Moe and Tyrrell (1979) to predict daily methane yields (Y_j MJ CH_4/head/day) is:

$$Y_j = 3.406 + 0.510SR_j + 1.736H_j + 2.648C_j \quad (3.A.1c\_2)$$

Where SR_j = intake of soluble residue (kg/day)
H_j = intake of hemicellulose (kg/day)
C_j = intake of cellulose (kg/day)
SR_j H_j and C_j are calculated from the total feed intake of the animal and the proportion of intake that is soluble residue, hemicellulose and cellulose, for each animal class (Table A5.5.3.2).

The total daily production of methane (M_j kg CH_4/head/day) is thus:

$$M_j = Y_j \div F \quad (3.A.1c\_3)$$

Where F = 55.22 MJ/kg CH_4 (Brouwer 1965)

Methane production (Gg) for all classes of feedlot cattle across all States can then be calculated as:

$$E = \Sigma_i\Sigma_j(365 \times N_{ij} \times M_j) \times 10^{-6} \quad (3.A.1c\_4)$$

Where N_{ij} = numbers of feedlot cattle as an annual equivalent in each class in each State
M_j = methane production (kg/head/day)

Sheep (3.A.2)

Emissions from sheep are estimated based on Howden et al. (1994) who reported a close relationship between dry matter intake and methane production, based on an analysis of Australian respiration chamber experiments (Margan et al. (1985), (1987), (1988) and Graham (1964), (1964), (1967), (1969). Howden et al. (1994) found that feed intake alone explained 87 per cent of the variation in methane production.

The Agriculture and Food Research Council (AFRC 1990) equation for intake is used here, as it corresponded well with intakes reported by State experts for seasonal feed digestibilities common in their State. The CS approach to estimating feed intake for sheep implicitly takes account of all net energy requirements for activities such as wool production, growth and grazing over large areas.

Table 5.5 Symbols used in algorithms for sheep

State (i)	Season (j)	Sheep classes (k)
1 = ACT	1 = Spring	1 = Rams
2 = Northern Territory	2 = Summer	2 = Wethers
3 = NSW	3 = Autumn	3 = Maiden ewes (intended for breeding)
4 = Queensland	4 = Winter	4 = Breeding ewes
5 = Tasmania		5 = Other ewes
6 = South Australia		6 = Lambs and hoggets
7= Victoria		
8= Western Australia		

Potential intake is determined largely by body size and the proportion of the diet that is able to be metabolised by the animal. Potential intake (PI kg DM/head/day) is given by AFRC (1990) as:

$$PI_{ijk} = (104.7\, q_{m,ijk} + 0.307\, W_{ijk} - 15.0)\, W_{ijk}^{0.75} \div 1000 \quad (3.A.2\_1)$$

Where W_{ijk} = liveweight (kg) (Table A5.5.4.1)

$q_{m,ijk}$ = metabolizability of the diet. This is the ratio of metabolizable energy (ME) to gross energy (GE) in the diet (i.e. ME / GE). Metabolizable energy content is related to digestibility of dry matter (DMD_{ijk}) so, using the equation of Minson and McDonald (1987), $_{qm,\ ijk}$ = 0.00795 DMD – 0.0014 (DMD is expressed as a per cent)

The potential or maximum intake of feed by sheep occurs when feed is abundant and of high quality. However, the actual feed intake of animals is often less than the potential intake. This can be caused by many factors, including through low feed availability. Relative intake is defined as the proportion of potential intake that the animal will consume. The relative intake (RI_{ijk}) related to feed availability is given by White et al. (1983) as:

$$RI_{ijk} = 1 - \exp(-2(DMA_{ijk})^2) \quad (3.A.2\_2)$$

Where DMA_{ijk} = dry matter availability (t/ha) (Table A5.5.4.3)

Note: Actual feed intake will be less than potential intake only when feed availability is less than 1.63 tonnes/hectare. The actual intake (I_{ijk} kg DM/head/day) of a sheep is thus:

$$I_{ijk} = PI_{ijk} \times RI_{ijk} \times MA_{ijk=4} \quad (3.A.2\_3)$$

Where MA_{ijk}=4 = additional intake for milk production (dimensionless factor)

Feed intakes can increase by up to 60 per cent during lactation (ARC 1980). For emissions estimates, the intake of all breeding ewes was assumed to increase by 30 per cent during the season in which lambing occurs, based on relationships presented in (SCA 1990).

The additional intake for milk production ($MA_{ijk=4}$) is calculated by:

$$MA_{ijk=4} = (LE_{ijk=4} \times FA_{ijk=4}) + ((1 - LE_{ijk=4}) \times 1) \quad (3.A.2\_4)$$

Where LE_{ijk}=4 = proportion of breeding ewes lactating, calculated as the annual lambing rates x proportion of lambs receiving milk in each season (Table A5.5.4.6)

FA_{ijk}=4 = feed adjustment (assumed to be 1.3)

Methane production (M_{ijk} kg/head/day) is calculated using daily intake figures (I_{ijk}) via the relationship of Howden et al. (1994):

$$M_{ijk} = I_{ijk} \times 0.0188 + 0.00158 \qquad (3.A.2\_5)$$

Annual methane production (Gg) of Australian sheep is calculated as:

$$E = \Sigma_i \Sigma_j \Sigma_k (91.25 \times N_{ijk} \times M_{ijk}) \times 10^{-6} \qquad (3.A.2\_6)$$

Where N_{ijk} = numbers of sheep in each class for each season and state
M_{ijk} = methane production (kg/head/day)

Swine (3.A.3)

Swine are non-ruminant animals and convert a smaller proportion of feed energy intake into methane than ruminants. Whittemore (1993) suggested the output of methane by a 60 kg swine is about 0.2 MJ/day.

Assuming that on average, a 60 kg swine consumes 1.95 kg DM/day of a diet containing 18.6 MJ GE/kg, the gross energy (GE) intake was 36.3 MJ GE. Thus swine would convert around 0.6 per cent of gross energy into methane. Other values in the literature suggest methane conversions of 1.2 per cent of GE (Christensen 1987) , 0.6 to 0.8 per cent of GE (Moss 1993) and 0.4 per cent of GE (Kirchgessner 1991). A methane conversion of 0.7 per cent of GE intake is used for Australia.

Table 5.6 Symbols used in algorithms for swine

State (i)	Swine classes (j)
1 = ACT	1 = Boars
2 = Northern Territory	2 = Sows
3 = NSW	3 = Gilts
4 = Queensland	4 = Others
5 = Tasmania	
6 = South Australia	
7 = Victoria	
8 = Western Australia	

The relationship for enteric fermentation in swine gives the total daily production of methane (M_{ij} kg CH_4/head/day) as:

$$M_{ij} = I_{ij} \times 18.6 \times 0.007 \div F \qquad (3.A.3\_1)$$

Where I_{ij} = feed intake (kg DM/day) (Table A5.5.5.2)
F = 55.22 MJ/kg CH_4 (Brouwer 1965)
18.6 = MJ GE/kg feed DM

The annual production of methane (Gg) for all classes of swine is calculated as:

$$E = \Sigma_i \Sigma_j (N_{ij} \times M_{ij} \times 365) \times 10^{-6}. \qquad (3.A.3\_2)$$

Where N_{ij} = the number of swine in each class for each State
M_{ij} = methane production (kg/head/day)

Other livestock (3.A.4)

The contribution of other livestock to total methane production is comparatively small. A simplified tier 1 method is followed, using aggregated numbers of the various livestock types and an annual methane emissions factor. The annual EFs are mostly based on (IPCC 2006) defaults (Table 5.8).

The methane EFs for buffalo and emus/ostriches follow the (IPCC 2019), which is based on the latest internationally- assessed science. The Asian buffalo factor was adopted as most buffalo in Australia originated from Asia and are found in the Northern Territory, which experiences similar monsoonal climates to parts of Asia.

There is limited activity data for the livestock categories horses, camels, buffalo, deer, goat, mules and asses, alpacas, and emus and ostriches. As such, population data is only updated every five years, when more detailed census data is provided to the ABS.

Table 5.7 Symbols used in algorithms for other livestock

State (i)	Other livestock types (j)	Digestive type
1 = ACT	1 = Buffalo	ruminant
2 = Northern Territory	2 = Goats	ruminant
3 = NSW	3 = Deer	ruminant
4 = Queensland	4 = Camels	quasi-ruminant
5 = Tasmania	5 = Alpacas	quasi-ruminant
6 = South Australia	6 = Horses	non-ruminant (equine)
7 = Victoria	7 = Mules/asses	non-ruminant (equine)
8 = Western Australia	8 = Emus/ostriches	non-ruminant
	9 = Poultry	non-ruminant

By applying the EF to the number of each species in each State, total methane production (Gg) from the enteric fermentation of minor livestock types can be calculated as follows:

$$E = \Sigma_i(N_{ij} \times M_j \times 10^{-6}) \qquad (3.A.4\_1)$$

Where N_{ij} = numbers of other livestock types in each State

M_j = methane EF (kg/head/year) (Table 5.8)

Table 5.8 Other livestock – enteric fermentation EFs (kg CH_4/head/year)

Livestock type	EF	Source
Buffalo	76	IPCC (2019)
Goats	5	IPCC (2006)
Deer	20	IPCC (2006)
Camels	46	IPCC (2006)
Alpacas	8	IPCC (2006)
Horses	18	IPCC (2006)
Mules/asses	10	IPCC (2006)
Emus/ostriches	5	IPCC (2019)
Poultry	NE	not estimated by IPCC

5.2.3 Uncertainty assessment and time-series consistency

A quantitative assessment of uncertainty was undertaken and uncertainties for enteric fermentation were estimated to be in the order of 25 per cent. Further details on the analysis are provided in Annex 2.

Time series consistency is ensured by using consistent methods and full recalculations in the event of any refinement to methodology.

5.2.4 Category-specific QA/QC and verification

The Australian Bureau of Statistics (ABS) is the national statistical agency of Australia and is the key provider of activity data for this source category. The ABS has in place a range of quality assurance-quality control procedures associated with survey design, data input and consistency checks on the survey results and the aggregated values. Sampling errors are also evaluated. A reduced set of agricultural area and production statistics is available for the 2021–22 ABS Agricultural Commodities report. This is due to lower quality responses to the Rural Environment and Agricultural Commodities Survey, the main data input to this publication. In some cases, this meant that for this inventory year State and Territory data were estimated using previous results scaled by national-level changes.

These survey issues are being addressed by the ABS agricultural statistics modernisation program. Due to the increasing availability of other quality data, a commitment to reducing reporting burden and declining survey response rates, it is necessary to change the way in which Australia's official agricultural statistics are produced. This need to modernise the production of agricultural statistics is not unique to Australia and around the world other statistical agencies are making similar changes. The production of the National Greenhouse Accounts is engaged with the ABS throughout this modernisation, to ensure continuity of activity data for the *Agriculture* sector.

The ABS reports agricultural data to the United Nations Food and Agriculture Organization (FAO) annually. Some divergence occurs between the activity data in the inventory CRT tables and those published by the FAO. The reasons for these differences include recalculations made by the ABS for time series consistency, adjustments made to ensure feedlot cattle and chicken numbers are expressed in terms of annual-equivalent populations.

Changes in the trends of activity data are also monitored in the inventory, to ensure the drivers of change can be explained by factors such as economic or climatic variability.

Implied EFs

As tier 3 methods are used to estimate emissions from cattle, sheep and swine, the IEFs have been compared with values in the 2006 IPCC Guidelines (IPCC 2006) and the 2019 Refinement (IPCC 2019)(Table 5.9). The IEFs for pasture-based beef cattle and swine are generally consistent with the IPCC values.

The dairy cattle IEF is similar to the 2019 IPCC Refinement (IPCC 2019) value for Oceania (93 kg CH_4/head/year). Differences with IPCC EFs are due to the use of a more detailed age and animal class structure for Australia's dairy and beef cattle herds. The feedlot cattle IEF differs due to country-specific feed intakes.

The lower IEFs for sheep primarily reflect the inclusion of an age structure in the Australian method, and the use of actual intake as a proportion of potential intake to incorporate the likelihood of low feed quality and/or availability, which impacts upon the methane conversion rate.

Table 5.9 Implied EFs – enteric fermentation (kg CH_4/head/year)

Livestock type	Australia	IPCC2006	IPCC 2019
Dairy cattle	95.09	90	93
Beef cattle – pasture	50.3	60	63
Beef cattle – feedlot	68.76	60	63
Sheep	6.69	8	5 or 9
Swine	1.57	1.5	1 or 1.5

Sources: (IPCC 2006) and (IPCC 2019). EFs shown are for developed countries and/or Oceania. IPCC 2019 EFs for sheep and swine vary due to disaggregation by low or high productivity systems.

Feed intake

As Australia uses tier 3 methods for estimating feed intakes, these values have been compared with average intakes reported by other Parties.

Cattle

For dairy cattle, average herd feed intakes are within the range reported by other Parties (Table 5.10). The intakes of Australian dairy cattle are in the order of 1-3 per cent of live weight (range from 1.5 to 3.16 per cent) as recommended by the IPCC (2006).

Comparison of intakes for beef cattle between Parties is complicated as animals kept under feedlot conditions have not been reported separately from pasture-based animals, as is undertaken in the Australian inventory. The average herd intake for pasture-based animals is within the range reported by other Parties, while that for lot-fed animals is higher (Table 5.10).

Intake estimates for feedlot cattle have been based on the IPCC feed intake model, which was verified by comparison with industry practices. Intakes range from 2-2.1 per cent of live weights. Gross energy intake (GEI) for feedlot cattle was predicted using a diet GE of 19.2 MJ/kg DM based on the proportions of carbohydrate, protein and fat.

Table 5.10 Average herd intake (MJ GEI/head/day)

	Australia		Other Parties	
Livestock type	Range	Mean	Range	Mean
Dairy cows (dairy herd)	206-249	231	192-404	311
Non-dairy cattle			112-194	139
Beef cattle – pasture	116-136	124		
Beef cattle – feedlot (T2)	200	200		
Sheep	13-20	17	14-51	23

Source: Other Parties' herd intake from UNFCCC locator tool

Sheep

The CS method used to estimate intake from Australian sheep produces lower average intakes than those reported by other Parties (Table 5.10). However, an analysis of intake as percentage of liveweight shows that intakes are in the order of 1-3 per cent (range from 1.0 to 2.7 per cent) as recommended by the 2006 IPCC Guidelines (IPCC 2006).

In Australia, actual feed intake is often less than potential intake due to low feed availability on pastures. The Australian method calculates the proportion of the potential intake that the animal will actually consume (potential intake is restricted when feed availability is less than 1.63 tonnes/hectare). Restricted feed conditions generally occur in one or more seasons in all States, with animals experiencing weight loss over the season. When intakes are not limited, estimated intakes (average 20 MJ/day) are similar to levels reported by other Parties.

Methane conversion rates

As Australia uses tier 3 methods for estimating methane emissions, methane conversion rates (Y_m) have been compared against IPCC values.

Cattle

The 2006 IPCC Guidelines (IPCC 2006) indicate that animals fed diets containing 90 per cent concentrates should use a Y_m of 3.0 per cent. The Australian methodology for feedlot cattle accounts for the different proportion of grain and forage in diets, which are lower than the 90 per cent concentrates. This results in estimated conversion rates of 4.9-5.2 per cent or an average of 183 g CH_4/head/day. Kurihara et al. (1999), corrected by Hunter (2007) found similar conversion rates (5.6 per cent) for cattle fed on high grain (75 per cent) plus lucerne diets, measured using calorimetry chambers. Open path laser measurements of methane (enteric and manure) from Australian feedlots by McGinn et al. (2008) and Loh et al. (2008) have estimated enteric fermentation emissions of 161 g/head/day.

The conversion rates for dairy and beef cattle on pastures (6.1-6.2 per cent) are also consistent with 2019 IPCC Refinement (IPCC 2019) values (Dairy cattle: 5.7-6.5 per cent, beef cattle on pasture: 6.3-7.0 per cent).

Sheep

The methodology for estimating emissions from sheep has been independently verified. Leuning et al. (1999) found close agreement between the methane emissions estimated by the inventory methods and direct field measurements made using micrometeorological mass-balance and SF_6 tracer techniques. Using the inventory methods and default livestock characterisation, Leuning et al. (1999) estimated CH_4 emissions to be 12.6 g/head/day compared with 11.9 (±1.5) and 11.7 (±0.4) g/head/day measured by the mass-balance and SF_6 tracer techniques respectively. When the experimental livestock characterisation was used with inventory methods, CH_4 emissions were estimated to be 11.1 g/head/day.

In addition, an analysis of Australian respiration chamber experiments by Williams and Wright (2005) showed a very similar relationship between methane output and dry matter intake ($CH_4 = 0.0187 * DMI – 0.0003$) to that reported in Howden et al. (1994) ($CH_4 = 0.0188 * DMI + 0.00158$).

The herd average Y_m for Australian sheep is 6.2 per cent which is within the range of the (IPCC 2019) value (6.7 per cent).

External Review

Comprehensive expert peer review of the methodologies, activity data and livestock characterisation data were conducted for sheep in 2000–01; dairy and feedlot cattle, swine and poultry in 2014; and QLD/NT beef cattle on pastures in 2015 (Bray, et al. 2015). These reviews involved agricultural experts from industry, government and academia.

5.2.5 Category-specific recalculations

A recalculation to the 2021 emissions estimate was made, updating the statistics for the number of lactating cows. This affects the calculation of feed intake, and hence the estimate of enteric fermentation. This recalculation is presented in Table 5.11.

Table 5.11 Enteric fermentation (3.A): recalculations of total CO_2-e emissions, 1989–90 to 2020–21

	2023 submission	2024 submission	Change		Reasons for Recalculation ($Gg CO_2$-e)
Year	($Gg CO_2$-e)		($Gg CO_2$- e)	(Per cent)	A
1989-90	72,389	72,389	-	0%	-
1994-95	64,110	64,110	-	0%	-
1999-00	67,094	67,094	-	0%	-
2004-05	64,251	64,251	-	0%	-
2009-10	55,261	55,261	-	0%	-
2014-15	56,896	56,896	-	0%	-
2019-20	51,796	51,796	-	0%	-
2020-21	54,260	54,277	17	0.03%	17

5.2.6 Category-specific planned improvements

For enteric fermentation the following areas have been identified for review and/or change:

1. *Feedlot Cattle methods and parameters* – review methods, parameters and activity data used to estimate emissions from feedlot cattle in consultation with industry.
2. *Sheep methods and parameters* – review methods and parameters used to estimate enteric fermentation emissions from sheep using recent published data.
3. *Feed and animal characteristics* – As these characteristics can change as industry practices change over time, the current values need to be reviewed periodically.
4. *Modernisation of ABS Agricultural Statistics* – as described in section 5.2.4, the department is consulting with the Australian Bureau of Statistics as they modernise the production of agricultural statistics. This may entail changes to the age class information and spatial location of the national herd, including time-series recalculations.

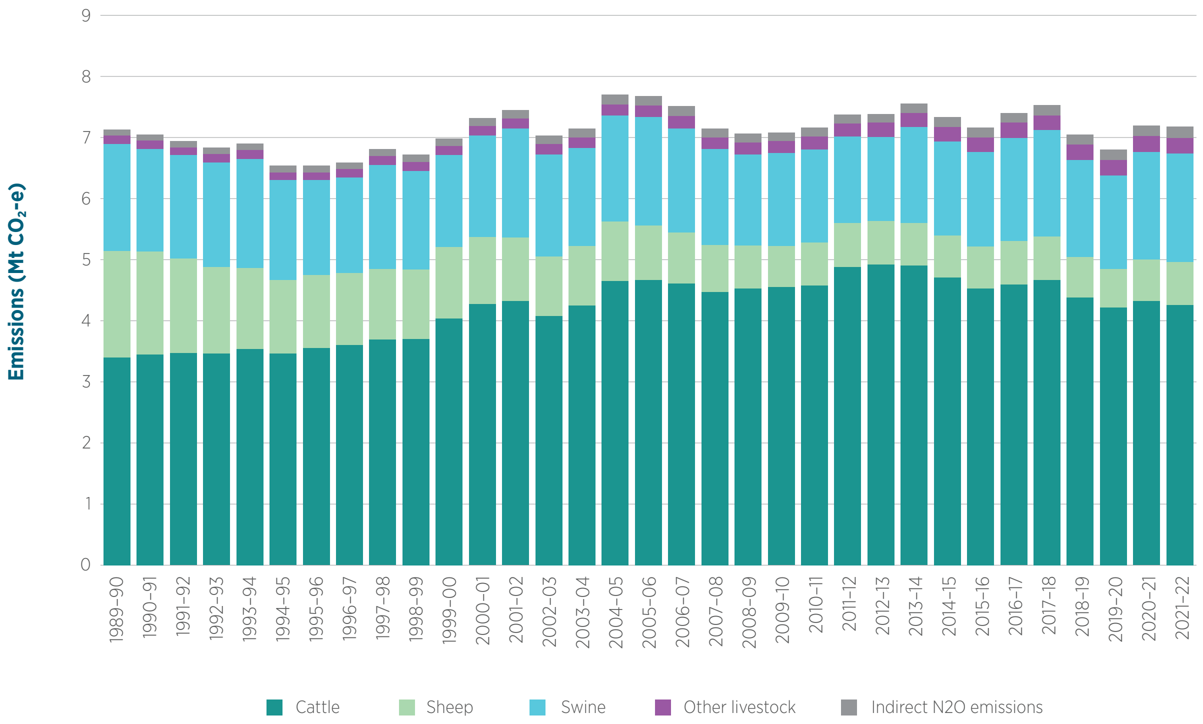
5.3 **Manure Management** (CRT category 3.B)

5.3.1 Category description

Methane is produced from the decomposition of organic matter remaining in manure under anaerobic conditions. These conditions occur when large numbers of animals are managed in a confined area, where manure is typically stored in large piles or lagoons.

Direct N_2O emissions from manure management systems (MMS) can occur via combined nitrification and denitrification of ammoniacal nitrogen contained in the wastes. The amount released depends on the systems and duration of waste management. Indirect N_2O emissions occur via runoff and leaching, and the atmospheric deposition of N volatilised from the MMS.

Figure 5.5 Manure management emissions by source, Australia, Mt CO_2-e



5.3.2 Methodological issues

As manure from intensive livestock industries may pass through multiple treatment stages, Australia applies a tier 3 mass flow approach to estimating emissions whereby the volatile solid and nitrogen inputs and losses are estimated at each treatment state. Inputs into the secondary treatment stage take into account losses from the primary stage (see Figure 5.6).

Activity data is the same as used for enteric fermentation. Subscripts for the algorithms are the same as used for calculating enteric fermentation (Table 5.2 to Table 5.7) with an additional MMS component (Table 5.12).

Figure 5.6 Mass flow method of estimating manure management emissions – feedlot cattle example

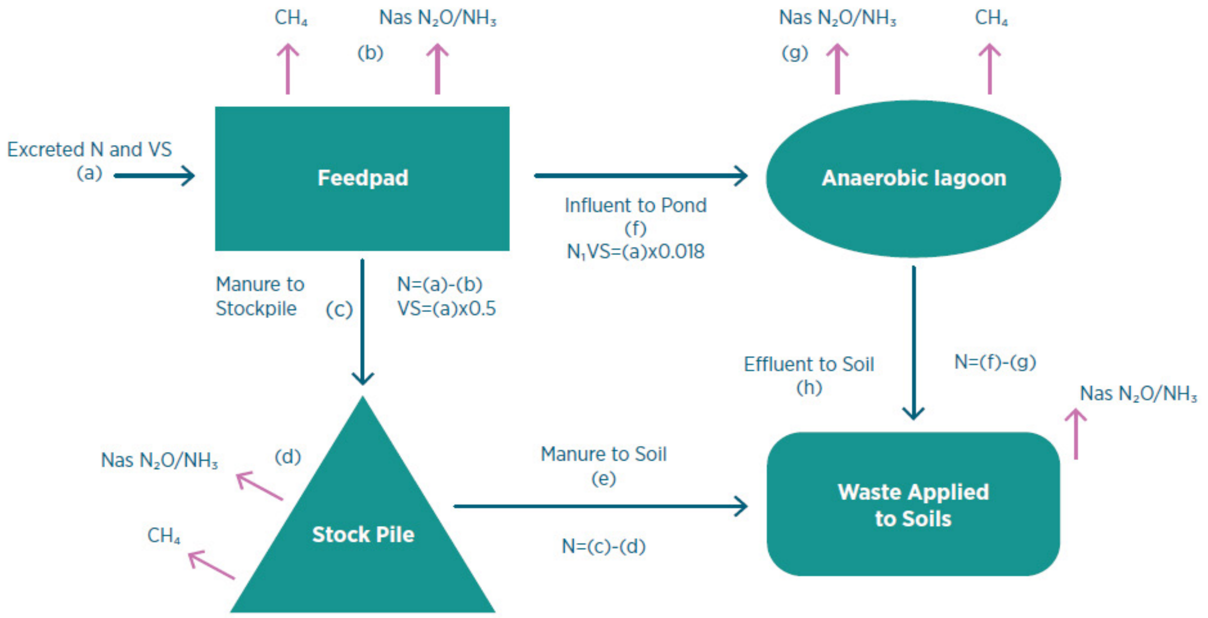


Table 5.12 Additional symbols used in algorithms for manure related emissions

Manure Management Systems (MMS)	
1 = Anaerobic lagoon	8 = Deep litter
2 = Liquid systems	9 = Pit storage
3 = Daily spread	10 = Poultry manure with bedding
3a = Sump and dispersal system	11 = Poultry manure without bedding
3b = Drains to paddock	11a = Belt manure removal
4 = Solid storage	11b = Manure stored in house
5 = Drylot (feed pad)	12 = Direct processing
6 = Composting (passive windrow)	13 = Direct application
7 = Digester/covered lagoons	14 = Pasture range and paddock

Methane

Methane emissions from livestock into MMS

Methane production from the manure of dairy cattle, feedlot cattle, swine and poultry is calculated based on the volatile solids entering the MMS, and CS and default IPCC methane conversion factors (MCF). An integrated methane conversion factor (iMCF) has been calculated taking into account the proportion of manure managed in each system, the MCF of each system, and VS losses from earlier stages in the MMS. The specific allocations of manure to the different MMS, the VS loss assumptions, and the applied MCFs are documented in Annex 5.5.

Manure management emissions for feedlot beef, swine and poultry exceed 100 per cent in the allocation of MMS, as manure from intensive livestock industries may pass through multiple treatment stages. The same manure is allocated to multiple manure management system categories in these cases. For example, 100 per cent of the volatile solids will first pass through a primary system such as a feed pad. The same manure will then pass through a secondary treatment such as composting, and then through to a tertiary treatment such as an effluent pond.

Methane emissions from livestock onto pasture, range and paddock (PRP)

There are two components to methane emission estimates from range-kept livestock (e.g. pasture-based beef cattle, sheep, goats etc.):

- Emissions from dung deposited onto PRP
- Emissions from dung deposited into constructed ponds/anaerobic lagoons

The proportion of manure allocated to anaerobic lagoons is five per cent of total PRP manure. This fraction is calibrated to the estimated difference between methane emissions from constructed ponds servicing livestock and those servicing crop production, as reported in Grinham et al. (2018) and Ollivier et al. (2019), and assuming that this difference is wholly attributable to manure from livestock. Details of these calculations and total emissions for the source (farm dams) are given in *Wetlands* (Chapter 6.7).

Country specific factors used to calculate methane emissions from pasture-based livestock are shown in Table 5.13, primarily from the 2019 IPCC Refinement (IPCC 2019), in which a default VS excretion rate for Oceania is provided and methane EFs have been further disaggregated.

Table 5.13 Factors used to calculate CH_4 emissions from pasture-based livestock

Factor type and units	Factor	Source
VS excretion rate for other cattle – Oceania (1000 kg animal mass/day)	8.7	CS, (IPCC 2019)
TAM for cattle (Typical Animal Mass – kg)	352.4	derived from average Australian pasture-based cattle liveweights across all cattle classes
CH_4 EF for PRP (g CH_4 kg VS-1 for all animals, high and low productivity systems)	0.6	CS, (IPCC 2019)
CH_4 EF for uncovered anaerobic lagoons (g CH_4 kg VS-1 for non-dairy cattle in low productivity systems, in warm climate zones)	69.7	CS, (IPCC 2019)

The annual volatile solid excretion (kg VS/animal/year) is calculated as:

VS = (VS excretion rate x TAM ÷ 1000) x 365 (3.B_1)

To calculate weighted EFs for PRP and lagoons, the CH_4 EFs in Table 5.12 are multiplied by the annual VS excretion rate. Resulting factors are:

- EF_{prp} = 0.67 kg CH_4/head/year
- EF_{lagoon} = 78.00 kg CH_4/head/year

A combined weighted IEF (kg CH_4/head/year) is calculated as:

Weighted IEF = (EF_{PRP} x PRP share (95%)) + (EF_{lagoon} x lagoon share (5%)) (3.B_2)

The weighted IEF using these values is 4.54 kg CH_4/head/year. This is then converted to kg CH_4/kg DM manure for temperate and warm climatic conditions, using the ratio change between the new combined weighted IEF (4.54) and the overall CH_4 IEF for Australian conditions (0.02 kg CH_4 /head/year). The revised EFs are:

EFW = 0.012 kg CH_4/kg DM manure
EFT = 0.003 kg CH_4/kg DM manure

Where EFW = the EF for methane from manure in warm climates

EFT = the EF for methane from manure in temperate climates

EFW and EFT are then used to calculate daily CH_4 emissions (kg) per cattle class and state, using Equation 3.B.1b_1.

Nitrous oxide

Nitrogen excretion from cattle, sheep, swine, and poultry are estimated using CS tier 2 mass balance approaches where N excretion = N input – N retention. For other livestock, CS excretion rates are applied. The N_2O EF and volatilisation factors are based on a combination of default IPCC and country-specific values depending on the type of livestock.

Where multiple manure treatment stages occur, an integrated nitrous oxide EF (iNOF) and an integrated volatilisation factor (iFracGASMMMS) have been calculated taking into account the proportion of manure managed in each system, the N_2O EF and iFracGASMMMS of each system, and N losses from earlier stages in the MMS (see Annex 5.5).

To estimate atmospheric deposition emissions, country-specific EFs are used. As the highest ammonia deposition rates (kg/ha) are found within a few hundred meters of the emission source, the fertiliser EFs of neighbouring production systems were considered to provide a more accurate estimate of emissions than the IPCC default EF. While the majority of volatilised N is advected away from the MMS, it undergoes significant dilution and is deposited to the wider landscape at very low rates (Dr Matt Redding, per. comm., QLD DAFF, 2014).

A FracLEACH_MS value from the 2019 IPCC Refinement is used to calculate N that is lost through leaching and runoff associated with manure management. The factor in the 2019 IPCC Refinement (IPCC 2019) incorporated results from recent studies in Australia and New Zealand, and is therefore better able to reflect Australia's situation than the defaults in the 2006 IPCC Guidelines (IPCC 2006).

Dairy cattle (3.B.1.a)

Methane

Dairy cattle are generally kept in higher rainfall areas than other Australian livestock. This, and the disposal of excreta washed from milking sheds, gives opportunities for the generation of methane. However, only a small fraction of the potential methane emissions appears to be released. Williams (1993) measured methane production from dairy cattle manure under field conditions in Australia and found that only about 1 per cent of the methane production potential was achieved. This is higher than the default 2019 IPCC value of 0.47 per cent.

Methane from manure is formed from the organic fraction of the manure (volatile solids). Volatile solid production for dairy cattle (VS/kg/head/day) was estimated using the data developed to calculate enteric methane production as this included information on intakes and dry matter digestibility. For dairy cattle, volatile solids were calculated as:

$$VS_{ij} = (I_{ij} \times (1 - DMD_{ij}) + (0.04 \times I_{ij})) \times (1 - A) \qquad (3.B.1a\_1)$$

Where I_{ij} = dry matter intake calculated as for enteric fermentation

DMD_{ij} = dry matter digestibility expressed as a fraction (Table A5.5.1.4)

A = ash content expressed as a fraction (assumed to be 8 per cent of faecal DM)

Methane production from manure (M_{ij} kg/head/day) is then calculated as:

$$M_{ij} = VS_{ij} \times B_o \times iMCFi \times \rho \qquad (3.B.1a\_2)$$

Where B_o = emissions potential – 0.24m^3 CH_4/kg VS (IPCC 2019)
$iMCF_i$ = integrated methane conversion factor (Table A5.5.1.6)
ρ = density of methane (0.6784 kg/m^3) – Taken from the *National Greenhouse and Energy Reporting (Measurement) Determination 2008* (the Determination) (2008)

Methane produced by pre-weaned calves (MPW_{MANURE}) is given in Table A5.5.1.5. The annual methane production (Gg) from manure of dairy cattle is calculated as:

$$Total = \Sigma_i \Sigma_j ((N_{ij=1,2,4} \times M_{ij=1,2,4} \times 365) + (N_{ij=3,5} \times M_{ij=3,5} \times 281) + (N_{ij=3,5} \times MPW_{MANUREij=3,5} \times 84)) \times 10^{-6} \qquad (3.B.1a\_3)$$

Where N_{ij} = numbers of dairy cattle in each State, class and season
M_{ijk} = methane production (kg/head/day)
$MPW_{MANUREij}$ = methane production for pre-weaned calves (kg/head/day) (Appendix 5.A.5)

Direct nitrous oxide emissions

The methodology for calculating the excretion of nitrogen from dairy cattle makes use of the following algorithms to calculate crude protein input (CP_{ij} and N retention (NR_{ij}), and from these the output of nitrogen in faeces and urine.

The crude protein intake CPI_{ij} (kg/head/day) of dairy cattle is calculated thus:

$$CPI_{ij} = I_{ij} \times CP_{ij} \qquad (3.B.1a\_4)$$

Where I_{ij} = dry matter intake (kg/day) as calculated for enteric fermentation
CP_{ij} = crude protein content of feed intake expressed as a fraction (Table A5.5.1.4)

The amount of nitrogen retained by the body (NR_{ij} kg/head/day) is calculated as the amount of nitrogen retained in milk and body tissue such that:

$$NR_{ij} = (0.032 \times MP_{ij}/6.38) + \{\{0.212-0.008(L_{ij} - 2) - [(0.140-0.008(L_{ij} - 2)) \div (1+\exp(-6(Z_{ij} - 0.4)))]\} \times (LWG_{ij} \times 0.92)\} \div 6.25 \qquad (3.B.1a\_5)$$

Where MP_{ij} = milk production in kg/head/day (Table A5.5.1.10)
L_{ij} = Intake relative to that needed for maintenance. Calculated as actual intake divided by maintenance intake (i.e. intake of non-lactating animal with LWG set to zero calculated by equation 3.A.1a_1)
Z_{ij} = relative size – (liveweight ÷ standard reference weight (Tables A5.5.1.1 and A5.5.1.3))
LWG_{ij} = liveweight gain (kg/day) (Table A5.5.1.2)

Nitrogen excreted in faeces (F_{ij} kg/head/day) is calculated using functions developed by SCA (1990) and Freer et al. (Freer 1997), as the indigestible fraction of the undegraded protein from solid feed and the microbial crude protein plus the endogenous faecal protein, such that:

$$F_{ij} = \{0.3(CPI_{ij} \times (1-[(DMD_{ij}+10) \div 100])) + 0.105(ME_{ij} \times I_{ij} \times 0.008) + (0.0152 \times I_{ij})\} \div 6.25 \qquad (3.B.1a\_6)$$

Where DMD_{ij} = dry matter digestibility expressed as a per cent (Table A5.5.1.4)
ME_{ij} = metabolizable energy (MJ/kg DM) calculated as: 0.1604 DMD_{ij} – 1.037 (Minson 1987)
I_{ij} = dry matter intake (kg/day)

Nitrogen excreted in urine (U_{ij} kg/head/day) is calculated by subtracting NR_{ij}, F_{ij} and dermal protein loss from nitrogen intake such that:

$$U_{ij} = (CPI_{ij}/6.25) - NR_{ij} - F_{ij} - [(1.1 \times 10^{-4} \times W_{ij}^{0.75}) \div 6.25] \tag{3.B.1a\_7}$$

Where W_{ij} = liveweight (Table A5.5.1.1)

Pre-weaned dairy calves are usually removed from their mothers and receive milk or milk replacer and feed pellets. The nitrogen excreted in faeces (FPW) and urine (UPW) of pre-weaned calves is given in Table A5.5.1.5.

The total annual faecal (AF_{ij} Gg) and urinary (AU_{ij} Gg) nitrogen excreted is calculated as:

$$AF_{ij} = \Sigma_j((N_{ij=1,2,4} \times F_{ij=1,2,4} \times 365) + (N_{ij=3,5} \times F_{ij=3,5} \times 281) + (N_{ij=3,5} \times FPW_{ij=3,5} \times 84)) \times 10^{-6}. \tag{3.B.1a\_8a}$$

$$AU_{ij} = \Sigma_j((N_{ij=1,2,4} \times U_{ij=1,2,4} \times 365) + (N_{ij=3,5} \times U_{ij=3,5} \times 281) + (N_{ij=3,5} \times UPW_{ij=3,5} \times 84)) \times 10^{-6} \tag{3.B.1a\_8b}$$

Where N_{ij} = the number of dairy cattle in each State and class

The annual faecal ($FN_{ij}\text{MMS}$ Gg) and urinary ($UN_{ij}\text{MMS}$ Gg) nitrogen in the different MMS can then be calculated as follows:

$$FN_{ij}\text{MMS} = (AF_{ij} \times \text{MMS}) \tag{3.B.1a\_9a}$$

$$UN_{ij}\text{MMS} = (AU_{ij} \times \text{MMS}) \tag{3.B.1a\_9b}$$

Where MMS = the fraction of nitrogen that is managed in the different MMS (Table A5.5.1.8)

The total emissions of nitrous oxide from the different MMS can then be calculated as follows:

$$\text{Faecal}_{ij}\text{MMS} = (FN_{ij}\text{MMS} \times EF(\text{MMS}) \times C_g) \tag{3.B.1a\_10a}$$

$$\text{Urine}_{ij}\text{MMS} = (FN_{ij}\text{MMS} \times EF(\text{MMS}) \times C_g) \tag{3.B.1a\_10b}$$

$$\text{Total}\text{MMS} = \Sigma_i\Sigma_j(\text{Faecal}_{ij}\text{MMS} + \text{Urine}_{ij}\text{MMS}) \tag{3.B.1a\_10c}$$

Where EF(MMS) = emission factor (N_2O-N kg/ N excreted) for the different MMS (Table A5.5.1.9)

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Indirect nitrous oxide emissions – Atmospheric Deposition

The mass of dairy waste volatilised (Gg N) from the MMS is calculated as:

$$MN\text{ATMOS}_i = \Sigma_j\Sigma\text{MMS}((FN_{ij}\text{MMS} + UN_{ij}\text{MMS}) \times \text{FracGASM}\text{MMS}). \tag{3.B.5a\_1}$$

Where FracGASMMMS = the fraction of N volatilised for dairy MMS (Table A5.5.1.9)

Atmospheric deposition emissions from dairy MMS are calculated as:

$$E = \Sigma_i (MN\text{ATMOS}_i \times EF \times C_g). \tag{3.B.5a\_2}$$

Where E = annual emissions from atmospheric deposition (Gg N_2O)

EF = 0.0059 (Gg N_2O-N/Gg N) (Inorganic Fertiliser EF for irrigated pasture – Table 5.21)

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Indirect nitrous oxide emissions – Leaching and Runoff

Emissions associated with leaching and runoff are only estimated for the solid storage MMS. Leaching and runoff from dairy effluent ponds is considered negligible and leaching and runoff from waste deposited on pasture or distributed to pasture through drains or sump dispersal systems is estimated and reported in the agricultural soils section.

A FracLEACH_MS value for leaching and runoff is used from the 2019 IPCC Refinement (IPCC 2019). The factor in the 2019 IPCC Refinement (IPCC 2019) incorporated results from recent studies in Australia and New Zealand, and is therefore better able to reflect Australia's situation than the defaults in the 2006 IPCC Guidelines (IPCC 2006).

The amount of N available for leaching and runoff (MNLEACH) is calculated as:

$$\mathrm{MNLEACH} = \Sigma_i \Sigma_j ((\mathrm{FN}_{ijMMS=4} + \mathrm{UN}_{ijMMS=4}) \text{ x } \mathrm{FracWET}_{MMSi} \text{ x } \mathrm{FracLEACH\_MS}) \quad \text{(3.B.5a\_3)}$$

Where $\mathrm{FN}_{ijMMS=4}$ and $\mathrm{UN}_{ijMMS=4}$ = mass of N in solid storage

$\mathrm{FracWET}_{MMSi}$ = fraction of N available for leaching and runoff (Table A5.5.10.2)

FracLEACH = 0.24 (Gg N/Gg applied) (CS EF, source IPCC (2019)) fraction of N lost through leaching and runoff

Annual leaching and runoff emissions from dairy MMS are calculated as:

$$E = \mathrm{MNLEACH} \text{ x } EF \text{ x } C_g \quad \text{(3.B.5a\_4)}$$

Where MNLEACH = mass of N lost through leaching and runoff (Gg N)

EF = 0.011 (Gg N_2O-N/Gg N) (CS EF, source IPCC (2019))

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Beef cattle on pastures (3.B.1.b)

Methane

Methane production from the manure (M_{ijk}l kg/head/day) of pasture-based beef cattle is calculated as:

$$M_{ijkl} = I_{jkln} \text{ x } (1 - DMD_{ijk}) \text{ x } ((PW_j \text{ x } EFW) + (PT_j. \text{ x } EFT)) \quad \text{(3.B.1b\_1)}$$

Where I_{jkln} = dry matter intake calculated for enteric fermentation

DMD_{ijk} = dry matter digestibility (expressed as a fraction) (Table A5.5.2.3)

EFW = warm emission factor (kg CH_4 / kg DM Manure)

EFT = temperate emission factor (kg CH_4 / kg DM Manure)

PW_j = proportion of animals in warm climate region (Table A5.5.2.7)

PT_j = proportion of animals in temperate climate region (Table A5.5.2.7)

The annual methane production (Gg) from the manure of pasture based beef cattle is calculated as:

$$\text{Total} = \Sigma_i \Sigma_j \Sigma_k \Sigma_l (N_{ijkl} \text{ x } M_{ijkl} \text{ x } 91.25) \text{ x } 10^{-6} \quad \text{(3.B.1b\_2)}$$

Where N_{ijkl} = numbers of beef cattle in each State, class and season

M_{ijkl} = methane production (kg/head/day)

Nitrous oxide emissions

As the manure of pasture-based beef cattle is deposited direct to pasture range and paddock (PRP), there are no direct or indirect manure management N_2O emissions. The nitrogen voided in dung and urine of grazing livestock, as calculated in this section, provides the basis for calculating nitrous oxide emissions from agricultural soils in source category 3D.

The amount of nitrogen retained by the body ($NR_{i|kln}$ kg/head/day) is calculated as the amount of nitrogen retained as milk and body tissue such that:

$$NR_{ijkln} = (0.032 \times MP_{ijkln} \div 6.38) + \{\{0.212-0.008(L_{ijkln} - 2) - [(0.140-0.008(L_{ijkln} - 2)) \div (1+\exp(-6(Z_{ijkln} - 0.4)))]\} \times (LWG_{ijkln} \times 0.92)\} \div 6.25) \quad (3.B.1b\_3)$$

Where MP_{ijkln} = milk production (kg/head/day) calculated as: proportion of cows lactating (LC_{ijkl}) x milk production

In areas where Brahman cross breeds are dominant (NT, Qld and Kimberly WA) milk production is 4 kg/day for cows >2 years old in the first season after calving and 3 kg/day in the second season. In other areas where Hereford or Shorthorn breeds are dominant (all other States) milk production is considered to be 6 and 4 kg/day respectively (Table A5.5.2.5)

L_{ijkln} = Intake relative to that needed for maintenance. Calculated as actual intake divided by maintenance intake (i.e. intake of non-lactating animal with LWG set to zero calculated by equation 3A.1b_1)

Z_{ijkln} = relative size – (liveweight ÷ standard reference weight (Tables A5.5.2.1 and A5.5.2.6))

$LWG_{ijkl}n$ = liveweight gain (kg/day) (Table A5.5.2.2)

Nitrogen excreted in faeces (Fi|kln kg/head/day) is calculated, using equations developed by the SCA (1990) and Freer et al. (1997), as the indigestible fraction of the undegraded protein from solid feed, microbial crude protein and milk protein plus the endogenous faecal protein, such that:

$$F_{ijkln} = (\{0.3((I_{ijkln} \times CP_{ijkl}) \times (1-[(DMD_{ijkl}+10) \div 100])) + 0.105(ME_{ijkl} \times I_{ijkln} \times 0.008) + (0.0152 \times I_{ijkln})\} \div 6.25) + (0.08(0.032 \times MC_{ijkl}) \div 6.38) \quad (3.B.1\ b\_4)$$

Where I_{ijkln} = dry matter intake (kg/head/day) as calculated for enteric fermentation

CP_{ijkl} = crude protein content of feed dry matter expressed as a fraction (Table A5.5.2.4)

DMD_{ijkl} = dry matter digestibility (expressed as a per cent) (Table A5.5.2.3)

ME_{ijkl} = metabolizable energy (MJ/kg DM) calculated by Minson and McDonald (1987) as: ME = 0.1604 DMD_{ijkl} – 1.037; (DMD expressed as per cent)

MC_{ijkl} = milk intake (kg/head/day). In areas where Brahman cross breeds are dominant (NT, Qld and Kimberly WA) milk intake is 4 kg/day for animals in the first season after birth and 3 kg/day in the second season

In other areas where Hereford or Shorthorn breeds are dominant (all other States) intake is 6 and 4 kg/day (Table A5.5.2.5)

Nitrogen excreted in urine ($U_{i|kln}$ kg/head/day) is calculated by subtracting $NR_{i|kl}$, $F_{i|kl}$ and dermal protein loss from the nitrogen intake such that:

$$U_{ijkln} = (I_{ijkln} \times CP_{ijkl} \div 6.25) + (0.032 \times MC_{ijkl} \div 6.38) - NR_{ijkl} - F_{ijkl} - [(1.1 \times 10^{-4} \times W_{ijkl}^{0.75}) \div 6.25] \quad (3.B.1b\_5)$$

Where W_{ijkl} = liveweight (Table A5.5.2.1)

The total annual faecal ($AF_{ijkln\ MMS=14}$ Gg) and urinary ($AU_{ijkln\ MMS=14}$ Gg) nitrogen excreted to PRP is calculated as:

$$AF_{ijkln}\ MMS{=}14 = (N_{ijkln} \times F_{ijkln} \times 91.25) \times 10^{-6}\ . \quad (3.B.1b\_6a)$$

$$AU_{ijkln}\ MMS{=}14 = (N_{ijkln} \times U_{ijkln} \times 91.25) \times 10^{-6}. \quad (3.B.1b\ 6b)$$

Where N_{ijkln} = the number of beef cattle adjusted for feedlot cattle in each State, region, season and class

Beef cattle in feedlots (3.B.1.c)

Methane

The high density of animals in feedlots results in high concentrations of manure from which methane can be produced when the dung pack becomes moistened and anaerobic microsites occur. Emissions may also arise from compacted manure stockpiles which are typically anaerobic, and from effluent storage ponds built to contain runoff. These storage ponds are usually anaerobic, providing conditions conducive to methane production.

However, as most manure is handled in drylot and solid storage, only a small fraction of the potential methane emissions are generated.

Volatile solid production for beef cattle in feedlots (VS. kg/head/day) was estimated using a calculation from the mass balance model developed for Australian feedlots – BeefBal (McGahan et al. (2004) and the intakes developed to calculate enteric methane production:

$$VS_j = I_j \times (1 - DMD_j \times (1- A) \qquad (3.B.1\ c\_1)$$

Where I_j = dry matter intake as calculated for enteric fermentation

DMD_j =DM digestibility expressed as a fraction (Table A5.5.3.2)

A = ash content expressed as a fraction (16 per cent) – The ash content fraction is used in BeefBal, and is based on measured data from Australia. Data presented in Gopalan et al. (2013) confirmed VS fractions in fresh manure of between 79 per cent and 88 per cent with an average of 83 per cent. These results support the use of an ash content of manure of 16 per cent.

Methane production from the manure management (Mj kg/head/day) is then calculated as:

$$M_j = VS_j \times B_O \times iMCF_i \times \rho \qquad (3.B.1c\_2)$$

Where B_O = emissions potential (0.19m3 CH_4/kg VS (IPCC 2019))

Australia's B0 value is based on independent research measuring average B0 values in Australian feedlots. Results obtained were very similar to the IPCC values for North America, and therefore, it was recommended that the North American B0 value be applied to Australia (Wiedemann et al. (2014)). These findings constitute an independent validation of the use of the default value for North America as a CS value.

iMCFi = integrated MCF for feedlot cattle in each state (Table A5.5.3.3)

ρ = density of methane (0.6784 kg/m^3) – Taken from the Determination

Annual methane production (Gg) from the manure of beef cattle in feedlots is calculated as:

$$E = \Sigma_i\Sigma_j(365 \times N_{ij} \times M_j \times 10^{-6}) \qquad (3B.1c\_3)$$

Where N_{ij} = Annual equivalent numbers of beef cattle in feedlots

Mj = methane production (kg/head/day)

Direct nitrous oxide emissions

The excretion of nitrogen from feedlot cattle is estimated from nitrogen intake (NI_j) and the fraction retained (NR_j).

Nitrogen intake NI_j (kg/head/day) of feedlot cattle is calculated by:

$$NI_j = I_j \times CP_j \div 6.25 \qquad (3.B.1c\ 4)$$

Where I_j = dry matter intake as calculated for enteric fermentation

CP_j = crude protein content of feed expressed as a fraction (Table A5.5.3.2)

6.25 = factor for converting crude protein into nitrogen

Nitrogen excretion NE_j (kg/head/day) is calculated by:

$$NE_j = NI_j \times (1- NR_j) \qquad (3.B.1c\_5)$$

Where NR_j = nitrogen retention expressed as a fraction of intake (Table A5.5.3.1)

Annual nitrogen excretion (AE_{ij} Gg/year) from feedlot cattle is calculated as:

$$AE_{ij} = N_{ij} \times NE_j \times 365 \times 10^{-6} \qquad (3.B.1c\_6)$$

Where N_{ij} = Annual equivalent numbers of beef cattle in each class in each State

Total direct emissions of nitrous oxide from feedlot cattle (Gg) can be calculated as follows:

$$\text{Total}\textsc{mms} = \Sigma_i\Sigma_j (AE_{ij} \times \text{iNOF} \times C_g) \qquad (3.B.1c\_7)$$

Where iNOF= integrated N_2O emission factor for each feedlot class and state (Table A5.5.3.3)

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Indirect nitrous oxide emissions – Atmospheric Deposition

Integrated FracGASMMMS values (Table A5.5.3.3) based on the IPCC (2006) default and Australian research (Table A5.5.3.7) are used to estimate N volatilisation.

The mass of feedlot waste volatilised (Gg) is calculated as:

$$\text{MNATMOS}_{ij} = = \Sigma_i\Sigma_j (N_{ij} \times AE_{ij} \times \text{iFracGASMMMS}) \qquad (3.B.5c\_1)$$

Where AE_{ij} = mass of nitrogen excreted, calculated in Equation 3.B.1c_6.

iFracGASMMMS = integrated fraction of N volatilised from feedlot cattle (Table A5.5.3.3)

Annual atmospheric deposition emissions (Gg N_2O) from MMS are calculated as:

$$E = \text{MNATMOS} \times EF \times C_g \qquad (3.B.5c\_2)$$

Where MNATMOS = mass of N volatilised (Gg N)

EF = 0.0041 (Gg N_2O-N/Gg N) (Inorganic fertiliser EF for non-irrigated cropping – Table 5.21)

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Leaching and Runoff

Australian feedlots are managed with strict environmental controls on leaching, requiring the use of an impermeable barrier depending on underlying strata (MLA 2012), Skerman (2000)). Leaching is therefore assumed to be zero, while runoff from feedlots is captured in effluent ponds. Emissions associated with waste runoff are therefore included in the direct emission estimates.

Sheep (3.B.2)

Methane

Methane production from manure (M_{ijk} kg/head/day) of sheep is calculated as:

$$M_{ijk} = I_{ijk} \times (1 – DMD_{ijk}) \times EFT \qquad (3.B.2\_1)$$

Where I_{ijk} = dry matter intake calculated for enteric fermentation

DMD_{ijk} = digestibility expressed as a percentage (Table A5.5.4.2)

EFT = temperate emission factor (kg CH_4 / kg DM Manure)

The annual methane production (Gg) from sheep manure is calculated as:

$$\text{Total} = \Sigma_i\Sigma_j\Sigma_k (N_{ijk} \times M_{ijk} \times 91.25) \times 10^{-6} \qquad (3.B.2\_2)$$

Where N_{ijk} = numbers of sheep in each State, class and season

M_{ijk} = methane production (kg/head/day)

Nitrous oxide emissions

As sheep manure is deposited direct to PRP, there are no direct or indirect manure management N_2O emissions. The nitrogen voided in dung and urine of grazing livestock, as calculated in this section, provides the basis of calculating nitrous oxide emissions from agricultural soils in source category 3D.

The methodology for calculating excretion of nitrogen from sheep makes use of the following algorithms to calculate crude protein input (CPI_{ijk}) and N retention (NR_{ijk}) and from these, the output of nitrogen in faeces and urine.

Crude protein intake CPI_{ijk} (kg/head/day) of sheep is calculated as:

$$CPI_{ijk} = I_{ijk} \times CP_{ijk} + (0.045 \times MC_{ijk}) \qquad (3.B.2\_3)$$

Where I_{ijk} = feed intake (kg DM/head/day) as calculated for enteric fermentation

CP_{ijk} = crude protein content of feed intake expressed as a fraction (Table A5.5.4.4)

MC_{ijk} = milk intake (kg/head/day) calculated as: proportion of lambs receiving milk in each season x milk intake (Table A5.5.4.6). Milk intake assumed to be 1.6 kg/day for the first three months after the birth of lambs

The amount of nitrogen retained by the body (NR_{ijk} kg/head/day) is calculated as the nitrogen retained in milk, wool and body tissue such that:

$$NR_{ijk} = \{(0.045 \times MP_{ijk}) + (WP_{ijk} \times 0.84) + \{[(212-4\{[(EBG_{ijk} \times 1000) \div (4 \times SRW_{ijk}^{0.75})] - 1\}) - (140 - 4\{[(EBG_{ijk} \times 1000) \div (4 \times SRW_{ijk}^{0.75})] - 1\}) \div \{1+\exp(-6(Z_{ijk}-0.4))\}] \times EBG_{ijk}\} \div 1000\} \div 6.25 \qquad (3.B.2\_4)$$

Where MP_{ijk} = milk production (kg/day) calculated as: proportion of ewes lactating (LE_{ijk}) x milk production

Milk production is considered to be 1.6 kg/day for breeding ewes in the first three months after the birth of lambs

WP_{ijk} = clean wool production (kg/day) based on ABS average greasy wool production per head multiplied by State average clean yield percentage. Wool production may be reduced by 50 per cent for lactating ewes (SCA 1990). Accordingly, wool production of ewes was apportioned pro rata to give recorded annual average wool production. It is assumed that clean wool consists of 16 per cent water and 84 per cent protein.

EBG_{ijk} = empty body gain, equivalent to LWG_{ijk} x 0.92

SRW_{ijk} = standard reference weight (SCA 1990) in Table A5.5.4.7

Z_{ijk} = relative size (liveweight ÷ standard reference weight) (Tables A5.5.4.1 and A5.5.4.7)

Nitrogen excreted in faeces (F_{ijk} kg/head/day) is calculated using functions developed by SCA (1990) and Freer et al. (1997), as the indigestible fraction of the un-degraded protein from solid feed, the microbial crude protein and milk protein plus the endogenous faecal protein, such that:

$$F_{ijk} = \{0.3(CPI_{ijk} \times (1-[(DMD_{ijk}+10) \div 100])) + 0.105(ME_{ijk} \times I_{ijk} \times 0.008) + 0.08(0.045 \times MC_{ijk}) + 0.0152 \times I_{ijk}\} \div 6.25 \qquad (3.B.2\_5)$$

Where DMD_{ijk} = digestibility expressed as a percentage (Table A5.5.4.2)

ME_{ijk} = metabolizable energy (MJ/kg DM) calculated as 0.1604 DMD_{ijk} -1.037 (Minson and McDonald 1987)

MC_{ijk} = milk intake (kg/day) calculated as: proportion of lambs receiving milk in each season x milk intake (Appendix 5.D.6). Milk intake assumed to be 1.6 kg/day for the first three months after the birth of lambs

1/6.25 = factor for converting crude protein into nitrogen

Nitrogen excreted in urine (U_{ijk} kg/head/day) is calculated by subtracting the nitrogen retained (NR_{ijk}) and the nitrogen excreted in the faeces (F_{ijk}) from the nitrogen intake such that:

$$U_{ijk} = (CPI_{ijk} \div 6.25) - NR_{ijk} - F_{ijk} \quad (3.B.2\_6)$$

The annual faecal (AF_{ijk} Gg) and urinary (AU_{ijk} Gg) nitrogen excreted to PRP is calculated as:

$$AF_{ijk\,MMS=14} = (N_{ijk} \times F_{ijk} \times 91.25) \times 10^{-6} \quad (3.B.2\_7a)$$

$$AU_{ijk\,MMS=14} = (N_{ijk} \times U_{ijk} \times 91.25) \times 10^{-6} \quad (3.B.2\_7b)$$

Where N_{ijk} = the number sheep in each State, season and class

Swine (3.B.3)

Methane

In Australia, swine are generally housed and the liquid waste slurry produced during cleaning is often channelled into lagoons. These lagoons tend to create anaerobic conditions, resulting in a high proportion of the volatile solids being fermented with the formation of methane.

A significant proportion of feed given to swine can be wasted (ranging from 5–20 per cent). This waste feed also contributes volatile solids to the MMS and will result in methane emissions. For completeness, emissions are estimated from all waste entering the MMS.

PIGBAL (Skerman et al. 2013) is a nutrient balance model for intensive piggeries in Australia. By entering typical animal characteristics, feed intakes, diet compositions and wastage rates, the model calculates the volatile solids (VSN kg/head/day) in the animal manure (including urine) and waste feed (Annex 5.5).

Using this information, CH_4 production from wastes (M_{ij} kg/head/day) can be calculated as:

$$M_{ij} = VS_{ij} \times B_o \times iMCF_i \times \rho \quad (3.B.3\_1)$$

Where VS_{ij} = volatile solids production (kg/head/day) (Table A5.5.5.4)

B_o = methane emission potential (0.45m3 CH_4/kg VS – (IPCC 2019))

$iMCF_j$ = integrated methane conversion factor based on the proportion of different manure management regimes (Table A5.5.5.5)

ρ = density of methane (0.6784kg/m^3) – From the Determination

The annual methane production (Gg) from the wastes of Australian swine is calculated as:

$$E = \Sigma_i \Sigma_j (365 \times N_{ij} \times M_{ij} \times 10^{-6}) \quad (3.B.3\_2)$$

Where N_{ij} = numbers of swine in each class for each State

M_{ij} = methane production (kg/head/day)

Direct nitrous oxide emissions

Swine are fed high quality diets with high levels of crude protein. The rapid growth rates of most swine results in a relatively high proportion of this nitrogen being retained in the body. Swine may excrete between 45 and 65 per cent of nitrogen consumed in feed (King and Brown (1993), King et al. (1993)).

Wasted feed also contributes nitrogen to the MMS and is included in the estimation of emissions for completeness. The nutrient balance model PIGBAL (Skerman et al. (2013)) is used to estimate total nitrogen in wastes based on typical animal characteristics, feed intakes, feed types and wastage rates (Annex 5.5).

Allocations to the different MMS have changed over time (Table A5.5.5.6), with an increase in swine being housed on deep litter resulting in a decrease of allocations to effluent ponds (Wiedemann et al. (2014). Intensification of the industry has also occurred, with typical animal mass increasing across every State throughout the timeseries, while N excretion rates have decreased. This has resulted in a continual increase to the N_2O IEF.

Annual nitrogen (AE_{ij} Gg/year) from swine manure and waste feed is calculated as:

$$AE_{ij} = N_{ij} \times E_{ij} \times 10^{-6} \qquad (3.B.3\_3)$$

Where N_{ij} = numbers of swine in each class in each State
E_{ij} = nitrogen in waste (kg/head/year) as calculated by PIGBAL (Table A5.5.5.4)

Total emissions of nitrous oxide from the different MMS (Gg) can then be calculated as follows:

$$Total_{MMS} = \Sigma_i \Sigma_j \, (AE_{ij} \times iNOF \times C_g) \qquad (3.B.3\_4)$$

Where iNOF = the integrated nitrous oxide emission factor for swine in each state (Table A5.5.5.5)
C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Indirect nitrous oxide emissions – Atmospheric deposition

Australia has developed integrated $FracGASM_{MMS}$ values (Table A5.5.5.5) for swine based on default IPCC and CS values (Table A5.5.5.9).

The mass of piggery waste volatilised is calculated as:

$$M_{ATMOS} = \Sigma_i \Sigma_k \, (N_{ij} \times AE_{ij} \times iFracGASM_{MMS}) \qquad (3.B.5c\_1)$$

Where AE_{ij} = mass of nitrogen excreted, calculated in Equation 3.B.3_3
$iFracGASM_{MMS}$ = the integrated fraction of N volatilised for the swine industry (Table A5.5.5.5)

Annual indirect nitrous oxide production (Gg N_2O) from swine MMS is calculated as:

$$E = MN_{ATMOS} \times EF_{ij} \times C_g \qquad (3.B.5c\_2)$$

Where MN_{ATMOS} = mass of N volatilised (Gg N)
EF_{ij} = 0.0041 (Gg N_2O-N/Gg N) (Inorganic Fertiliser EF for non-irrigated cropping – Table 5.21)
C = 44/28 factor to convert elemental mass of N_2O to molecular mass

Leaching and runoff

Leaching and runoff from piggery facilities (with the exception of outdoor piggeries) is considered negligible because of strict environmental regulations in all States of Australia. The emissions associated with leaching and runoff are therefore only estimated for the drylot MMS.

$$\mathrm{MN_{LEACH}}_{ij} = \Sigma_i \Sigma_k (N_{ij} \times AE_{ij} \times MS_{iMMS=5} \times FracWET_{MMSi} \times Frac_{LEACH\_MS}) \qquad \text{(3.B.5c\_3)}$$

Where $\mathrm{MN_{LEACH}}_{ij}$ = mass of N lost through leaching and runoff (Gg N)

AE_{ij} = mass of nitrogen in waste, calculated in equation 3.B.3_3

$MS_{iMMs=5}$ = fraction of waste handled through drylot (Table A5.5.5.6)

$FracWET_{MMSi}$ = fraction of N available for leaching and runoff (Table A5.5.10.2)

$Frac_{LEACH\_MS}$ = 0.22 (Gg N/Gg applied) (CS EF, source IPCC (IPCC 2019) fraction of N lost through leaching and runoff

Annual leaching and runoff emissions (Gg N_2O) from swine MMS are calculated as:

$$E = \mathrm{MN_{LEACH}}_{ij} \times EF \times C_g \qquad \text{(3.B.5c\_4)}$$

Where EF = 0.011 (Gg N_2O-N/Gg N) (CS EF, IPCC (IPCC 2019))

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Poultry (3.B.4.g)

Table 5.14 Symbols used in algorithms for poultry

State (i)	Poultry Classes (j)	Poultry subclass
1 = ACT	1 = Layer	
2 = Northern Territory	2 = Meat	2a = Meat Chicken Growers
3 = NSW		2b = Meat Chicken Breeders
4 = Queensland		2c = Other
5 = Tasmania		
6 = South Australia		
7 = Victoria		
8 = Western Australia		

Methane

The majority of Australia's poultry population are housed indoors which promotes conditions for the concentration and concentrated treatment of faecal wastes. Methane from manure is formed from the organic fraction of the manure (volatile solids).

Volatile solid production (VS_{ij} kg/head/day) for poultry was estimated using information on feed intakes and dry matter digestibility:

$$VS_{ij} = I_{ij} (1 - DMD_{ij}) \times (1 - A) \qquad \text{(3.B.4g\_1)}$$

Where I_{ij} = dry matter intake (Table A5.5.6.1)

DMD_{ij} = digestibility expressed as a fraction (Table A5.5.6.1)

A = ash content of manure expressed as a fraction (Table A5.5.6.1)

Methane production from poultry manure (M_{ij} kg/head/day) can then be calculated as:

$$M_{ij} = VS_{ij} \times B_o \times iMCF_{ij} \times \rho \qquad \text{(3.B.4g\_2)}$$

Where B_o = emission potential (0.36 m^3 CH_4/kg VS for meat and 0.39 m3 CH_4 / kg VS for layers (IPCC 2019))

$iMCF_{ij}$= Integrated methane conversion factor (Table A5.5.6.2)

ρ = density of methane (0.6784 kg/m^3) – From the Determination

Annual methane production (Gg) for poultry is calculated as:

$$E = \Sigma_i \Sigma_j (365 \times N_{ij} \times M_{ij} \times 10^{-6}) \qquad (3.B.4g\_3)$$

Where N_{ij}= number of birds in each class and state

M_{ij} = methane production (kg/head/day)

Direct nitrous oxide emissions

The methodology for calculating excretion of nitrogen from meat chickens and layers makes use of the following algorithms to calculate nitrogen intake (NI_{ij}) and retention (NR_{ij}) and from these, the output of nitrogen in manure.

The nitrogen intake NI_j (kg/head/day) of poultry is calculated by:

$$NI_j = I_j \times CP_j \div 6.25 \qquad (3.B.4g\_4)$$

Where I_j = dry matter intake in kg/day (Table A5.5.6.1)

CP_j = dietary crude protein expressed as a fraction (Table A5.5.6.1)

6.25 = factor for converting crude protein into nitrogen

Nitrogen excretion (NE_{ij}) (Gg/head/year) is calculated by:

$$NE_{ij} = NI_j (1 - NR_j) \times 365 \times 10^{-6} \qquad (3.B.4g\_5)$$

Where NR_j = nitrogen retention as a proportion of intake (Table A5.5.6.1)

Total emissions of nitrous oxide from the different MMS (Gg) can then be calculated as follows:

$$Total_{MMS} = \Sigma_i \Sigma_j (N_{ij} \times NE_j \times iNOF_j \times C_g) \qquad (3.B.4g\_6)$$

Where N_{ij} = annual equivalent number of birds in each class and state

NE_{ij} = N excretion (Gg/head/year)

$iNOF_j$ = the integrated nitrous oxide emission factor (Table A5.5.6.2)

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Indirect nitrous oxide emissions – Atmospheric deposition

Integrated FracGASM values (Table A5.5.6.2) based on default IPCC (2006) and CS values (Table A5.5.6.7) are used to estimate N volatilisation from poultry.

Mass of poultry waste volatilised (Gg N) is calculated as:

$$M_{ATMOS} = \Sigma_i \Sigma_j (N_{ij} \times NE_{ij} \times iFracGASM_{MMS_j}) \qquad (3.B.5d\ 1)$$

Where NE_{ij} = mass of nitrogen excreted (Gg/head/year), calculated in Equation 3.B.4g_5

$iFracGASM_{MMS_j}$ = the integrated fraction of N volatilised for the meat and layer industries (Table A5.5.6.2)

Annual atmospheric deposition emissions (Gg N_2O) from poultry MMS are calculated as:

$$E = MN_{ATMOS} \times EF_{ij} \times C_g \qquad (3.B.5d\_2)$$

Where EF_{ij} = 0.0018 (Gg N_2O-N/Gg N) (Meat = inorganic fertiliser EF for non-irrigated pastures)

EF_{ij} = 0.0041 (Layers = inorganic fertiliser EF for non-irrigated cropping – Table 5.21)

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Indirect nitrous oxide emissions – Leaching and runoff

Leaching and runoff from poultry facilities (with the exception of free range operations and manure stockpiles) is considered negligible. Therefore the emissions associated with waste leaching and runoff are only estimated for manure stockpiles. Emissions from free range operations are estimated in the agricultural soils category 3D.

$$MN\text{LEACH} = \Sigma_i\Sigma_j\ (N_{ij} \times NE_{ij} \times MS_{iMMS=4\text{-}5} \times FracWET_{MMSi} \times Frac\text{LEACH\_MS}) \qquad (3.B.5d\_3)$$

Where $MN\text{LEACH}_{ij}$ = mass of N lost through leaching and runoff (Gg N)

NE_{ij} = mass of nitrogen excreted (Gg/head/year), calculated in Equation 3B.4g_5

$MS_{iMMs=4\text{-}5}$ = fraction of waste handled through drylot and solid storage (Table A5.5.6.3)

$FracWET_{MMSi}$ = Fraction of N available for leaching and runoff (Table A5.5.10.2)

FracLEACH_MS = 0.02 (Gg N/Gg applied) (CS EF, source IPCC (2019)) fraction of N lost through leaching and runoff

Annual leaching and runoff emissions (Gg N_2O) from poultry MMS are calculated as:

$$E = \Sigma_i\Sigma_j\ (MN\text{LEACH}_{ij} \times EF \times C_g) \qquad (3.B.5d\_4)$$

Where EF = 0.011 (Gg N_2O-N/Gg N) (CS EF, source IPCC (2019))

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Other livestock (including 3.B.4.a-f, h and i)

Methane

Goats, deer, buffalo, camels, alpaca, horses, mules and asses, emus and ostriches are range-kept livestock and hence, manure deposition typically occurs in a dispersed fashion. Little is known about the amount of manure produced by the livestock types in this group. In the absence of adequate information, it is assumed that the rates of manure production (DMM_{ij} kg DM/head/year) can be scaled to those calculated for either sheep or beef cattle, based on the comparative size of the animals (Table A5.5.7.1). For example, the IPCC default weight for horses (377 kg) and buffalo (380 kg) are consistent with the average weight of beef cattle (380 kg), while the default weight of mules/asses (130 kg) and goats (38.5 kg) are consistent with one third of beef cattle (127 kg) and sheep (45 kg) weights respectively.

Methane production from the manure of other livestock (M_{ij} kg/head/day) is calculated as:

$$M_{ij} = (DMM_{ij} \times PW_i \times EFW) + (DMM_{ij} \times PTi \times EFT) \qquad (3.B.4\_1)$$

Where DMM_{ij} = dry matter in manure (Table A5.5.7.1)

EFW = warm emission factor (kg CH_4 / kg DM Manure)

EFT = temperate emission factor (kg CH_4 / kg DM Manure)

PW_i = proportion of animals in warm climate region (Table A5.5.7.3)

PT_i = proportion of animals in temperate climate region (Table A5.5.7.3)

Annual methane production (Gg) from manure of other livestock is calculated as:

$$Total = \Sigma_i\Sigma_j(N_{ij} \times M_{ij}) \times 10^{-6} \qquad (3.B.4\_2)$$

Where N_{ij} = numbers of animals in each State

M_{ij} = methane production (kg/head/day)

Nitrous oxide emissions

As the manure of other livestock is deposited direct to PRP, there are no direct or indirect manure management N_2O emissions. The nitrogen voided in dung and urine of grazing livestock, as calculated in this section, provides the basis of calculating nitrous oxide emissions from agricultural soils in source category 3D.

In the absence of adequate species specific information, it is assumed that the rates of nitrogen excretion (E_{ij} kg/head/year) can be scaled to those calculated for either sheep or beef cattle, based on the comparative size of the animals (Table A5.5.7.2).

The annual nitrogen (AE_{ij} Gg/year) excreted to PRP is calculated as:

$$AE_{ijMMS=14} = (N_{ij} \times E_{ij}) \times 10^{-6} \qquad (3.B.4\_3)$$

Where N_{ij} = numbers in each State
E_{ij} = nitrogen excreted (kg/head/year) (Table A5.5.7.2)

The annual nitrogen excreted in faeces (AF_{ij}) and Urine (AU_{ij}) to PRP is calculated as:

$$AF_{ij\ MMS=14} = \Sigma_j (AE_{ij\ MMS=14} \times PMF) \qquad (3.B.4\_4)$$

$$AU_{ij\ MMS=14} = \Sigma_j (AE_{ij\ MMS=14} \times PMU) \qquad (3.B.4\_5)$$

Where PMF = the proportion of waste that is faeces. Assumed to be 0.29 (based on average of cattle and sheep)
PMU = the proportion of waste that is urine. Assumed to be 0.71 (based on average of cattle and sheep)

5.3.3 Uncertainty assessment and time-series consistency

A quantitative assessment of uncertainty was undertaken and uncertainties for manure management were estimated to be in the order of 37-55 per cent. Further details are provided in Annex 2.

Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to methodology.

5.3.4 Category-specific QA/QC and verification

Activity data

The Australian Bureau of Statistics (ABS) is the national statistical agency of Australia and is the key provider of activity data for this source category. The ABS has in place a range of procedures associated with survey design, data input and consistency checks on the survey results and the aggregated values.

This source category is also covered by the general QA/QC procedures of the inventory. The QC procedure “ensuring consistency in data between categories” is of specific importance for this category. AGEIS ensures that activity and livestock characterisation data used across multiple categories is entered only once and that intakes or emissions calculated in one category form the input for other categories.

Implied EFs

As tier 3 methods are used to estimate emissions from cattle, sheep, pigs and poultry, the IEFs have been compared with IPCC defaults (Table 5.15).

Table 5.15 Implied EFs – Methane manure management (kg/head/year)

Livestock type	Australia	IPCC default (Oceania)
Dairy cattle	13.98	23–31
Beef cattle on pastures	4.71	1–2
Beef cattle in feedlots	3.64	1–2
Sheep	0.34	0.19–0.37
Swine	23.25	11–24
Poultry	0.04	0.02–1.4

Source: IPCC (2006).

The IEFs for dairy cattle differ from the IPCC defaults due to the allocation of waste to different MMS. Australia assumes that 80-88 per cent of waste is voided at pasture compared with 76 per cent in the IPCC (2006) default.

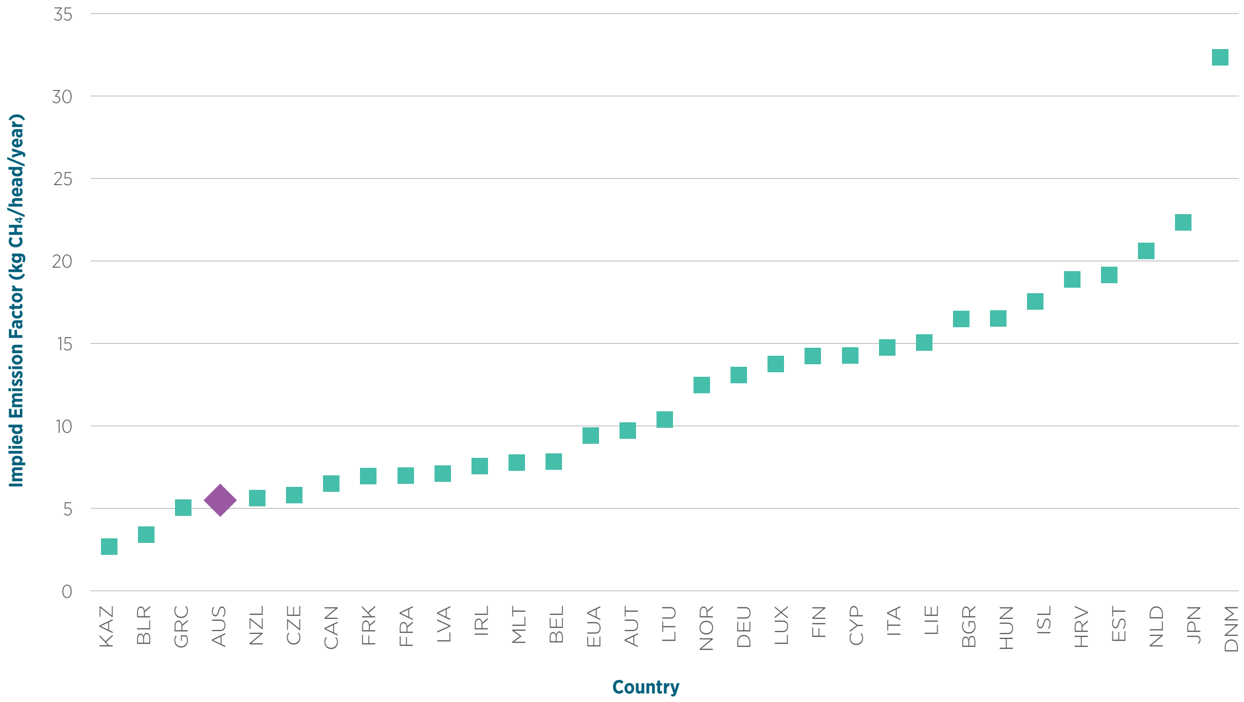
The IEF for beef cattle on pastures is higher than the IPCC default EF range. Reasons for this difference include:

- Australia assumes that 5 per cent of pasture beef cattle manure is deposited into constructed ponds, which is included in manure management CH_4 emissions. The anaerobic lagoon EF applied to constructed ponds is significantly higher than the PRP EF, therefore, raising Australia's overall IEF.
- The default factors for Oceania include a number of developing nations in the region, which have different production systems for livestock compared to those in Australia.

The IPCC default B0 value for North America has been chosen for beef cattle in feedlots based on the recommendations contained in Wiedemann et al. (2014). They noted that the IPCC (2006) default for Oceania did not correspond with measurements by Gopalan et al. (2013) from four Australian feedlots, which were more aligned to the IPCC default for North America.

Australia's approach to the estimation of emissions from manure deposited by cattle places Australia's IEF within the range of Annex-1 IEFs (Figure 5.8). The Australian value falls near the top of the lower third of reporting countries.

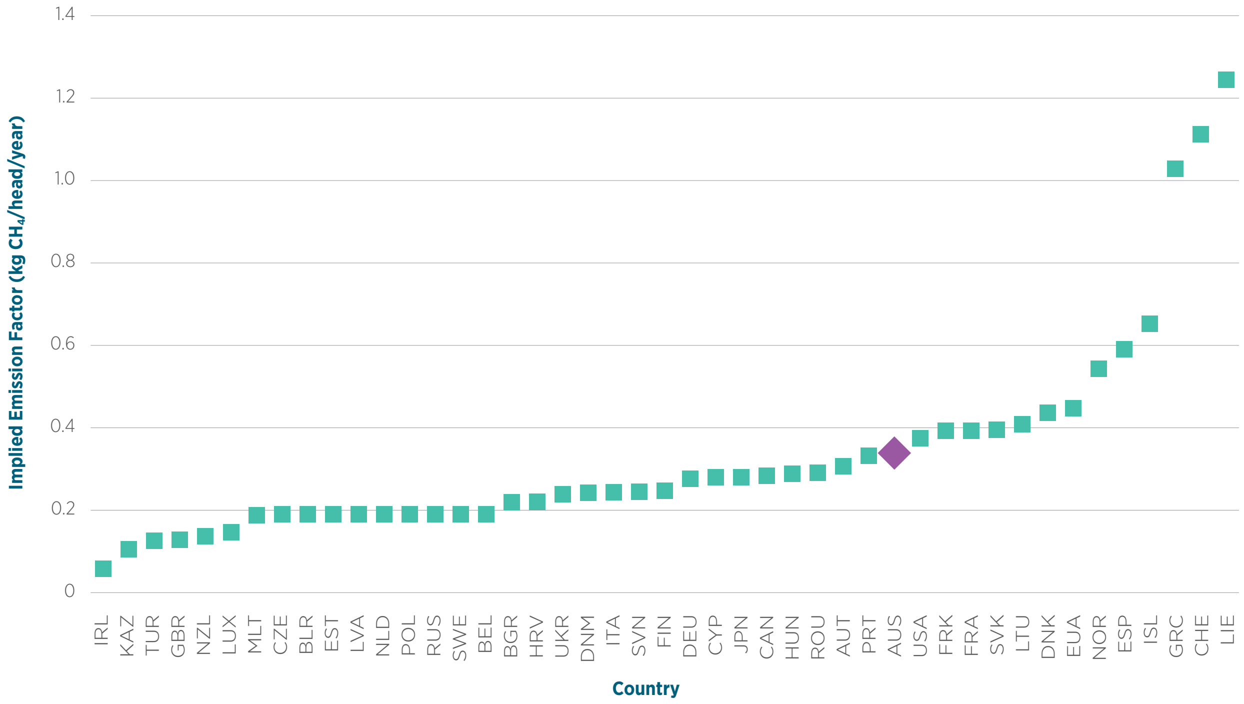
Figure 5.7 **Cattle manure management implied emission factors for Annex I countries (2023 submission) and Australia (2024 submission), kg CH_4 per head per year**



Australia's manure management CH_4 IEF for cattle is also highly comparable to Annex I parties with similar livestock production systems, such as New Zealand.

Australia's sheep IEF is similarly within the range of other parties, as shown in Figure 5.9.

Figure 5.8 **Sheep manure management implied emission factors for Annex I countries (2023 submission) and Australia (2024 submission), kg CH_4 per head per year**



The reasons for being at the higher end of the range are:

- Australia assumes that 5 per cent of sheep manure is deposited into constructed ponds, which is included in manure management CH_4 emissions. The anaerobic lagoon EF applied to constructed ponds is significantly higher than the PRP EF, therefore, raising Australia's overall IEF.
- The default factors for Oceania include a number of developing nations in the region which have different production systems for livestock compared to those in Australia.

The swine IEF is on the high end of the IPCC range. The IPCC (2006) default assumes that 50 per cent of manure passes through an anaerobic pond, while Australian management practices for swine see this elevated to around 70 per cent. The poultry IEF is within the range of the IPCC (2006) default EFs.

Volatile solids

The major source of methane emissions from manure management are from the intensive livestock industries.

As the intake calculation for cattle and the volatile solid calculations for swine and poultry differ from the IPCC tier 2 methodologies, the estimated volatile solids were compared against the IPCC defaults. These were found to be comparable for dairy cattle, swine and poultry (Table 5.16). The volatile solid production of feedlot cattle was lower than the IPCC (2006) defaults, as an ash content of 16 per cent is used compared with the default of 8 per cent. The slightly higher values reported for swine are likely the consequence of including VS from feed waste.

Table 5.16 Volatile solids (kg/head/day)

Livestock type	Australia	IPCC 2019
Dairy cows	3.3	2.9-5.4
Beef cattle – Feedlot	1.7	2.3-3.9
Swine		
Breeders	0.4-0.55	0.3-0.6
Other pigs	0.39	0.3-0.32
Poultry		
Layers	0.014	0.02
Meat	0.016-0.017	0.01-0.02

Source: IPCC (2019).

Nitrogen excretion

The CS estimates of nitrogen excretion were compared against the IPCC defaults (Table 5.17). Feedlot cattle, sheep and poultry excretion rates are consistent with IPCC (2019) values.

For other animals, excretion rates differ from the IPCC values. However, the IPCC *Guidelines* do not provide the data on which the default excretion/retention rates are based, so it is impossible to determine whether it is the assumption regarding feed quality causing the difference in excretion rates.

Dairy cattle excretion rates are consistent with the IPCC (2019) values. The CS method was compared with excretion rates generated by the IPCC tier 2 and New Zealand methods, and was found to give comparable results. Excretion rates for mature animals were almost identical, while for rapidly growing animals (< 1 year old), the CS method estimated slightly lower N retention and hence, higher N excretion that the other methods. Excretion rates for pasture fed beef cattle are just outside the range given by the IPCC. Australia would expect to be at the low end of the range of excretion rates due to the quality of pasture available for range-kept cattle consumption.

Swine N excretion rates were generally consistent with IPCC (2019) values, although Australia's 'other pig' rate was slightly higher. Differences could be related to different feed intake, crude protein intake or N retention assumptions compared to the IPCC.

Table 5.17 Nitrogen excretion rates (kg/head/year)

Livestock type	Australia	IPCC 2006 default	IPCC 2019
Dairy cattle (455 kg)	124	58-80	42-142
Beef cattle			38-94 (other cattle)
Pasture (378 kg)	42	43-69	43-69
Feedlot (524 kg)	71	60-96	60-96
Sheep (43 kg)	7	5-8	5-9
Swine			
Sows (188 kg)	18	21-34	11-27
Growers (39 kg)	11	4-7	7-17
Poultry	0.6-0.7	0.6-1.0	0.4-0.7

Source: IPCC (2006) and (2019).

External review

Comprehensive expert peer review of the methodologies, activity data and livestock characterisation data were conducted for sheep in 2000-01; dairy and feedlot cattle, swine and poultry in 2014; and QLD/NT beef cattle on pastures in 2015. The reviews involved agricultural experts from industry, government and academia.

5.3.5 Category-specific recalculations

Recalculations of *emissions from* manure *management* reported in the current submission are shown in Table 5.18 and are due to:

A. Revisions to Emission Factors for fertilisers.

Emission factors for fertiliser use on crop and pasture land were updated based on a new meta-analysis of N_2O emissions from Australian agriculture from 2003 to 2021 (Grace, et al. 2023). The new EFs are provided in Table 5.21. These source-specific EFs are also used to calculate the indirect emissions from manure management.

B. Dairy: Updates to some activity data, and the MCF for liquid manure management

From 2015 onward, MMS allocation for Dairy cattle was updated based on the Dairy Australia's *Land, Water and Carbon Survey Report* (2020). Additionally, in response to ERT recommendation A.16 (2022) the Methane Conversion Factor (MCF) for anaerobic lagoons and drains to paddocks has been estimated for each year using the annual temperature of dairy regions in each State and Territory.

C. Swine: Updates to the MCF for liquid manure management

As for Dairy (as described in the previous paragraph) the Methane Conversion Factor (MCF) for anaerobic lagoons and drains to paddocks has been estimated for each year using the annual temperature of piggery regions in each State and Territory.

Table 5.18 Manure Management (3.B): recalculations of total CO_2-e emissions, 1989–90 to 2020–21

	2023 submission	2024 submission	Change		Reasons for Recalculation (Gg CO_2-e)		
Year	(Gg CO_2-e)		(Gg CO_2- e)	(Per cent)	A	B	C
1989-90	7,093	7,131	38	0.5%	44	-3	-2
1994-95	6,508	6,544	36	0.6%	48	-5	-6
1999-00	6,944	6,988	44	0.6%	52	-7	-2
2004-05	7,630	7,692	62	0.8%	66	-9	5
2005-06	7,610	7,671	62	0.8%	68	-9	3
2006-07	7,421	7,507	86	1.2%	68	2	16
2007-08	7,069	7,134	65	0.9%	56	2	7
2008-09	7,012	7,062	50	0.7%	55	-9	4
2009-10	7,008	7,082	74	1.1%	56	4	15
2010-11	7,137	7,176	40	0.6%	57	-11	-7
2011-12	7,328	7,386	57	0.8%	57	0	0
2012-13	7,327	7,389	62	0.9%	57	2	3
2013-14	7,468	7,547	79	1.1%	59	3	17
2014-15	7,346	7,322	-24	-0.3%	67	-97	6
2015-16	7,168	7,164	-4	-0.1%	66	-87	17
2016-17	7,409	7,396	-13	-0.2%	67	-81	2
2017-18	7,527	7,529	2	0.0%	71	-84	15
2018-19	7,042	7,054	12	0.2%	72	-74	14
2019-20	6,806	6,806	0	0.0%	73	-79	6
2020-21	7,190	7,186	-4	-0.1%	73	-83	4

5.3.6 Category-specific planned improvements

For manure management the following areas have been identified for review and/or change:

1. *Manure mass and* N_2O *emissions* – Recent Australian research (Redding et al. (2015)) directly measured emissions from the manure layers on several feedlot surfaces using a large chamber. A key finding of this research was that there was no significant relationship between manure N-mass and N_2O emission, contrary to the IPCC (2006) approach. This finding was supported by the recent review of the drylot N_2O EF by Wiedemann and Longworth (2020) who noted that as manure nitrogen is not the first limiting factor driving N_2O emissions from drylots, reducing manure N is less likely to influence emissions than would be suggested by the EF. Research to provide a prediction method based on key drivers; temperature, rainfall and manure moisture (Parker et al. (2018), Redding et al. (2015), Sun et al. (2016), Waldrip et al. (2016)), may lead to better process knowledge and a revised emission factor or prediction method in the future. (Wiedemann & Longworth (2020))

2. *Methane Capture and Destruction* – a number of piggeries and poultry operations are capturing and destroying methane from digesters/covered lagoons. Those farms who participated in the Emissions Reduction Fund have now reported data to the Clean Energy Regulator. This data will be reviewed to determine if it can be used to develop a more accurate MCF based on measurement data.

3. *Modernisation of ABS Agricultural Statistics* – as described in section 5.2.4, the department is consulting with Australian Bureau of Statistics as they modernise the production of agricultural statistics. This may entail changes to the age class information and spatial location of the national herd, including time-series recalculations.

5.4 Rice Cultivation (CRT category 3.C)

5.4.1 Category description

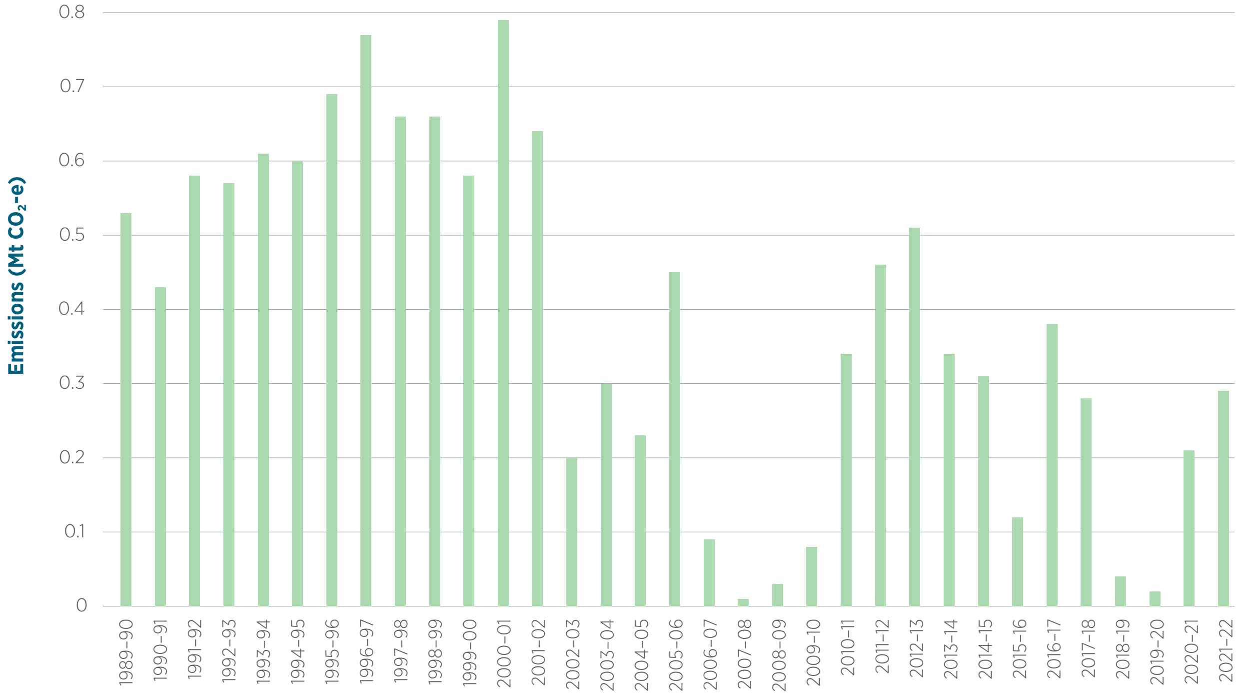
Methane is generated during rice growing from the decomposition of plant residues and other organic carbon material in the soil. This generation occurs through microbial action under anaerobic conditions following flooding of the rice crop.

Methane emission rates vary widely, both diurnally in response to immediate environmental factors such as temperature, and also throughout the season in response to crop development and accompanying changes in soil condition. Emission rates are also dependent on more stable factors including soil type and cultivation method (e.g. irrigation regimes, fertiliser application).

All Australian rice is grown under flooded cultivation and production is highly variable from year to year, reflecting water availability and the prices of alternative crops. Australian rice cultivation does not have large inputs of organic matter as rice stubble is usually burnt and urea fertilisers are used rather than manures.

Most of the rice grown in Australia is concentrated in the Murrumbidgee and Murray valleys of southern New South Wales. Small areas of rice are also grown in northern Victoria. These climates are considered temperate. There has also been very small amounts of rice grown in the warmer areas of northern Queensland and Northern territory since 2010.

Figure 5.9 Rice cultivation emissions, Australia, 1989–90 to 2021–22, Mt CO_2-e



5.4.2 Methodological issues

A tier 1 method is applied to estimate emissions from rice cultivation, but drawing upon updates to default emission factors provided in the 2019 Refinement (IPCC 2019).

Activity data is sourced from the ABS (Agricultural Commodities).

The IPCC (2019) EF of 1.19 kg CH_4/ha/day is used, with appropriate scaling factors applied for a continuously flooded water regime (SFw = 1) and a non-flooded pre-season of >180 days (SFp = 0.89). These factors were selected as they are based on the latest science, are disaggregated by water regime type prior to and during cropping, and they have reduced levels of uncertainty than IPCC (2006) defaults.

Over the average 150 day growing season this gives an emission rate for Australia of 158.9 kg CH_4/ha as per Equation 5.2 in IPCC 2019:

$$\text{Rice EF} = EF_c \times SF_w \times SF_p \times SF_o$$

Where EF_c is the baseline EF for continuously flooded fields without organic amendments (1.19 kg CH_4/ha/day x 150 days)

SF_W is the scaling factor to account for the differences in water regimes during the cultivation period (irrigated, continuously flooded production systems)

SF_P is the scaling factor to account for the differences in water regimes in the pre-season before the cultivation period (non-flooded pre-season >180 days)

SF_O is the scaling factor for organic amen$_{dm}$ents (as fertiliser is used rather than manure, this factor is not applied and set to 1)

Australia's Rice EF = (1.19 x 150) x 1 x 0.89 x 1 = 158.9

Table 5.19 Symbols used in algorithms for rice cultivation

State (i)
1 = ACT
2 = Northern Territory
3 = NSW
4 = Queensland
5 = Tasmania
6 = South Australia
7 = Victoria
8 = Western Australia

Annual production of methane from rice cultivation (E_i Gg) is calculated as:

$$E_i = A_i \times EF \times 10^{-6} \qquad (3.C\_1)$$

Where A_i = area under rice cultivation (ha)

EF = emission factor integrated over the whole season (158.9 kg CH_4/ha)

The area under rice cultivation by State for the entire Inventory time series is provided in Annex 5.5.12.

5.4.3 Uncertainty assessment and time-series consistency

A quantitative assessment of uncertainty was undertaken and uncertainties for rice cultivation were estimated to be in the order of 50 per cent. Further details on the analysis are provided in Annex 2. Time series consistency is ensured by the use the same methods and data sources for the full time series.

5.4.4 Category-specific QA/QC and verification

This source category is covered by the general QA/QC procedures detailed in Annex 4.

5.4.5 Category-specific recalculations

There are no recalculations associated with rice cultivation in this submission.

5.4.6 Category-specific planned improvements

All data and methodologies are kept under review.

On a trend assessment, rice cultivation has been assessed as a key category. Tier 2 emissions factors are being considered for incorporation into the inventory as time and resources permit. Rice cultivation in Australia is highly responsive to water availability, so the trend in rice area under cultivation and the resultant emissions can be highly variable from year to year.

5.5 **Agricultural Soils** (CRT category 3.D)

5.5.1 Category description

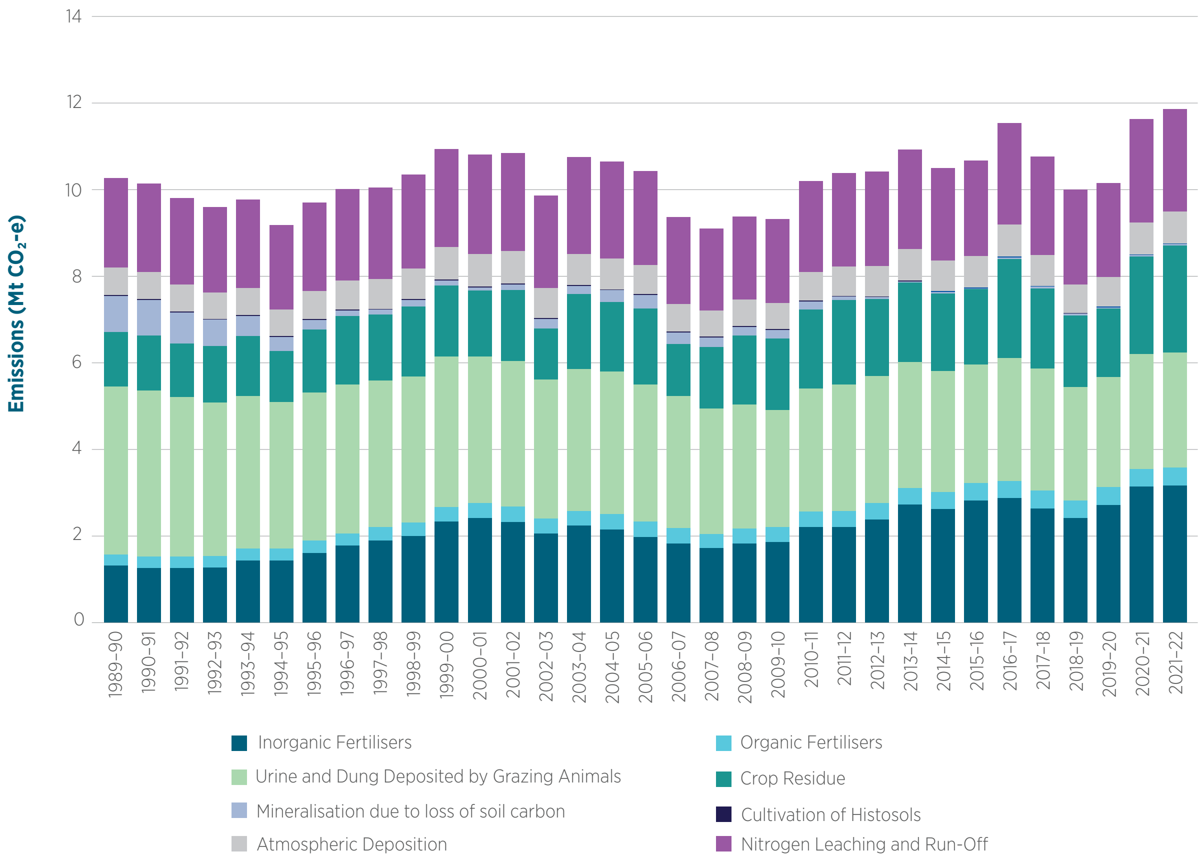
Direct and indirect emissions of nitrous oxide from soils arise from microbial and chemical transformations that produce and consume nitrous oxide in the soil. The transformations involve inorganic nitrogen compounds in the soil, namely ammonium, nitrite and nitrate.

Nitrogen compounds can be added to the soil through the following processes:

a. the application of inorganic nitrogen fertilisers
b. the application of animal wastes and sewage sludge to pastures
c. the application of crop residues
d. mineralisation due to loss of soil carbon
e. mineralisation due to cultivation of organic soils
f. atmospheric nitrogen deposition

A further source of nitrous oxide is associated with leaching of N from soils and surface runoff, and subsequent denitrification in rivers and estuaries.

Figure 5.10 Agricultural Soil emissions by source, Australia, Mt CO_2-e



5.5.2 Methodological issues

Inorganic fertilisers (3.D.a.1)

Activity data is sourced from Fertilizer Australia, and the ABS (Water use in Australia).

A tier 2 method is used to estimate emissions from inorganic fertilisers. The EFs are based on analyses of Australian measurement studies (Grace et al. (2023),Scherbak and Grace (2014); Scherbak et al. (2014)), including those undertaken through programs such as the Nitrous Oxide Research Program (NORP) and the National Agricultural Nitrous Oxide Research Program (NANORP). This research on the application of fertilisers to different production systems and climatic regions in Australia has shown large variations across different classes of crop and pasture systems. The EFs for all production systems except sugar cane fall within the default range provided in IPCC (2019) for N inputs in dry climates, which reflects the climatic conditions of most agricultural land in Australia. The EF for sugar cane is at the upper end of the IPCC (2019) default range for wet climates, also reflecting the climate of the region where cane is grown. The studies compiled in the meta-analyses by Grace et al. (2023) and Scherbak and Grace (2014) are mostly based on urea fertiliser, which represents more than 60% of the nitrogen in inorganic nitrogen fertilisers.

Variation in EFs with region and production system is to be expected. For example, the majority of Australian grain production is from rain-fed cultivation in relatively low rainfall areas where low rates of nitrogen fertiliser inputs, low decomposition rates and low levels of microbial activity (Barton et al. (2008)) contribute to a lower denitrification potential.

It is also apparent that the EFs in some production systems increase with nitrogen application rates. For example, Scherbak et al. (2014) have developed a two component (linear + exponential) model for cotton which gives EF (per cent) = 0.29 + 0.007($e^{0\ 037'\text{N application rate}}$ -1) -f N application rate.

The EFs used in the inventory for inorganic fertiliser are provided in Table 5.21.

Calculation of fertiliser applied to each production system

Total fertiliser use in each State is provided by Fertilizer Australia. The fraction of fertiliser applied to each production system (FN_{ij}) was determined for each State by first estimating the mass of N-fertiliser applied to irrigated crops, irrigated pasture, cotton, sugar cane and horticulture using the production areas reported by ABS (see Table A5.5.8.1) and the average fertiliser application rates for each of these crops. The balance of the fertiliser is then distributed to rain-fed crops and modified pastures (derived from Stewart et al. 2001) in proportion to their respective areas.

Fertiliser application rates assigned to irrigated crops, irrigated pastures, cotton, and horticultural crops and vegetables are respectively 80 kg N/ha, 80 kg N/ha, 246 kg N/ha, and 125 kg N/ha. For sugar cane, a variable application rate is used (see Table A5.5.8.2). Sugar cane fertiliser application rates in QLD have declined significantly over the time series in response to environmental management legislation.

Table 5.20 Symbols used in algorithms for inorganic fertiliser

State (i)	Activity (j)
1 = ACT	1 = Irrigated pasture
2 = Northern Territory	2 = Irrigated crop
3 = NSW	3 = Non-irrigated pasture
4 = Queensland	4 = Non-irrigated crop
5 = Tasmania	5 = Sugar cane
6 = South Australia	6 = Cotton
7 = Victoria	7 = Horticulture
8 = Western Australia	

Table 5.21 Nitrous oxide EFs for inorganic fertiliser

Production system	Emission factor (a) (Gg N_2O-N/ Gg N)
Irrigated pasture	0.0059
Irrigated crop	0.007
Non-irrigated pasture	0.0018
Non-irrigated crop	0.0041 (b)
Sugar cane	0.0199 (c)
Cotton	0.0053
Horticulture	0.0064

(a) Based on (Grace, et al. 2023) .

(b) Weighted EF assuming 77 per cent of non-irrigated crops occur on low rainfall areas. Low rainfall EF = 0.0029 and high rainfall EF = 0.008. The threshold between low and high rainfall areas is annual rainfall = 600 mm.

(c) Based on Scherbak and Grace (2014).

Limited amounts of fertiliser are also used in Australian forests. Currently there is no data available to allocate fertiliser use specifically to forestry activities. Given the approach taken to allocating fertiliser, it is assumed that any fertiliser applied for forestry activities will fall under the non-irrigated systems and have an EF of 0.18 per cent applied.

The mass of fertiliser applied to soils via crop production systems (M_{ij} Gg N) is calculated as:

$$M_{ij} = TM_{ij} \times FN_{ij} \quad . (3.D.A\_1)$$

Where TM_{ij} = total mass of fertiliser (Gg N)

FN_{ij} = fraction of N applied to production system J

Annual nitrous oxide production from the addition of organic fertilisers (E_{if} Gg N_2O) is calculated as:

$$E_{ij} = \Sigma_i \Sigma_j (M_{ij} \times EF_{ij} \times C_g) \quad (3DA\_2)$$

Where EF_{ij} = emission factor (Gg N_2O-N/Gg N applied) (Table 5.21)

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Organic fertilisers (3.D.a.2)

Direct emissions from organic fertilisers arise from both animal wastes applied to soils and sewage sludge applied to land.

Animal wastes applied to soils (3.D.a.2.a)

Nitrous oxide is emitted from soil through the metabolism of animal manure derived principally from dairies, feedlots, piggeries and poultry houses and applied to crops and pastures as organic fertiliser. The IPCC (2006) default EF for N_2O emissions from animal wastes applied to soils (1 per cent) is used for dairies, feedlots and poultry houses. Piggeries use an EF of 0.0059 Gg N_2O-N/Gg N deposited.

Inputs to this subsector are calculated using MMS equations in Chapter 5.3.

Table 5.22 Symbols used in algorithms for animal wastes applied to soils

State (i)	Activity (j)
1 = ACT	1 = Dairy cattle
2 = Northern Territory	2 = Beef cattle – feedlot
3 = NSW	3 = Swine
4 = Queensland	4 = Poultry
5 = Tasmania	
6 = South Australia	
7 = Victoria	
8 = Western Australia	

The amount of nitrogen applied to soils is the nitrogen excreted, adjusted for the nitrogen that has already been lost as N_2O, NH_3 and NO_x during storage in the different MMS.

Thus the nitrogen content of animal wastes applied to agricultural soils (MN Soil_{ij}) is calculated as:

$$\text{MN Soil}_{ij} = \Sigma_{MMS} (((AE_{ij\ MMS=1\text{-}13} \times (1 - EF_{MMS=1\text{-}13} - \text{FracGASM}_{j\ MMS=1\text{-}13})) - \text{MNLEACH}_{ij\ MMS=1\text{-}13}) \qquad (3.D.A\_3)$$

Where $AE_{ij\ MMS=1\text{-}13}$ = mass of N excreted, as calculated for manure management. For dairy cattle AE_{ij} is the sum of faecal (AF) and urinary (AU) nitrogen

$EF_{MMS=1\text{-}13}$ = direct nitrous oxide EF from the different MMS (Annex 5.5)

$\text{FracGASM}_{j\ MMS=1\text{-}13}$ = fraction of animal waste N volatilised from the different MMS (Annex 5.5)

$\text{MNleach}_{ij\ MMS=1\text{-}13}$ = mass of animal waste N from leaching and runoff, as calculated for manure management

Annual nitrous oxide production from animal wastes applied to soils (E_{ij} Gg N_2O) is calculated as:

$$E_{ij} = \Sigma_i \Sigma_j (\text{MN Soil}_{ij} \times EF \times C_g) \qquad (3.D.A\_4)$$

Where EF = 0.00503 (Gg N_2O-N/Gg N deposited) (weighted average calculated from IPCC 2019)

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Sewage sludge applied to land (3.D.a.2.b)

Treated sewage sludge is applied to land in Australia for the purposes of disposal rather than as a fertiliser for agricultural production, due to health concerns. A CS EF based on studies where sewage sludge was applied to soils (Bouwman et al. (2002)) is used to estimate emissions. The experiments gave an average N_2O EF of 0.9 per cent (range 0.8 to 1.0 per cent).

Activity data is from the *waste* sector (category 5.D wastewater treatment and discharge – domestic and commercial). The quantity of sewage sludge removed from wastewater treatment plants for application to land is reported by wastewater treatment plants under the National Greenhouse and Energy Reporting (NGER) scheme. See Chapter 7.5 for further information.

Table 5.23 Symbols used in algorithms for sewage sludge applied to land

State (i)
1 = ACT
2 = Northern Territory
3 = NSW
4 = Queensland
5 = Tasmania
6 = South Australia
7 = Victoria
8 = Western Australia

Annual nitrous oxide production from sewage sludge applied to land (E_i Gg N_2O) is calculated as:

$$E_i = \Sigma_i (M_i \times EF \times C_g) \qquad (3.D.A\_5)$$

Where M_i = Mass of sewage sludge N applied to lands (Gg)

EF = 0.009 (Gg N_2O-N/Gg N) Bouwman et al. 2002

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Urine and dung deposited by grazing animals (3.D.a.3)

Nitrous oxide is emitted from soil through the metabolism of urine and faeces deposited directly onto pastures.

Urine experiments conducted on rain-fed legumes and annual pastures in central NSW (Galbally et al. (1994)), and irrigated pastures in Victoria (Galbally et al. (2005)) found emission rates of 0.4 per cent. There are still relatively few measurements of EFs from animal faeces deposited directly to soil in the absence of urine but Flessa et al. (1996), Yamulki and Jarvis (1997), and Oenema et al. (1997) have reported emission rates from dung of 0.3-0.7 per cent. As such, an EF of 0.4 per cent (0.004 Gg N_2O-N/Gg N), is used to estimate N_2O emissions from urinary and faecal N deposition to soil. This value is within the uncertainty range for both the IPCC (2006) and IPCC (2019) EF.

Table 5.24 Symbols used in algorithms for urine and dung deposited by grazing animals

State (i)	Activity (j)
1 = ACT	1 = Dairy cattle
2 = Northern Territory	2 = Beef cattle – pasture
3 = NSW	3 = Sheep
4 = Queensland	4 = Poultry
5 = Tasmania	5 = Other livestock
6 = South Australia	
7 = Victoria	
8 = Western Australia	

Annual nitrous oxide production from urine and dung deposited by grazing animals (E_{ij} Gg N_2O) is calculated as:

$$E_{ij} = \Sigma_i \Sigma_j ((AF_{ij\ MMS=14} \times EF_j \times C_g) + (AU_{ij\ MMS=14} \times EF_j \times C_g)) \qquad (3.D.A\_6)$$

Where $AF_{ij\ MMS=14}$ and $AU_{ij\ MMS=14}$ = mass of faecal and urinary nitrogen excreted on pasture range and paddock as calculated for manure management. For poultry all N excreted is assumed to be faeces

EF_j = 0.004 (Gg N_2O-N/Gg N deposited)

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Crop Residues (3.D.a.4)

The method used to estimate emissions from crop residues returned to the soil is based on the IPCC tier 2 method and EFs. Activity data is sourced from the ABS (Agricultural Commodities) and ABARES (Australian Crop Report).

This subsector also includes emissions from pasture residues returned to the soil, based on activity data derived from FullCAM simulations in LULUCF. The climate-zone-dependent IPCC (2019) default EF for N_2O emissions from crop residues (0.5 per cent in dry zones and 0.6 per cent in wet zones) are used. A weighted national average EF is calculated based on the nitrogen production and climate zone of each crop. The weighted EF is 0.503 per cent, reflecting the dominance of dry climate zones in Australian cropland.

Table 5.25 Symbols used in algorithms for crop residues

State (i)	Crops (j)	Pasture (k)	Pasture renewal system (l)
1 = ACT	1 = Wheat	1 = Lucerne	1 = Intensive (1 in 10 years)
2 = NT	2 = Barley	2 = Other legume pasture	2 = Other (1 in 30 years)
3 = NSW	3 = Maize	3 = Grass clover mixture	
4 = Qld	4 = Oats	4 = Perennial pasture	
5 = Tas	5 = Rice	5 = Annual grass	
6 = SA	6 = Sorghum		
7 = Vic	7 = Triticale		
8 = WA	8 = Other cereals		
	9 = Pulses		
	10 = Tubers and roots		
	11 = Peanuts		
	12 = Sugar cane		
	13 = Cotton		
	14 = Hops		
	15 = Oilseeds		
	16 = Forage crops		

The mass of N in crop residues returned to soils (M_{ijk} Gg N) is calculated as:

$$M_{ijk} = (P_{ij} \times R_{AGj} \times (1 - F_{ij} - FFOD_{ij}) \times DM_j \times NC_{AGj}) + (P_{ij} \times R_{AGj} \times R_{BGj} \times DM_j \times NC_{BGj}) \quad (3.D.A\_7)$$

Where P_{ij} = annual production of crop (Gg)

R_{AGj} = residue to crop ratio (kg crop residue/kg crop) (Table A5.5.9.1)

R_{BGj} = below ground-residue to above ground residue ratio (kg /kg) (Table A5.5.9.1)

F_{ij} = fraction of crop residue that is burnt (Table A5.5.9.1)

$FFOD_{ij}$ = fraction of the crop residue that is removed (Table A5.5.9.1)

DM_j = dry matter content (kg dry weight/kg crop residue) (Table A5.5.9.1)

NC_{AGj} = nitrogen content of above-ground crop residue (kg N/kg DM) (Table A5.5.9.1)

NC_{BGj} = nitrogen content of below-ground crop residue (kg N/kg DM) (Table A5.5.9.1)

The mass of N in pasture residues returned to soils (M_{ikl} Gg N) is calculated as:

$$M_{ikl} = (A_{ikl} \times Frac_{Renewal} \times (Y_k \div 1000) \times (1 - FFOD_{ik}) \times NC_{AGk}) + (A_{ikl} \times Frac_{Renewal} \times (Y_k \div 1000) \times R_{BGk} \times NC_{BGk} \quad (3.D.A\_8)$$

Where A_{ikl} = Area of pasture (ha)

$Frac_{Renewal}$ = Fraction of pasture renewed = 1/ X where X is the average renewal period in years: 10 years for intensive systems and 30 years for other systems

Y_k = Average yield (t DM/ha) (Table A5.5.9.2)

R_{BGk} = below ground-residue: above ground residue ratio (kg /kg) (Table A5.5.9.1)

NC_{AGk} = N content of above-ground crop residue (kg N/kg DM) (Table A5.5.9.1)

NC_{BGk} = N content of below-ground crop residue (kg N/kg DM) (Table A5.5.9.1)

$FFOD_{ik}$ = fraction of pasture yield that is removed (Table A5.5.9.2)

Annual nitrous oxide production from crop residues (E_j Gg N_2O) is calculated as:

$$E_i = \Sigma_i\Sigma_k\Sigma_l (M_{ijkl} \times EF \times C_g) \qquad (3.D.A\_9)$$

Where M_{ijkl} = mass of N in crop residues (Gg N)
EF = 0.01 (Gg N_2O-N/Gg N) IPCC 2006 default
C_g = 44/28 factor to convert from elemental mass of N_2O to molecular mass

Mineralisation due to loss of soil carbon (3.D.a.5)

Where a loss of soil carbon in *cropland remaining cropland* occurs, this loss will be accompanied by a simultaneous mineralisation of N. This mineralised N is considered as an additional source of N available for conversion to N_2O, along with mineralised N released through the decomposition of crop residues (IPCC 2006). In years in which *cropland remaining cropland* is a net carbon sink there may be no emissions reported in this category. Soil carbon stock changes are estimated in LULUCF using FullCAM simulations.

The IPCC (2006) method, using CS parameters and EFs, is used to calculate N_2O emissions from this source. The C:N value used is 10, reflecting the approximate median value extracted from a survey of national estimates (Snowdon et al. 2005).

The CS EF for fertiliser additions to non-irrigated crops is then applied (see Table 5.21). The EF is based on analyses of Australian measurement studies (Grace et al. 2023, Scherbak and Grace 2014; Scherbak et al. 2014), including those undertaken through programs such as the Nitrous Oxide Research Program (NORP) and the National Agricultural Nitrous Oxide Research Program (NANORP). The EF applied (0.0041 Gg N_2O-N/Gg N) is a weighted EF assuming 77 per cent of non-irrigated crops occur on low rainfall areas, and falls within the default range provided in IPCC (2019) for N inputs in dry climates, which reflects the climatic conditions of most agricultural land in Australia.

Table 5.26 Symbols used in algorithms for mineralisation due to loss of soil C

State (i)
1 = ACT
2 = Northern Territory
3 = NSW
4 = Queensland
5 = Tasmania
6 = South Australia
7 = Victoria
8 = Western Australia

Annual nitrous oxide production from mineralisation due to loss of soil carbon (E_i Gg N_2O) is calculated as:

$$E_j = \Sigma_i (M_i \times NC \times EF \times C_g) \qquad (3.D.A\_10)$$

Where M_i = loss of soil carbon in *cropland remaining cropland* (Gg)
NC = nitrogen to carbon ratio for cropland soils
EF = 0.0041 (Gg N_2O-N/Gg N) (Scherbak and Grace 2014)
C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Cultivation of histosols (3.D.a.6)

The default IPCC tier 1 methodology is used to estimate emissions from the cultivation of histosols.

The area of cultivated histosols is very limited in Australia (known as organosols in the Australian Soil Classification 2016). Organosols occur in Queensland where they are mostly used for sugar cane production, and small locations in Victoria where peatlands were cleared and subsequently grazed or cropped. Individual patches are typically very small, which leads to significant uncertainty when estimating the national area. The land area for histosols was estimated using expert judgement (C. Meyer pers. comm.). There is also a large area of histosols in Tasmania, although this land is not cultivated, so is not included in Australia's calculations for cultivation of histosols.

The area of cultivated histosols used in the estimation of emissions from cultivated organic soils, is crosschecked with those reported in the LULUCF sector to ensure consistency.

The EF used takes into account the different climatic conditions associated with the two isolated areas.

A weighted average of 14 is applied, calculated from a factor of 16 for Queensland, for tropical organic crop and grassland soils, and 8 for Victoria, for temperate organic crop and grassland soils (IPCC 2006).

Table 5.27 Symbols used in algorithms for cultivation of histosols

State (i)
1 = ACT
2 = Northern Territory
3 = NSW
4 = Queensland
5 = Tasmania
6 = South Australia
7 = Victoria
8 = Western Australia

Annual nitrous oxide production from cultivation of histosols (E_i Gg N_2O) is calculated as:

$$E_i = \Sigma_i (A_i \times EF \times C_g \times 10^{-6}) \qquad (3.D.A\_11)$$

Where A_i = area of cultivated histosols (ha)

EF = 14 kg N_2O-N/ha (weighted average of IPCC (2006) default values)

C_g = 44/28 factor to convert elemental mass of N O to molecular mass

Atmospheric deposition (3.D.b.1)

A Tier 1 method using CS EFs is used to estimate indirect N_2O emissions by atmospheric deposition from inorganic fertilisers, manure and sewage sludge. As the highest deposition rates (kg/ha) are found within a few hundred meters of the emission source, the EFs applied for deposition are related to the source of N.

For N volatilised from inorganic fertilisers or sewage sludge, the EFs applied for atmospheric deposition are the same as those applied for direct N_2O emissions (see Table 5.21). The EFs are based on analyses of Australian measurement studies (Scherbak and Grace (2014); Scherbak et al. (2023)), including those undertaken through programs such as the Nitrous Oxide Research Program (NORP) and the National Agricultural Nitrous Oxide Research Program (NANORP). This experimental work showed large variations across different types of crop and pasture systems, with EFs within the default ranges provided in IPCC (2019).

For N derived from a manure source, the inorganic fertiliser EF which best represents the production system immediately surrounding the farm is used to estimate atmospheric deposition emissions.

Country specific FracGASMsoil and FracGASF values are used to calculate N volatilised from organic and synthetic fertilisers, and animal waste deposited on soils. They are based on syntheses of the latest internationally-assessed science, as reported in the 2019 IPCC Refinement (IPCC 2019).

Table 5.28 Symbols used in algorithms for atmospheric deposition

State (i)	Activity (j)
1 = ACT	1 = Inorganic fertilizer
2 = Northern Territory	2 = Manure
3 = NSW	3 = Sewage sludge applied to land
4 = Queensland	
5 = Tasmania	
6 = South Australia	
7 = Victoria	
8 = Western Australia	

The mass of N volatilised from inorganic fertiliser applied to soils ($M_{ij=1}$ Gg N) is calculated as:

$$M_{ij=1} = TM_{ij=1} \times FracGASF_j \qquad (3.D.B\_1)$$

Where $TM_{ij=1}$ = total mass of fertiliser (Gg N), as estimated for inorganic fertilizers

$FracGASF_j$ = 0.11 (Gg N/Gg applied) (IPCC 2019))

The mass of N volatilised from animal waste deposited on or applied to soils ($M_{ij=2}$ Gg N) is calculated as:

$$M_{ij=2} = \Sigma\,(MNsoil_{ij} + UNsoil_{ij} + FNsoil_{ij}) \times FracGASMsoil_{ij} \qquad (3.D.B\_2)$$

Where MNsoiL = mass of manure N applied to soils (Gg N)

$UNsoil_{ij}$ = mass of urinary N excretion on pasture (Gg N)

FNsoiL = mass of faecal N excretion on pasture (Gg N)

$FracGASMsoil_{ij}$ = 0.21 (kg NH_3-N + NO_x-N) (kg N applied or deposited)-1 (IPCC 2019))

The mass of N volatilised from sewage sludge applied to soils ($M_{ij=3}$ Gg N) is calculated as:

$$M_{ij=3} = TM_{ij=3} \times FracGASS_j \qquad (3.D.B\_3)$$

Where $TM_{ij=3}$ = total mass of sewage sludge (Gg N)

$FracGASS_j$ = 0.21 (Gg N/Gg applied) (CS EF, source IPCC (2019))

Annual nitrous oxide production from atmospheric deposition (E Gg N_2O) is calculated as:

$$E = \Sigma_i \Sigma_j\,(M_{ij} \times EF_{ij} \times C_g) \qquad (3.D.B\_4)$$

Where M_{ij} = mass of N volatilised from each sub-sector (Gg N)

EF_{ij} = source specific EF (Gg N_2O-N/Gg N)

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Leaching and runoff (3.D.b.2)

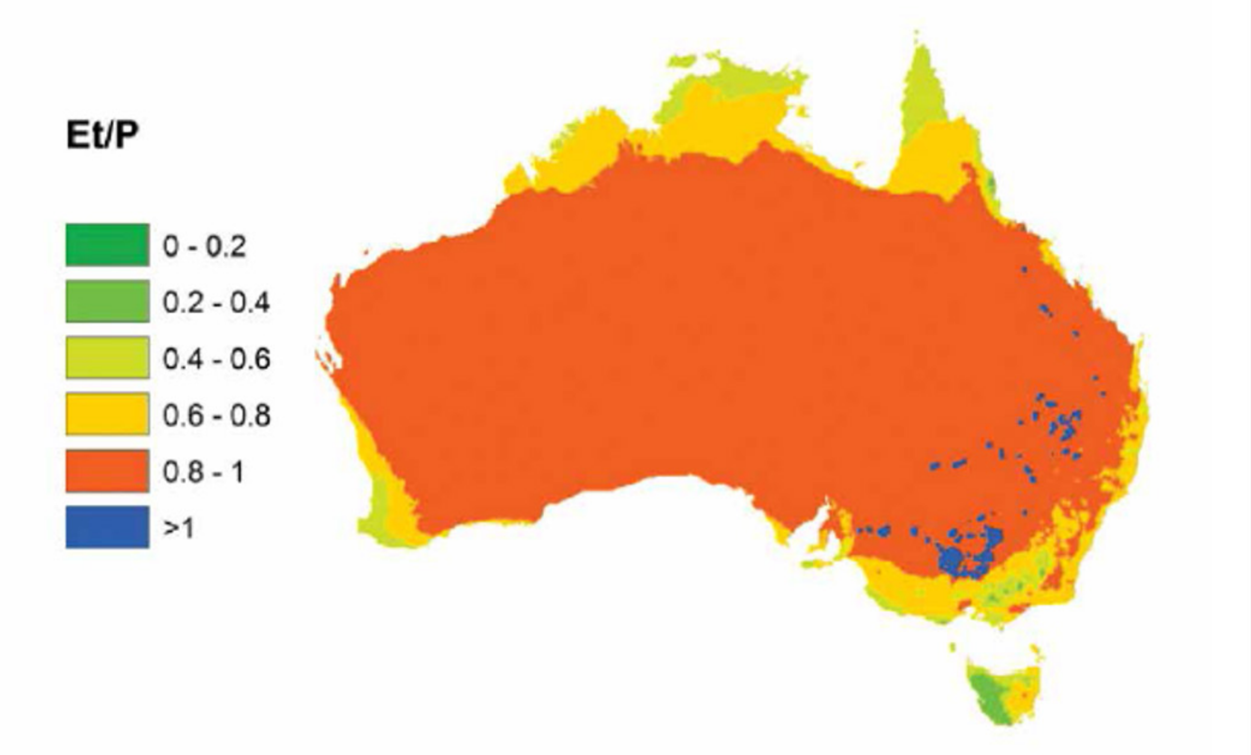
Australia is the driest continent, with substantially less runoff than all other continents. In Australia, much of the cropping takes place in semi-arid regions, or regions of marginal rainfall. Leaching of applied nitrogen into waterways and estuaries is unlikely where evaporation exceeds precipitation (IPCC 2019).

Areas in Australia which are unlikely to be susceptible to significant leaching can be identified using the ratio of evapotranspiration to annual precipitation (Et/P). Evapotranspiration is a better measure than evaporation as it takes into account climatic factors (rainfall, humidity, temperature, wind speed) as well as the effect of different vegetation types (forest, shrubland, grassland) on the demand for soil water.

Evapotranspiration has been estimated using the biogeochemical model BIOS (Raupach et al. (2000)) for the National Land and Water Audit. Et/P ranges up to 1 where all rainfall is returned to the atmosphere. In areas such as wetlands and irrigation areas in inland regions, where water supply additional to precipitation is available, Et/P can exceed 1.

In this methodology, we consider leaching to occur where Et/P <0.8 or Et/P >1 (Figure 5.11). Regions outside these areas are considered to be 'dryland' and not subject to leaching. The fraction of each crop and animal class occurring outside the dryland areas (FracWET) were determined by overlaying the dryland area mask onto the spatial map of crops, pastures and animal density from the 1997 Agricultural census (ABS (Australian Bureau of Statistics) 1999) (ABS 1999).

Figure 5.11 The ratio of mean annual evapotranspiration to annual precipitation (Et/P)



Indirect emissions from leaching and runoff arise from five sources:

- Inorganic fertiliser
- Animal wastes applied to soils
- Sewage sludge applied to land
- Crop residues
- Mineralisation due to loss of soil C

In the areas subject to leaching, FracLEACH value and N_2O EF values from IPCC (2019) are used to calculate N that is lost through leaching and runoff.

Table 5.29 Symbols used in algorithms for leaching and runoff

State (i)	Activity (j)
1 = ACT	1 = Inorganic fertilizer
2 = Northern Territory	2 = Animal waste
3 = NSW	3 = Sewage sludge
4 = Queensland	4 = Crop residues
5 = Tasmania	5 = Mineralisation due to loss of soil C
6 = South Australia	
7 = Victoria	
8 = Western Australia	

The mass of inorganic fertiliser N applied to soils that is lost through leaching and runoff ($M_{ij=1}$ Gg N) is calculated as:

$$M_{ij=1} = M_{ij} \times FracWET_{ij} \times FracLEACH \quad (3.D.B\_5)$$

Where M_{ij} = mass of fertiliser in each production system (Gg N), as calculated for inorganic fertilisers

$FracWET_{ij}$ = fraction of N available for leaching and runoff (Table A5.5.10.1)

FracLEACH = 0.24 (Gg N/Gg applied) (IPCC 2019))

The mass of animal waste N excreted or applied to soil that is lost through leaching and runoff ($M_{ij=2}$ Gg N) is calculated as:

$$M_{ij=2} = (MNsoil_{ij} + UNsoil_{ij} + FNsoil_{ij}) \times FracWETsoil_{ij} \times FracLEACH \quad (3.D.B\_6)$$

Where $MNsoil_{ij}$ = mass of manure N applied to soils (Gg N), as calculated for organic fertilisers

$UNsoil_{ij}$ = mass of urinary N excretion on pasture (Gg N), as calculated for atmospheric deposition

$FNsoil_{ij}$ = mass of faecal N excretion on pasture (Gg N), as calculated for atmospheric deposition

$FracWETsoil_{ij}$ = fraction of N available for leaching and runoff (Table A5.5.10.2)

FracLEACH = 0.24 (Gg N/Gg applied) (IPCC 2019))

The mass of sewage sludge N applied to soils that is lost through leaching and runoff ($M_{ij=3}$ Gg N) is calculated as:

$$M_{ij=3} = M_{ij} \times FracWET_{ij} \times FracLEACH \quad (3.D.B\_7)$$

Where M_{ij} = mass of sewage sludge N (Gg N), as calculated for organic fertilisers

$FracWET_{ij}$ = fraction of N available for leaching and runoff = 1.0

FracLEACH = 0.24 (Gg N/Gg applied) (IPCC 2019))

The mass of crop residue that is lost through leaching and runoff ($M_{ij=4}$ Gg N) is calculated as:

$$M_{ij=4} = M_{ij} \times FracWET_{ij} \times FracLEACH \qquad (3.D.B\_8)$$

Where M_{ij} = mass of crop residue N (Gg N), as calculated for crop residues
$FracWET_{ij}$ = fraction of N available for leaching and runoff (Table A5.5.10.1)
FracLEACH = 0.24 (Gg N/Gg applied) (IPCC 2019))

The mass of N mineralised due to a loss of soil C lost through leaching and runoff ($M_{ij=5}$ Gg N) is calculated as:

$$M_{ij=5} = M_{ij} \times FracWET_{ij} \times FracLEACH \qquad (3.D.B\_9)$$

Where M_{ij} = mass of N mineralised due to a loss of soil C (Gg N)
$FracWET_{ij}$ = fraction of N available for leaching and runoff (Table A5.5.10.1 – non-irrigated crops)
FracLEACH = 0.24 (Gg N/Gg applied) (IPCC 2019))

Annual nitrous oxide production from leaching and runoff (E Gg N_2O) is calculated as:

$$E = \Sigma_i \Sigma_j (M_{ij} \times EF \times C_g) \qquad (3.D.B\_10)$$

Where M_{ij} = mass of N lost through leaching and runoff (Gg N)
EF = 0.011 (Gg N_2O-N/Gg N) (IPCC 2019)
C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

5.5.3 Uncertainty assessment and time-series consistency

A quantitative assessment of uncertainty was undertaken and uncertainties for agricultural soils were estimated to be in the order of 56 per cent. Further details on the analysis are provided in Annex 2.

Time series consistency is ensured by the use of consistent methods and full time series recalculations for all refinements to methodology.

5.5.4 Category-specific QA/QC and verification

The Australian Bureau of Statistics (ABS) is the national statistical agency of Australia and is the key provider of activity data for this source category. ABS has in place a range of quality assurance-quality control procedures associated with survey design, data input and consistency checks on the survey results and the aggregated values. Sampling errors are also evaluated. Data quality used in the inventory is also kept under review by the Department.

This source category is also covered by the general QA/QC procedures detailed in Annex 4. In particular, AGEIS ensures that data used across multiple categories is entered only once and that intakes or emissions calculated in one category form the input for other categories.

Fertilizer Australia is the industry association representing manufacturers, importers and distributors of fertiliser in Australia. The FAO receives their data from the International Fertilizer Association (IFA), which originates from Fertilizer Australia (Fertilizer Australia provides data to IFA, which they share with FAO).

Inorganic N consumption data supplied by Fertilizer Australia and used in the inventory is compared with data published by the FAO. The results are very close between the two data sources (typically less than 1 per cent) throughout the time-series. There are two main reasons which account for these observed differences:

- The FAO rounds their published data to the nearest '000 tonnes, while Australia uses fertiliser data to the nearest tonne;
- Fertilizer Australia revises their data frequently to ensure accuracy. In a number of years revisions have occurred between the provision of data to IFA and to Department. These revisions are not reflected in the FAO data.

5.5.5 Category-specific recalculations

Recalculations of *agricultural soils* reported in the current submission are shown in Table 5.30 and are due to:

A. Updates to the Crop Residue Emission factor

The NIR 2021 calculation for emissions from crop residues was calculated with an emission factor of 0.01, the IPCC 2006 default. The 2019 Refinement to the 2006 IPCC Guidelines (Chapter 11) introduced two new disaggregated emissions factors in Table 11.1:

- Other N inputs in wet climates, Default value = 0.006
- All N inputs in dry climates = 0.005

These new default values were applied as a single weighted factor, calculated using the mass of nitrogen produced in wet climates compared to dry climates for each crop. The resulting EF is 0.00503, reflecting the dominance of dry climates in Australian cropland, and results in an average recalculation of -1,577 Gg CO_2-e per year over the time series.

B. Revisions to Emission Factors for fertilisers.

Emission factors for fertiliser use on crop and pasture land were updated based on a new meta-analysis of N_2O emissions from Australian agriculture from 2003 to 2021 (Grace, et al. 2023). The new EFs are provided in Table 5.21. While the EFs for individual production systems have been revised both up and down, overall the recalculations have increased emissions by an average of 326 Gg CO_2-e per year over the time series.

C. Revisions to soil carbon losses for nitrogen mineralisation

As described in Chapter 6 (LULUCF), the estimates for soil carbon are recalculated for the entire time series in every inventory. This leads to small changes in the estimates of nitrogen mineralisation due to loss of soil carbon.

Table 5.30 Agricultural soils (3.D): recalculations of total CO_2-e emissions, 1989–90 to 2020–21

	2023 submission	2024 submission	Change		Reasons for Recalculation (Gg CO_2-e)		
Year	(Gg CO_2-e)		(Gg CO_2- e)	(Per cent)	A	B	C
1989-90	11049	10074	-975	-9%	-1217	34	208
1994-95	9813	8989	-824	-8%	-1144	173	147
1999-00	11861	10701	-1161	-10%	-1589	326	102
2004-05	11545	10425	-1119	-10%	-1551	329	103
2005-06	11473	10191	-1281	-11%	-1690	228	181
2006-07	9982	9154	-828	-8%	-1157	210	118
2007-08	9980	8904	-1076	-11%	-1383	246	61
2008-09	10474	9176	-1298	-12%	-1553	247	7
2009-10	10291	9131	-1160	-11%	-1598	327	111
2010-11	11322	9983	-1339	-12%	-1760	315	106
2011-12	11732	10167	-1565	-13%	-1874	309	-1
2012-13	11549	10186	-1363	-12%	-1722	368	-9
2013-14	12069	10696	-1373	-11%	-1778	439	-34
2014-15	11524	10276	-1248	-11%	-1736	481	7
2015-16	11633	10444	-1189	-10%	-1685	489	7
2016-17	12988	11296	-1693	-13%	-2212	502	17
2017-18	11887	10534	-1353	-11%	-1779	434	-7
2018-19	11116	9785	-1331	-12%	-1602	278	-7
2019-20	10997	9929	-1068	-10%	-1531	528	-63
2020-21	13037	11387	-1650	-13%	-2177	631	-103

5.5.6 Category-specific planned improvements

For agricultural soils the following areas have been identified for review and/or change:

1. Use the most recent published information to locate source data to provide information on how inorganic fertiliser EFs are weighted by crop type, climate region, management system and fertiliser type.
2. Consider the disaggregation of inorganic fertiliser EFs into urea and non-urea fertiliser EFs.
3. Review the emission factor for pig waste applied to soils.

5.6 Prescribed Burning of Savannas (CRT category 3.E)

Non-CO_2 emissions from prescribed burning of savannas are reported under LULUCF category 4(IV) to align Australia's reporting with the categories specified in the 2006 IPCC Guidelines (IPCC 2006). Information on forest and grassland fires is included in Chapter 6.3.2.

5.7 Field Burning of Agricultural Residues (CRT category 3.F)

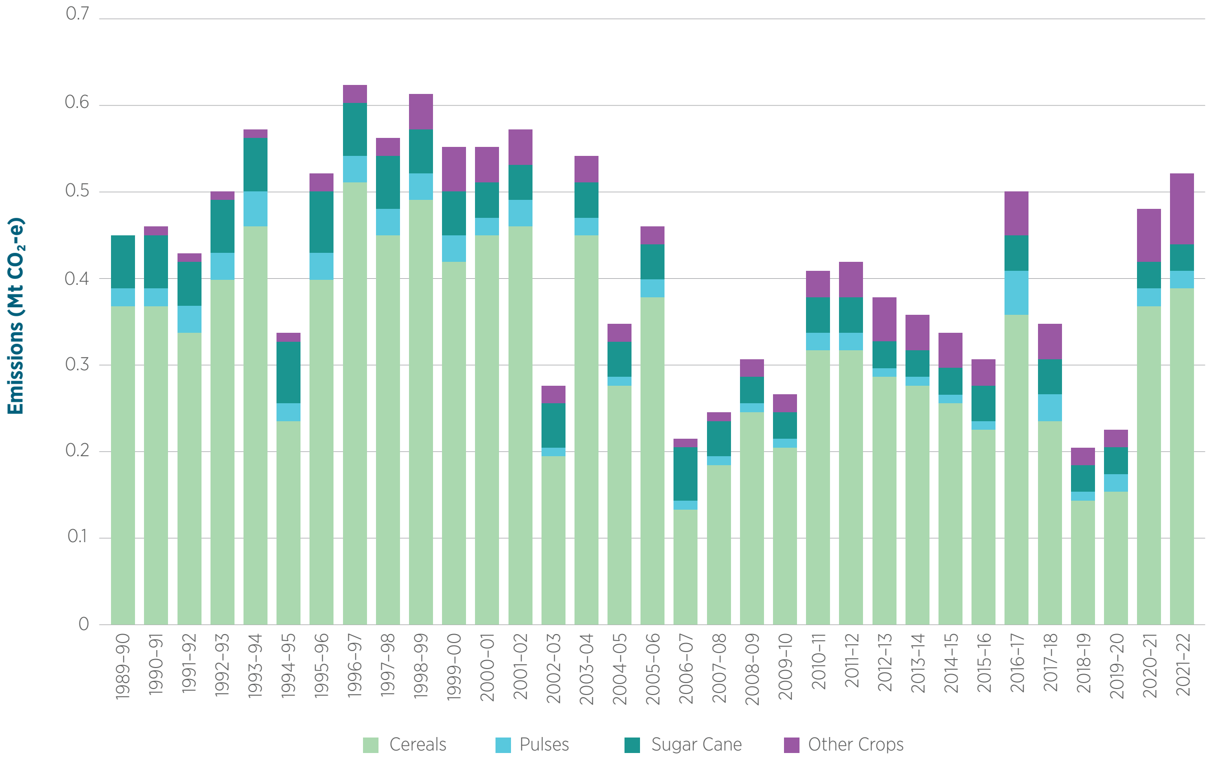
5.7.1 Category description

The burning of residual crop material releases CH_4, N_2O, CO, NO_x and NMVOCs into the atmosphere.

These gases are formed from carbon and nitrogen in the plant material during the combustion process. As per the IPCC *Guidelines* (IPCC 2006), the CO_2 emissions from burning of agricultural residues are not included in the inventory total since it is assumed that an equivalent amount of CO_2 was removed by the growing crop. However emissions from the other gases are included in the inventory.

Stubble burning involves firing the standing stalks in either late autumn or spring. Increasingly, this form of land management is being replaced by stubble retention, which reduces erosion and conserves nutrients. In this latter practice the stubble is grazed some weeks after harvest and the next crop is sown by drilling though the remaining vegetation. Firing of sugar cane has also become less common with the rapid introduction of green cane mechanical harvesting. Sugar cane crops are now burnt once every three or four years at the end of the sowing/ratoon cycle.

Figure 5.12 Emissions from field burning of agricultural residues, Australia, Mt CO_2-e



5.7.2 Methodological issues

The amount of crop residue at the time of burning is in most cases, less than that at the time of harvest.

This applies particularly to crops where there is a long interval between harvest and burning. Vegetation decay and grazing by animals can, over several months, reduce the amount of residue per unit area by one half (R. Jarvis pers. comm., Mulholland et al. (1976)). This loss is allowed for in the algorithm.

Activity data is sourced from the ABS (Agricultural Commodities), sugar industry associations, and Hop Products Australia.

Table 5.31 Burning of agricultural residues – EFs

Gas species	Emission factor EF_g (Gg element in species/ Gg element in fuel burnt)	Elemental to molecular mass conversion factor (C_g)
CH_4	0.0035	16/12
N_2O	0.0076	44/28
NO_x	0.2100	46/14
CO	0.0780	28/12
NMVOC	0.0091	14/12

Source: Hurst et al. (1994a), Hurst et al. (1994b).

Table 5.32 Symbols used in algorithms for burning of agricultural residues

State (i)	Subset (j)
1 = ACT	1 = Wheat
2 = Northern Territory	2 = Barley
3 = NSW	3 = Maize
4 = Queensland	4 = Oats
5 = Tasmania	5 = Rice
6 = South Australia	6 = Sorghum
7 = Victoria	7 = Triticale
8 = Western Australia	8 = Other cereals
	9 = Pulses
	10 = Tubers and roots
	11 = Peanuts
	12 = Sugar cane
	13 = Cotton
	14 = Hops
	15 = Oilseeds
	16 = Forage crops

The mass of residue burnt (M_{ij} Gg) is calculated as:

$$M_{ij} = P_{ij} \times R_j \times S_j \times DM_j \times Z \times F_{ij} \quad . (3.F\_1)$$

Where P_{ij} = annual production of crop (Gg)

R_j = residue: crop ratio (kg crop residue/kg crop) (Table A5.5.9.1)

S_j = fraction of crop residue remaining at burning (Table A5.5.9.1)

DM_j = dry matter content (kg dry weight/kg crop residue) (Table A5.5.9.1)

Z = burning efficiency (fuel burnt/fuel load) = 0.96 (Hurst et al. (1994); Hurst and Cook, (1994))

F_{ij} = fraction of the annual production of crop that is burnt (ha burnt/ ha harvested) (Tables A5.5.9.1 and A5.5.9.3)

The mass of fuel burnt is converted to emissions of CH_4, CO or NMVOC by multiplying by the carbon content of the fuel, and an EF:

$$E_{ij} = M_{ij} \times CC_j \times EF_g \times C_g \quad (3.F\_2)$$

Where E_{ij} = annual emissions from burning of crop residue (Gg)

CC_j = carbon mass fraction in crop residue (Table A5.5.9.1)

EF_g = emission factor (Gg element /Gg burnt) (Table 5.29)

C_g = factor to convert from elemental mass of gas to molecular mass (Table 5.29)

For N_2O and NO_x an additional term in the algorithm, the nitrogen to carbon ratio (NC_j), is required in order to calculate the fuel nitrogen content. Hence:

$$E_{ij} = M_{ij} \times NC_j \times EF_g \times C_g \quad (3F\_3)$$

Where E_{ij} = annual emissions from burning of crop residue (Gg)

NC_j = nitrogen content in above ground residue (Table A5.5.9.1)

EF_g = emission factor (Gg element /Gg burnt) (Table 5.29)

C_g = factor to convert from elemental mass of gas to molecular mass (Table 5.29)

5.7.3 Uncertainty assessment and time-series consistency

A quantitative assessment of uncertainty was undertaken and uncertainties for the burning of agricultural residues were estimated to be in the order of 60 per cent. Further details on the analysis are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full time series recalculations for all refinements to methodology.

5.7.4 Category-specific QA/QC and verification

The ABS has in place a range of quality assurance-quality control procedures associated with survey design, data input and consistency checks on the survey results and the aggregated values. Sampling errors are also evaluated. Data quality used in the inventory is also kept under review by the Department.

This source category is also covered by the general QA/QC procedures detailed in Annex 4.

5.7.5 Category-specific recalculations

There are no recalculations associated with the field burning of agricultural residues in this submission.

5.7.6 Category-specific planned improvements

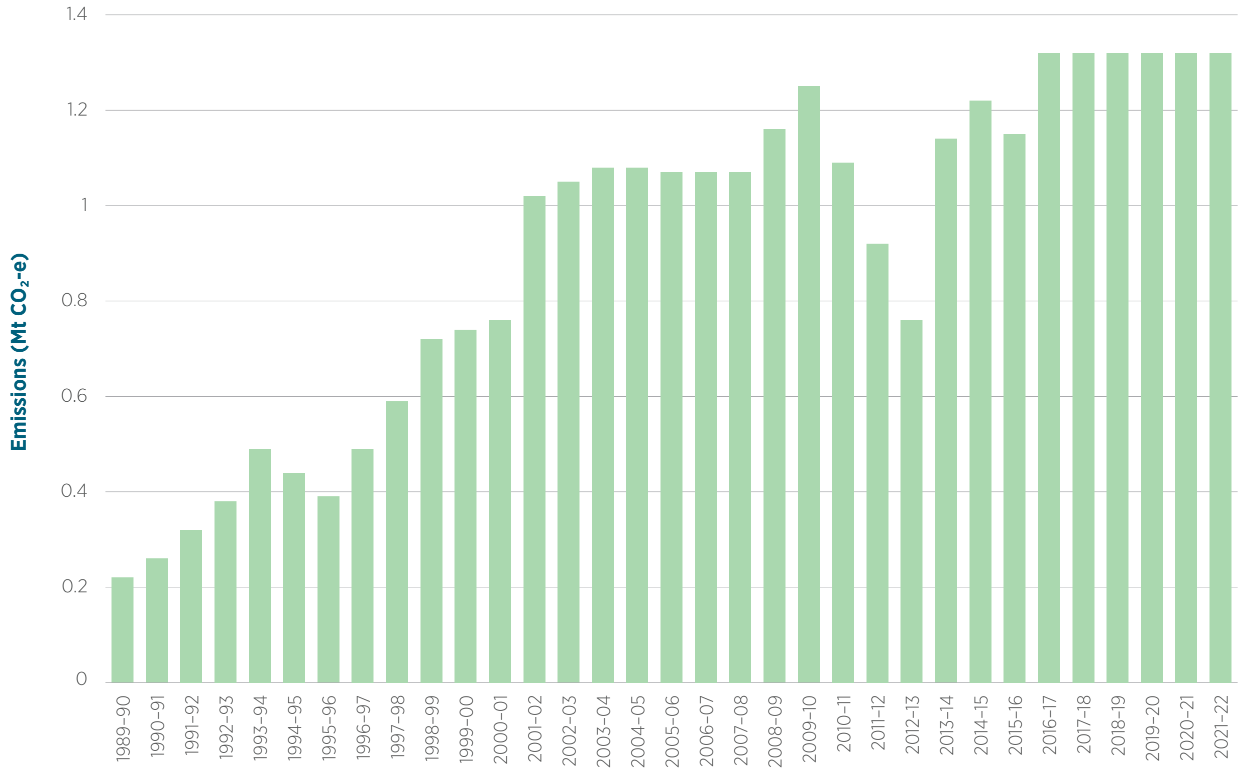
All data and methodologies are kept under review.

5.8 **Liming** (CRT category 3.G)

5.8.1 Category description

Limestone and dolomite are used in Australia to ameliorate soil acidity, improve soil structure, and improve plant growth in *cropland* and *grassland* and, to a very limited degree, in *forestland.* Adding carbonates to soils in the form of lime (e.g. calcic limestone ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$)) results in CO_2 emissions, as the carbonate reacts with acids in the soil to produce bicarbonate and eventually leading to the production of CO_2 and water.

Figure 5.13 Emissions from liming, Australia, Mt CO_2-e



5.8.2 Methodological issues

Table 5.33 Symbols used in algorithms for liming

State (i)	Subset (j)
1 = ACT	1 = Limestone
2 = Northern Territory	2 = Dolomite
3 = NSW	
4 = Queensland	
5 = Tasmania	
6 = South Australia	
7 = Victoria	
8 = Western Australia	

For lime application, the annual emissions of CO_2 (E_{ij} Gg) are calculated as:

$$E_{ij} = ((M_{ij} \times FracLime_{ij} \times P_{j=1} \times EF_{j=1}) + (M_{ij} \times (1-FracLime_{ij}) \times P_{j=2} \times EF_{j=2})) \times C_g \div 1000 \qquad (3G\_1)$$

Where MN = mass of limestone and dolomite applied to soils(tonne)

$FracLime_{ij}$ = fraction of lime as limestone or dolomite, derived from the ABS report “Land Management and Farming in Australia”. The values of $FracLime_{ij}$ for each State and year are provided in Appendix 5.K.

$P_{j=1}$ = fractional purity of limestone = 0.9 (DCC 2006)

$P_{j=2}$ = fractional purity of dolomite = 0.95 (DCC 2006)

$EF_{j=1}$ = 0.12 – IPCC (2006) default emission factor for limestone

$EF_{j=2}$ = 0.13 – IPCC (2006) default emission factor for dolomite

C_g = 44/12 factor to convert elemental mass of CO_2 to molecular mass

National data on limestone and dolomite application to agricultural soils are only available from the Australian Bureau of Statistics for eight years (1993, 1994, 1996, 2001, 2002, 2008, 2013 and 2014), with limestone and dolomite reported separately for the following years: 1996, 2001, 2002, 2008, 2013, 2015, 2016 and 2017. As no data have been reported since 2017, the values have been held constant. Investigation of an extrapolation method is a planned improvement.

The use of country-specific purity information on limestone and dolomite amends the emission factors as described in the 2006 IPCC Guidelines (IPCC 2006), making this a Tier 2 method.

Additional data is available for Western Australia (1991, 1995, 1998-2000 and 2004). Interpolation techniques were used to estimate the mass of limestone and dolomite applied in years for which data are not available. The fraction of the estimated mass applied that is assumed to be limestone was based on the average of years for which data are available.

5.8.3 Uncertainty assessment and time-series consistency

A quantitative assessment of uncertainty was undertaken and uncertainties for liming were estimated to be in the order of 54 per cent. Further details on the analysis are provided in Annex 2.

5.8.4 Category-specific QA/QC and verification

This source category is covered by the general QA/QC procedures detailed in Annex 4.

5.8.5 Category-specific recalculations

There are no recalculations associated with liming in this submission.

5.8.6 Category-specific planned improvements

All data and methodologies are kept under review.

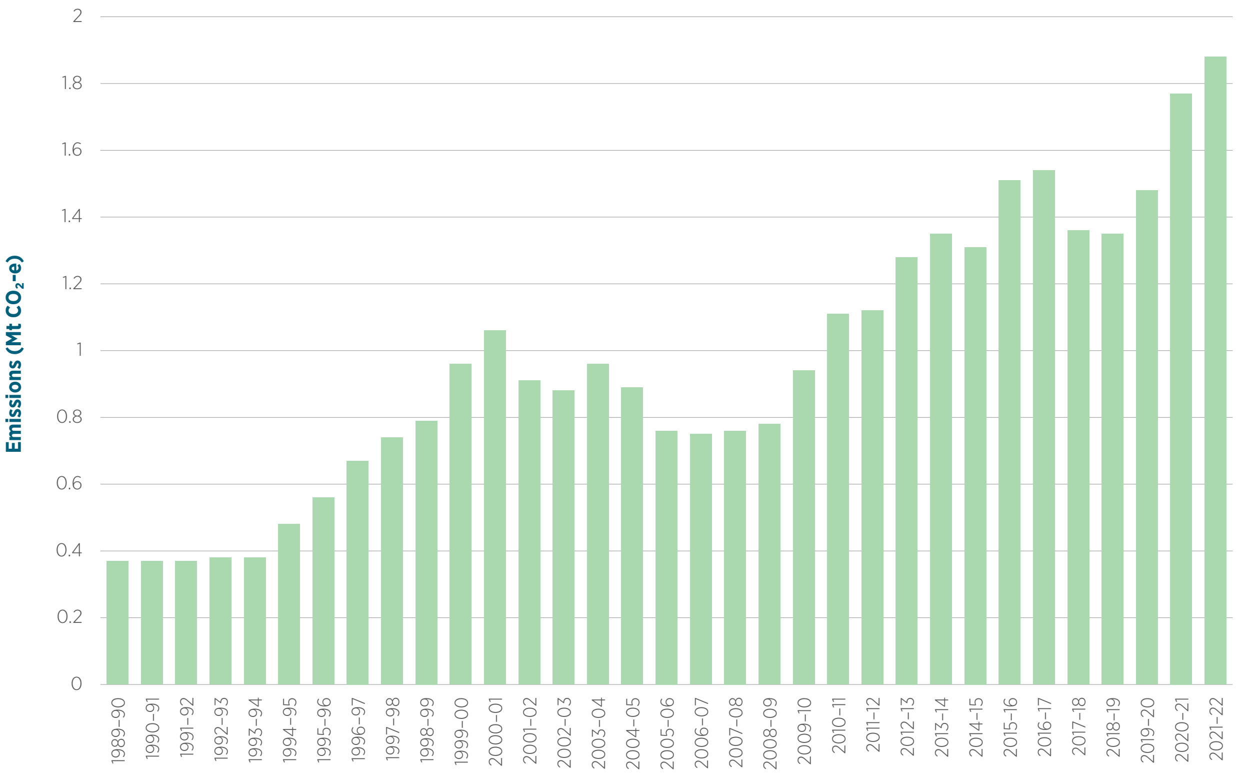
As the ABS have not updated the report of limestone and dolomite application to agricultural soils since 2017, alternative sources of activity data will be investigated.

5.9 **Urea Application** (CRT category 3.H)

5.9.1 Category description

Adding urea to soils for fertilisation leads to a loss of the CO_2 that was fixed during the manufacturing process. Similar to the reaction following the addition of lime, the bicarbonate that is formed evolves into CO_2 and water.

Figure 5.14 Emissions from urea application, Australia, Mt CO_2-e



5.9.2 Methodological issues

Activity data is sourced from Fertilizer Australia.

For urea application, the annual emissions of CO_2 (E_i Gg) are calculated using the tier 1 approach:

$$E_i = M_i \text{ X } EF \text{ X } C_g \div 1000 \qquad (3.H\_1)$$

Where M_i = mass of urea applied to soils(tonne)
EF = 0.2 (tonne C/tonne urea) (IPCC 2006))
C_g = 44/12 factor to convert elemental mass of CO to molecular mass

5.9.3 Uncertainty assessment and time-series consistency

A quantitative assessment of uncertainty was undertaken and uncertainties for application of urea were estimated to be in the order of 51 per cent. Further details on the analysis are provided in Annex 2. Time series consistency is ensured by the use of the same methods and data source for the full time series.

5.9.4 Category-specific QA/QC and verification

This source category is covered by the general QA/QC procedures detailed in Annex 4.

5.9.5 Category-specific recalculations

There are no recalculations associated with urea application in this submission.

5.9.6 Category-specific planned improvements

Country-specific information to estimate emission factors will be investigated.

6. Land Use, Land Use Change and Forestry

6.1 Overview of the sector and background information

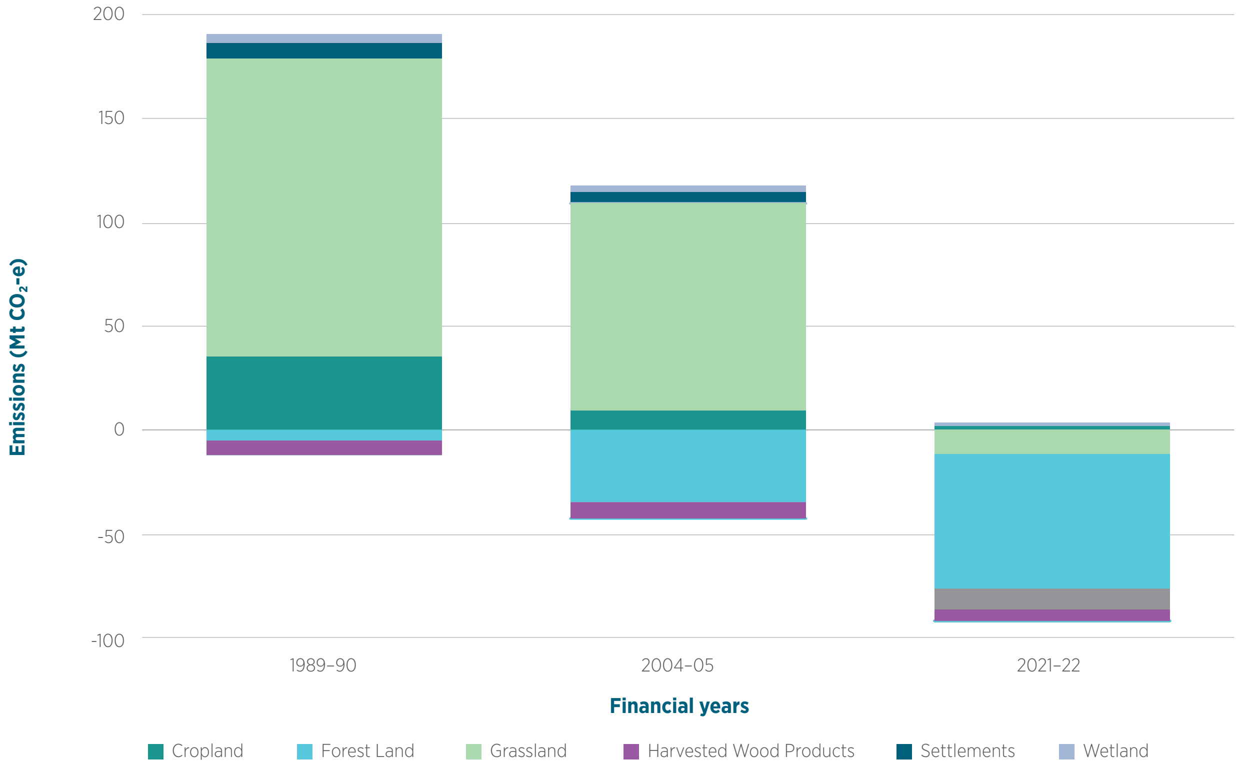
The land use, land use change and forestry (LULUCF) sector covers greenhouse gas emissions associated with land management practices that impact the carbon stored in vegetation and soils. Since vegetation can absorb carbon from the atmosphere, this sector has the ability to function as a net sink of emissions. LULUCF emissions by sub-sector for 2021–22 are shown in Figure 6.1.1, with changes since 1989–90, 2004–05 and 2020–21

Figure 6.1.1 LULUCF emissions by sub-sector, 2021–22 with change in emissions since 1989–90, 2004–05 and 2020–21 (Mt CO_2-e) (Mt CO_2-e) and percentage change (%)

		Change in 2021–22 emissions since:		
LULUCF Subsectors	**2021-22 emissions**	**1989–90**	**2004–05**	**2020–21**
4.A Forest land	-65 Mt	-59 Mt CO_2-e ▼ -1,170%	-30 Mt CO_2-e ▼ -86%	▲ +16% +12 Mt CO_2-e
4.B Cropland	-12 Mt	-47 Mt CO_2-e ▼ -133%	-21 Mt CO_2-e ▼ -227%	-2 Mt CO_2-e ▼ -18%
4.C Grassland	-10 Mt	-153 Mt CO_2-e ▼ -107%	-110 Mt CO_2-e ▼ -110%	-9 Mt CO_2-e ▼ -1,043%
4.D, E Wetlands and Settlements	4 Mt	-8 Mt CO_2-e ▼ -70%	-5 Mt CO_2-e ▼ -58%	-0.2 Mt CO_2-e ▼ -6%
4.G Harvested Wood Products	-6 Mt	▲ +21% +2 Mt CO_2-e	▲ +29% +2 Mt CO_2-e	-1 Mt CO_2-e ▼ -14%

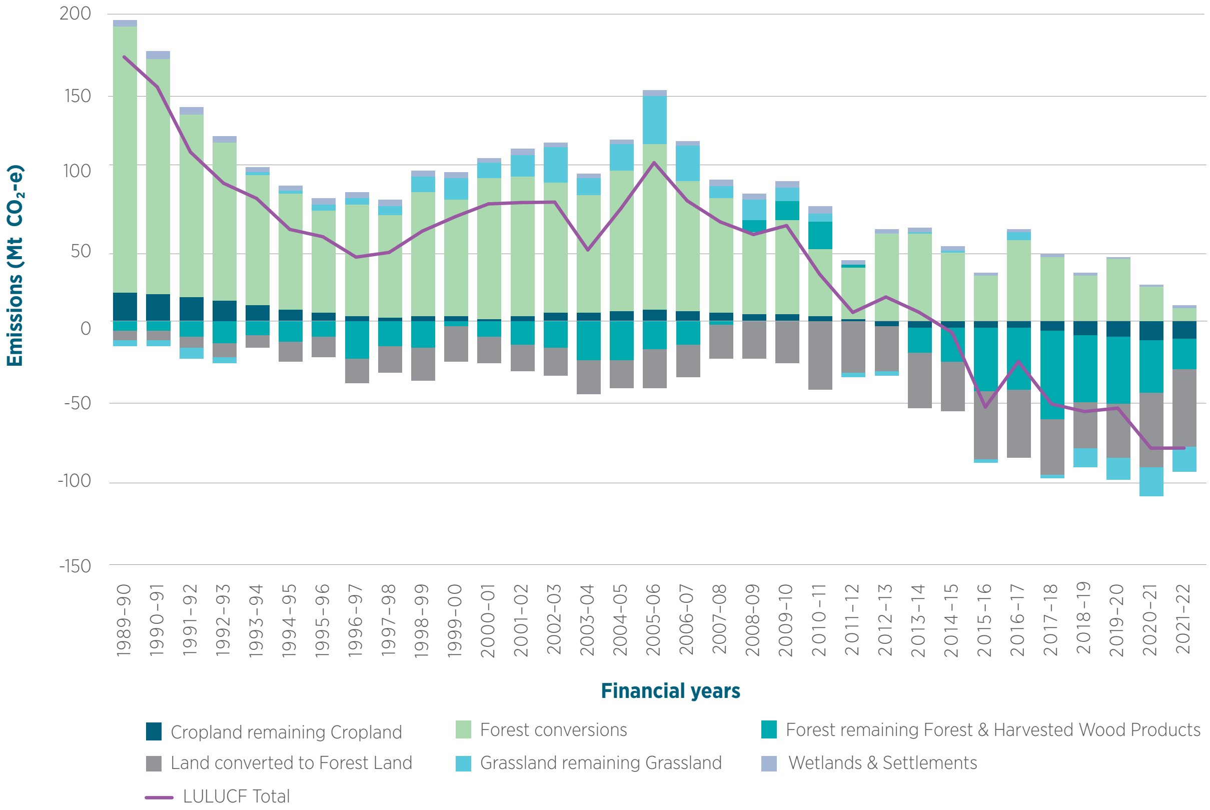
The share of emissions per sub-sector have changed significantly between the base years and the current year, with some sub-sectors changing from a net source to a net sink. Changes in LULUCF emissions by sub-sector in 1989–90, 2004–05, and 2021–22 are shown in Figure 6.1.2.

Figure 6.1.2 LULUCF emissions by sub-sector, 1989–90, 2004–05 and 2021–22 (Mt CO_2-e)



The underlying trend of declining emissions from *LULUCF* since 1990 has been mainly driven by the decline in emissions from forest land conversions to other land uses and the increase in removals through forest regrowth on previously cleared land (Figure 6.1.3) as well as, in recent years, declining net emissions from the harvest of native forests. Emissions remained relatively stable in 2022 as increasing sink in croplands and grasslands due to La Niña conditions were offset by increases in emissions in forest lands due to wildfires as well as increased rates of soil carbon decay also caused by wetter conditions.

Figure 6.1.3 Net CO_2-e emissions from Land Use, Land Use Change and Forestry, by sub-category, 1989–90 to 2021–22



One of the principal drivers of change in carbon fluxes across the Australian landscape relates to losses and gains of woody vegetation. The loss of woody vegetation is mainly reported under three classifications: *forest conversion to other land uses, forest land remaining forest land,* and *grassland remaining grassland.*

Permanent losses of woody vegetation that had previously been classed as *forest land* are reported under forest conversion to other land use classifications.

Temporary losses of woody vegetation on *forest land* are reported under the *forest land remaining forest land* classification. All forests subject to harvest events are monitored over time to ensure that the forest regenerates — if this does not happen, these areas are reported under forest conversion. Most wildfires in Australia are not stand-replacing and do not result in vegetation losses, however where forest cover loss occurs, these temporary losses are also included in monitoring for land use-change or salvage logging (see Chapter 6.4). A regeneration of forest following a harvest event or fire is reported under *forest land remaining forest land* as no change in land use has occurred.

Increases and losses of woody vegetation that are not classed as *forest land* (called sparse woody vegetation) — both permanent and temporary — are reported under *grassland remaining grassland, wetlands remaining wetlands* and *settlements remaining settlements.*

Increases in woody vegetation cover classed as *forest land* are reported under *land converted to forest land.* These changes include new plantations and forest regrowth on land previously cleared for other uses, environmental plantings and the regeneration of forest from natural seed sources including conversion of tidal marsh to mangrove.

Choice of Methods

Predominantly country specific methodologies and Tier 3 models (Table 6.1.1) are used for *LULUCF.* The methods used in the estimation of the *LULUCF* categories of the inventory are described in detail in Annex 5.6.

Australia's land sector inventory system integrates spatially referenced data with the Full Carbon Accounting Model (FullCAM), an empirically constrained, mass balance, carbon cycling ecosystem model, to estimate carbon stock changes and greenhouse gas emissions (including all carbon pools, gases, lands and land use activities).

FullCAM has been designed to comply with IPCC Guidelines and to meet the Australian Government's international treaty estimation and reporting commitments. It is designed to fully integrate the estimation of carbon stock changes and related emissions across the Australian landscape. Model parameterization has been informed by the latest empirical science and is continuously updated.

A comprehensive modelling approach to the estimation of carbon stock changes was originally chosen for the Australian land sector because of the absence of extensive forest inventory or measurement systems, reflecting the circumstance that timber industry activity has been confined in recent times to approximately 15 per cent of Australia's forest.

Spatial datasets for key disturbance events such as land clearing, forest planting and natural regeneration are derived from LandSat satellite imagery held by the Australian Geoscience Datacube (Digital Earth Australia). These datasets are processed by CSIRO Data61 and are informed by land use and vegetation datasets provided by the Australian Bureau of Agricultural and Resource Economics and Sciences and the Department of Climate Change, Energy, the Environment and Water.

Summary information on method and emission factor selection is provided in Table 6.1.1, with key categories identified as highlighted squares.

Table 6.1.1 Summary of methodologies and emission factors – LULUCF sector

Greenhouse Gas Source and Sink	CO_2		CH_4		N_2O	
	Method applied	EF	Method applied	EF	Method applied	EF
4. Land Use, Land Use Change and Forestry						
A. Forest Land						
1. Forest land remaining Forest land						
Harvested native forests	T2, T3	CS, M	4(IV)		4(III) & 4(IV)	
Other native forests	T2, T3	CS	4(IV)		4(III) & 4(IV)	
Pre-1990 Plantations	T3	M	4(IV)		4(III) & 4(IV)	
Fuelwood consumed	T2	CS	IE	NA	IE	NA
2. Land converted to Forest land	T3	M	4(IV)		4(III) & 4(IV)	
B. Cropland						
1. Cropland remaining Cropland	T3, T2	CS, M	IE	NA	IE	NA
2. Land converted to Cropland						
Forest converted to cropland	T3	M	4(IV)		4(III) & 4(IV)	
Wetlands converted to cropland	T1	D	NE	NA	NE	NA
C. Grassland						
1. Grassland remaining Grassland	T3, T2	M, CS	4(IV)		4(III) & 4(IV)	
2. Land converted to Grassland						
Forest converted to grassland	T3	M	4(IV)		4(III) & 4(IV)	
Wetlands converted to grassland	T1	D	NE	NA	NE	NA

Greenhouse Gas Source and Sink	CO_2		CH_4		N_2O	
	Method applied	EF	Method applied	EF	Method applied	EF
D. Wetlands						
1. Wetlands remaining Wetlands	T2	CS	4(II)		4(II)	
2. Land converted to Wetlands	T3	M	4(II)		4(II)	
E. Settlements						
1. Settlements remaining Settlements	T2	CS	IE	NA	IE	NA
2. Land converted to Settlements						
Forest converted to settlements	T3	M	4(IV)		4(III) & 4(IV)	
F. Other Lands	NO	NA	NO	NA	NO	NA
G. Harvested wood products	T3	M				
4(I) Direct nitrous oxide (N_2O) *emissions from nitrogen (N) inputs to managed soils (a)*					IE	NA
4(II) Emissions and removals from drainage and re wetting and other management of organic and mineral soils (b)	IE	NA	T1,T2	D,CS	NE	NA
4(III) Direct and indirect nitrous oxide (N_2O) *emissions from nitrogen (N) mineralization/immobilization associated with loss/gain of soil organic matter resulting from change of land use or management of mineral soils (c)*					T2	CS
4(IV) Biomass burning (c)	IE,T3	IE,CS	T2,T3	CS	T2,T3	CS
H. Other (d)	T2	CS	NA	NA	T1	D

(a) In accordance with footnote 6 of Common Reporting Table 4(I), Australia reports all N_2O emissions from N inputs to managed soils in the Agriculture sector.

(b) Emissions from reservoirs are discussed in this report under *wetlands.*

(c) Methods for nitrogen mineralisation, nitrogen leaching and run-off, and biomass burning are applied across all land use classifications.

(d) Emissions from seagrass dredging and aquaculture are discussed in this report under *wetlands.*

EF = emission factor, CS = country specific, D = IPCC default, M = Model, NA = not applicable, NE= not estimated, NO = not occurring, IE = included elsewhere, T1 = Tier 1, T2 = Tier 2 and T3 = Tier 3.

▨ = Key category

Forestry Activities

Harvesting in Australia's native forests, including multiple use forests and private native forests, is the key driver of human-induced emissions and removals in these forests. Over recent years, harvesting in the native forest sector has reached historically low levels (Figure 6.1.4). The areas of new plantations are shown in Figure 6.1.5.

Figure 6.1.4 Area harvested in native forests 1989–90 to 2021–22

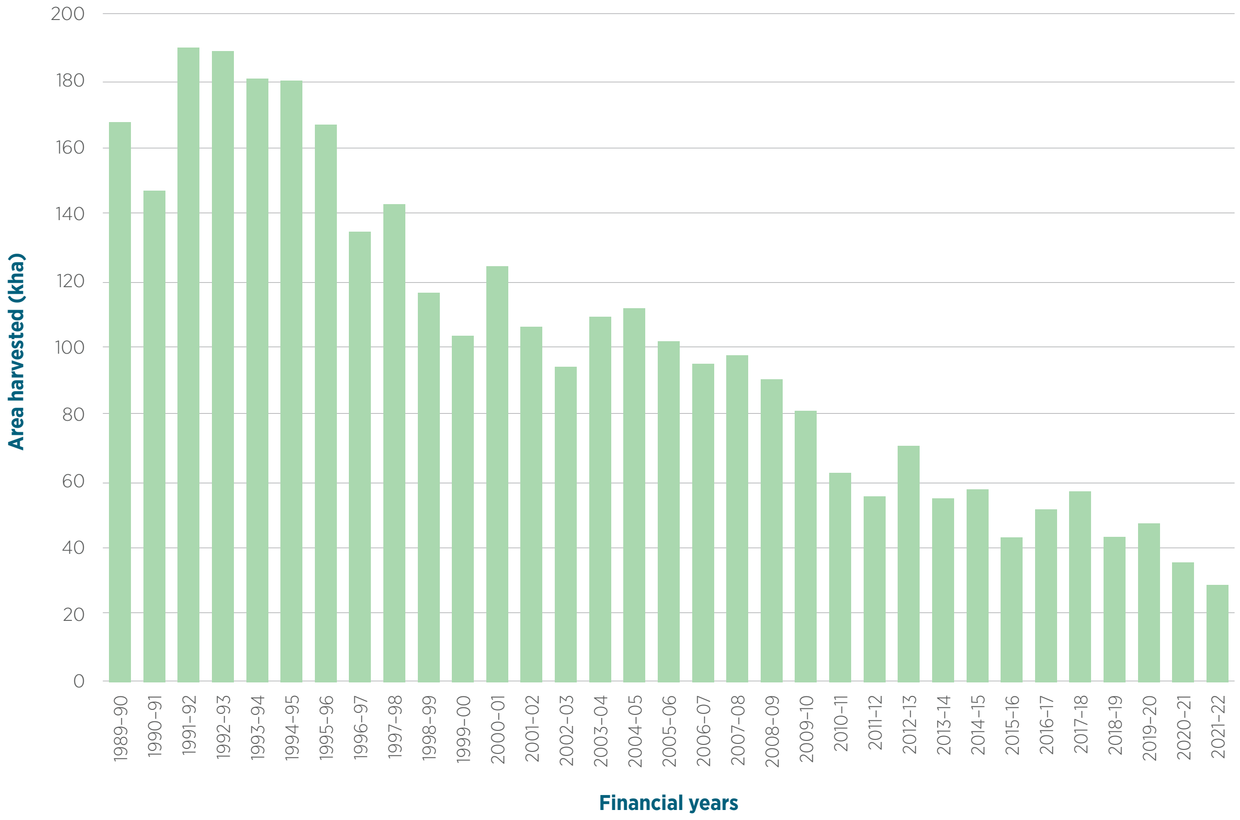
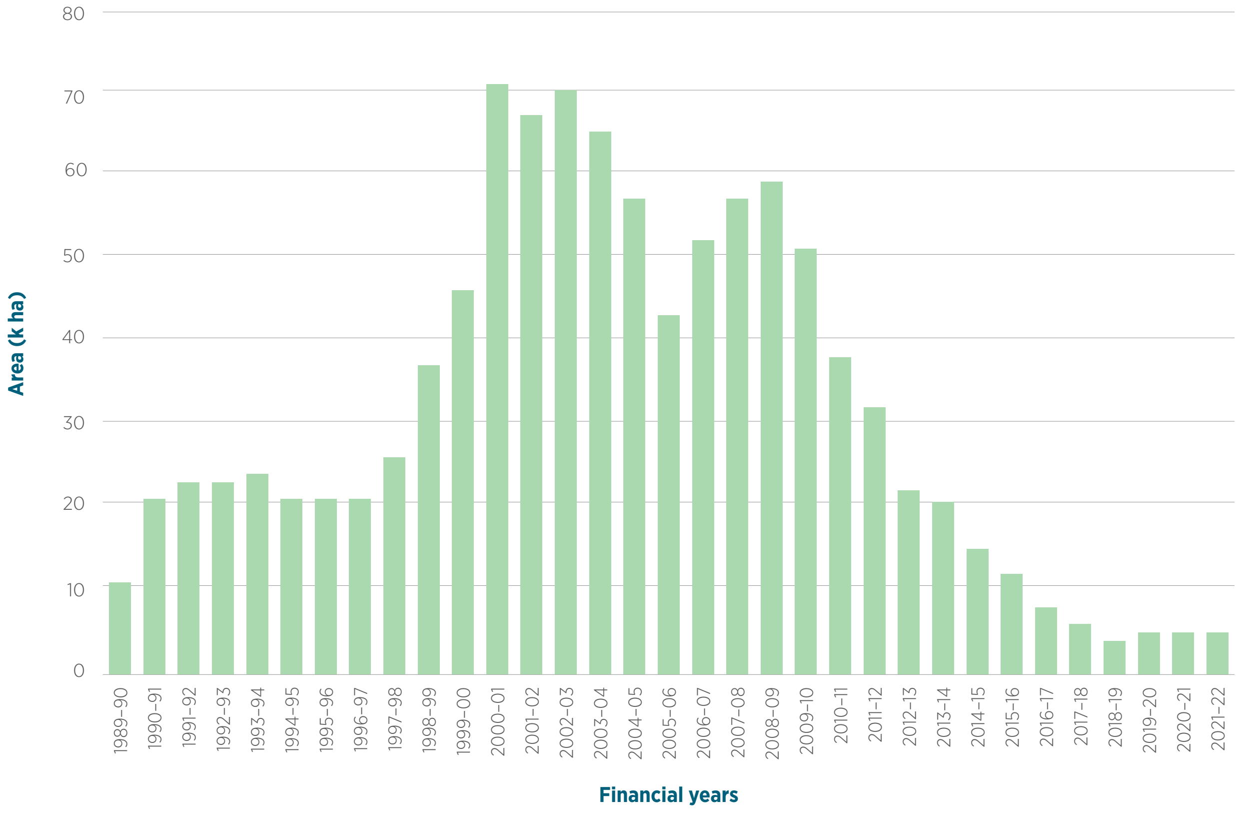


Figure 6.1.5 Area of new plantations 1989–90 to 2021–22



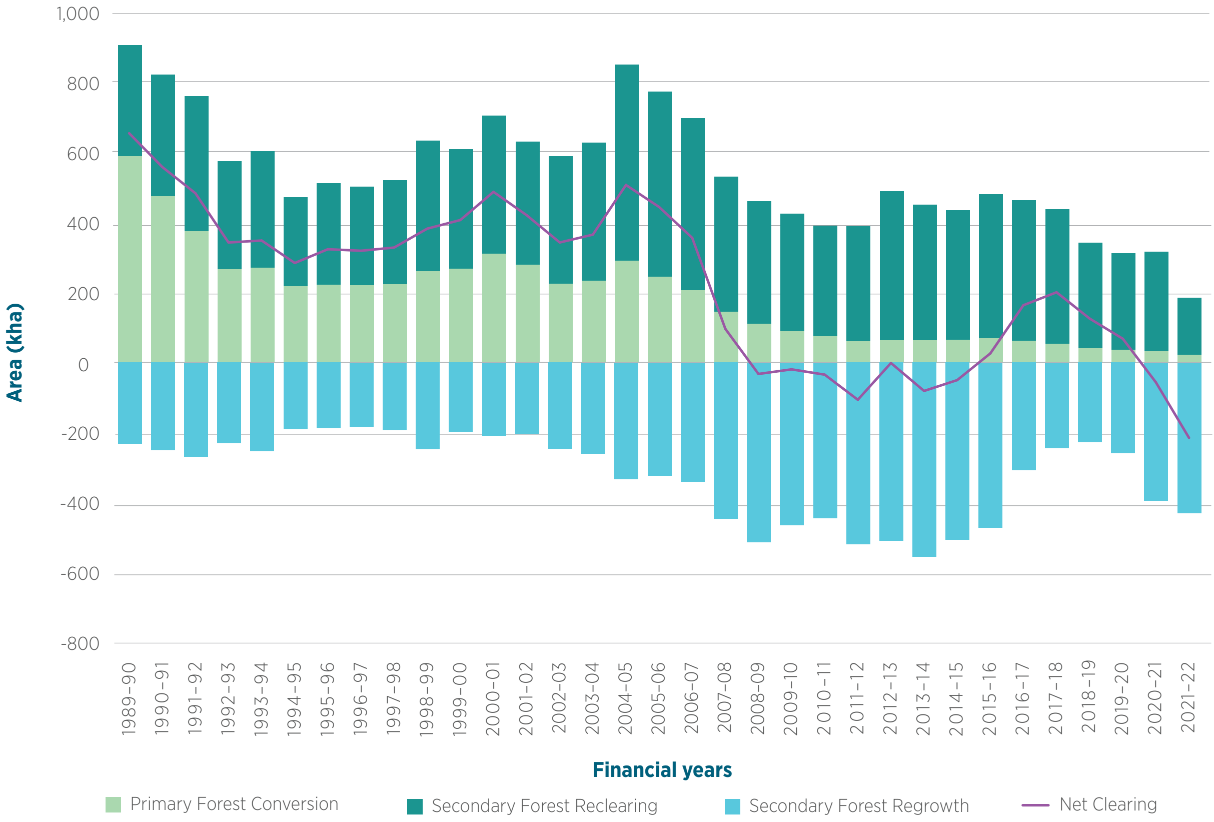
Forest land converted to other land uses

The total emissions associated with the transition from forest to a non-forest land use include the immediate loss of carbon as trees are cleared and burnt, as well as an ongoing loss of soil carbon as it decays to a new equilibrium stock level and other ongoing emissions and removals associated with the new land use. CO_2 removals associated with forest regrowth emerging on previously cleared land are accounted for as part of *land converted to forest land.*

The management of native vegetation and the majority of forest conversion processes in Australia are governed by State Governments in accordance with their own individual circumstances and land management practices and legislative frameworks. Land clearing is also regulated at a national level through the *Environmental Protection and Biodiversity Conservation Act 1999* if the clearing in question is likely to have a significant impact on matters of national environmental significance including threatened or endangered species.

Figure 6.1.6 illustrates the trend in forest land conversion to other land uses in Australia since 1990 and shows the contribution of conversion of mature primary forest and re-clearing of secondary forest cover that has re-grown on previously cleared land. Ongoing re-clearing, including of juvenile forest already converted to grassland and cropland, indicates an ongoing continuing and cyclical need of land managers to re-clear previously cleared areas. This is a common practice in many grazing regions due to regeneration from natural seed sources or resprouting from root masses following pushing of fodder species during droughts. Figure 6.1.6 also shows, for each year, the area on which forest has been observed to re-emerge on previously cleared land.

Figure 6.1.6 Area of primary and secondary forest conversion and regrowth, Australia, 1989–90 to 2021–22



Within this national native vegetation framework, economic considerations remain important drivers of the demand for forest conversion to alternative uses. Most forest land converted in Australia is used for cattle grazing but also for crop production, settlements and mining. For graziers and other landowners, economic considerations are an important driver of forest land conversion. When the prices of agricultural products, for example beef, are high, landowners have a strong incentive to clear land and expand production.

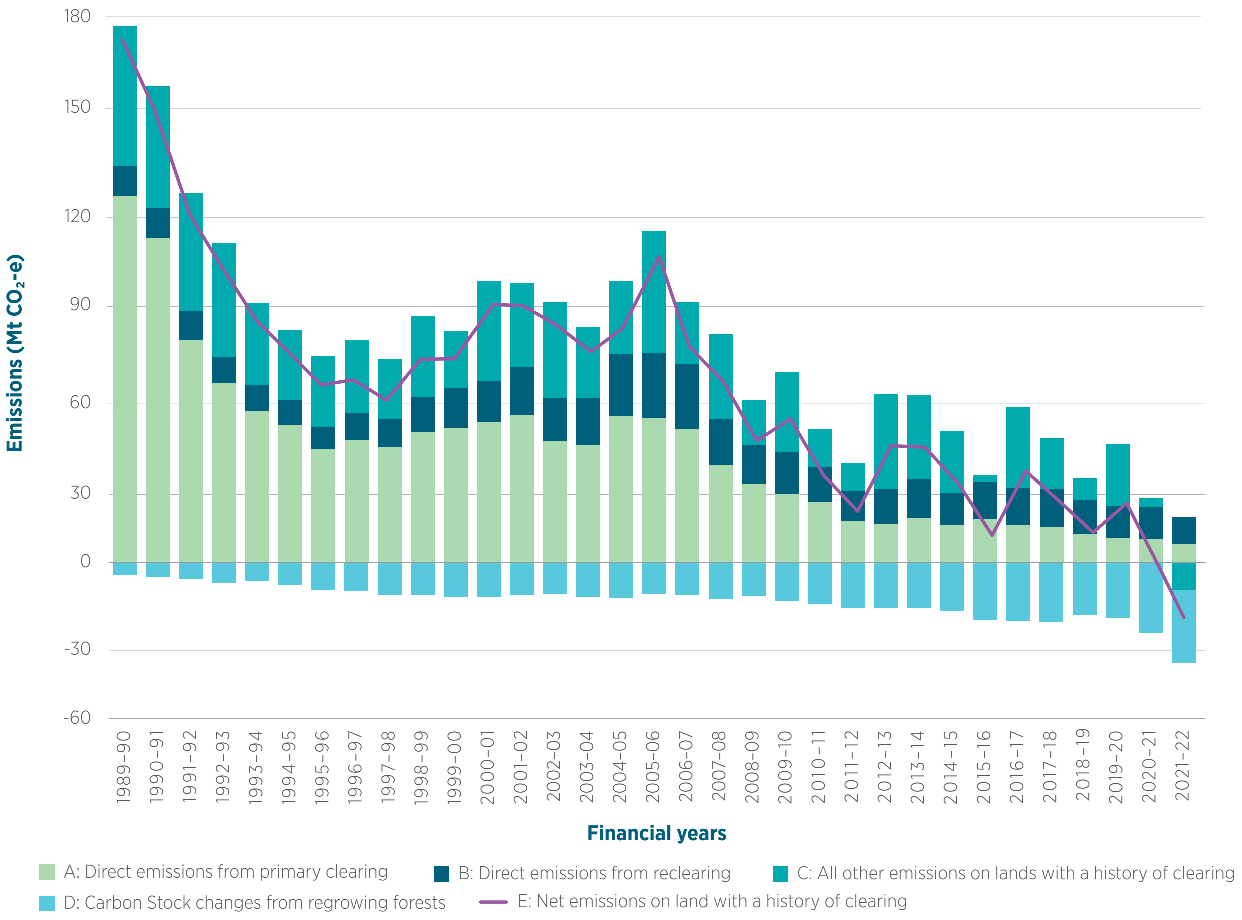
Although economic conditions are a factor, the effects of the more restrictive policy changes implemented in 2007 may be seen in the drop in first-time conversion from 2007-08 onwards (Figure 6.1.6). In addition, the sharpness of the decline may also reflect land managers bringing forward decisions to clear land to the period 2003–04 to 2006–07 – the period between the announcement of new policies and when they came into force.

The shift in the balance between first-time conversion and re-clearing evident in Figure 6.1.6 also contributes to the trend in emissions from *forest land converted to other land uses* in Figure 6.1.7. Where land is re-cleared the biomass stock at clearing will be significantly less than the initial biomass of first-time conversion.

National net forest conversions to cropland, grassland, wetlands (flooded land) and settlements emissions (Figure 6.1.7) are disaggregated as follows:

- Direct emissions from the forest clearing activity, including:
  - the emissions from the primary conversion of land that was forested in 1972; and
  - the emissions associated with secondary clearing (reclearing) of forest which has regrown on cleared land.
- Indirect emissions from the converted land under the changed land use – subcomponents include the gradual loss of soil carbon and other emissions and removals associated with the new land use.
- Removals of CO_2 from the atmosphere on previously converted land on which forest has re-emerged.

Figure 6.1.7 Disaggregated emissions and removals associated with forest conversions

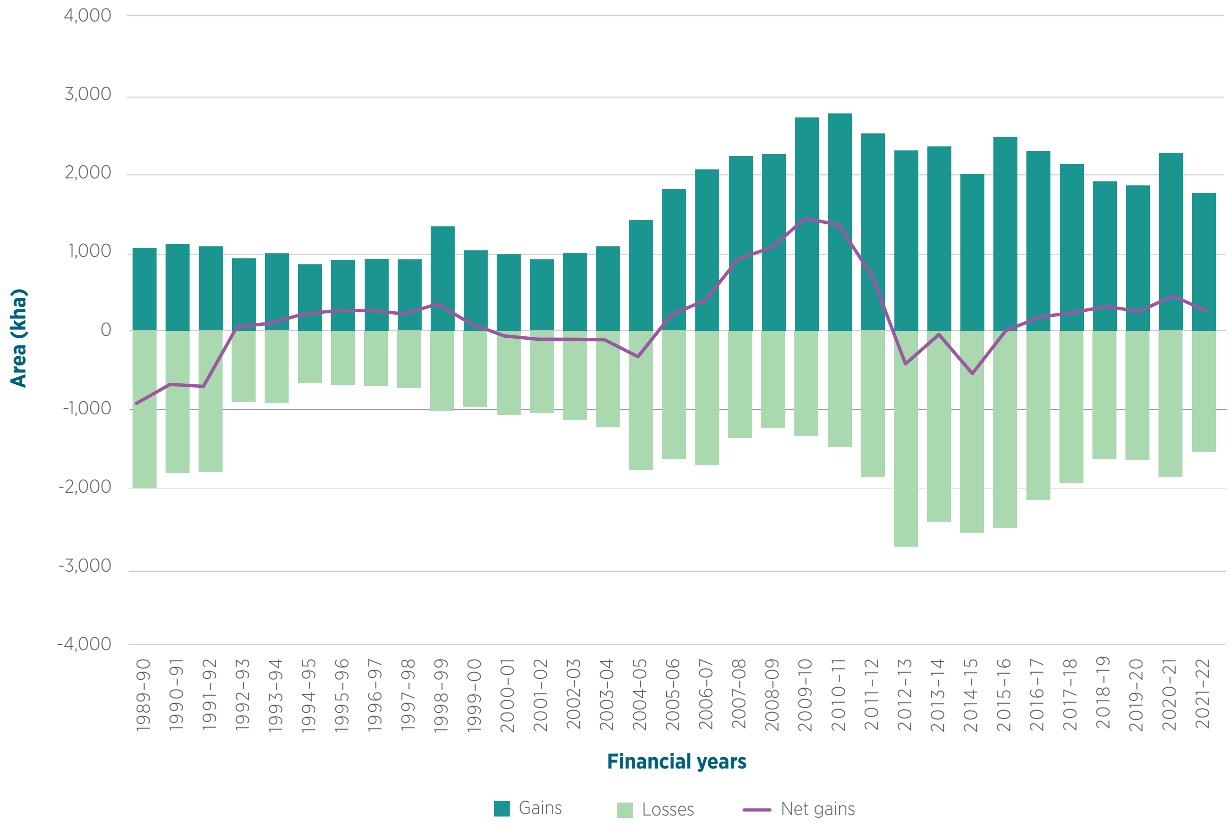


Sparse Woody Vegetation

Where the observed canopy cover does not reach the definition of a forest, it can instead be classified as sparse woody vegetation. Such woody shrubs and sparse woodlands are a key component of grassland ecosystems in semi-arid and arid regions of central Australia. Emissions and removals on these shrublands are driven by land management and transitions between shrubs and grasses.

Net changes in shrub or sparse woody vegetation appear to be strongly correlated with the El Nino Southern Oscillation Index (Bureau of Meteorology), but also reflect the incidence of fire and mechanical clearing activity by land managers. Annual area gains and losses of sparse woody vegetation, aggregated for reporting on grasslands, wetlands and settlements, are shown in Figure 6.1.8.

Figure 6.1.8 Area of sparse woody vegetation gains and losses, kha, 1989–90 to 2021–22



Temperate Fire

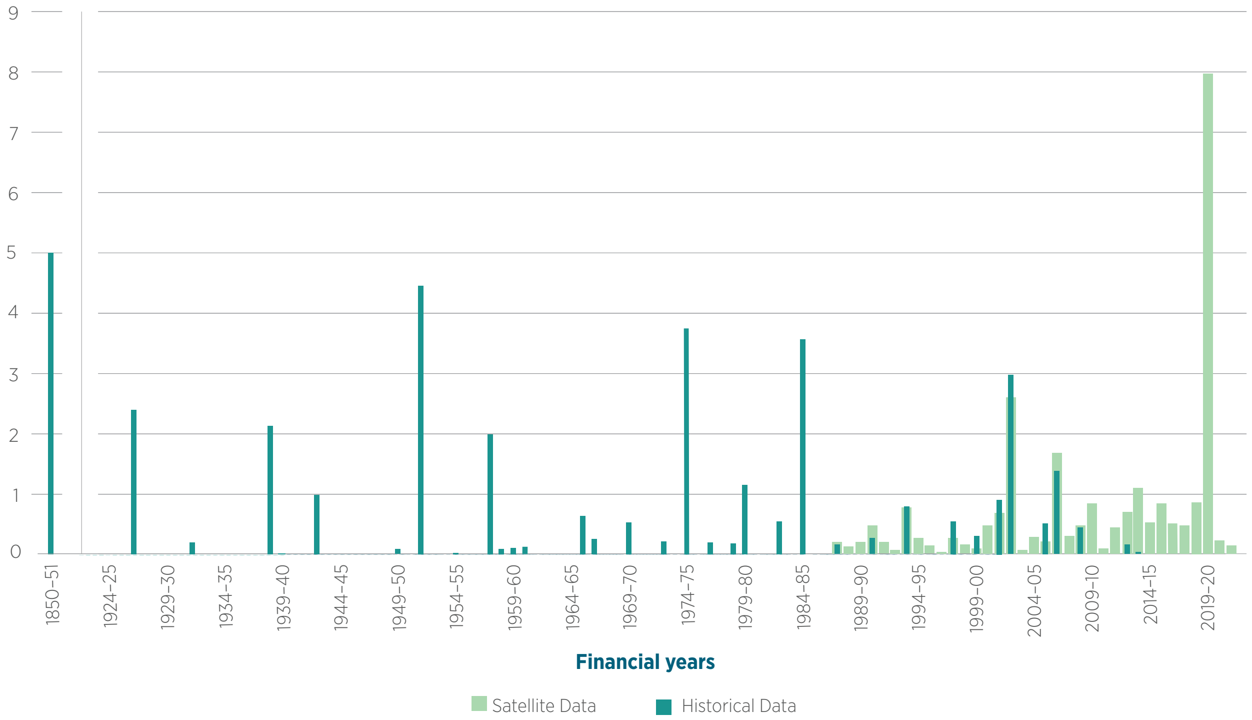
Wildfires are the largest cause of variability in emissions from *forest land remaining forest land.* Wildfires occur annually across Australia's forests with the area burnt varying considerably from year to year (Figure 6.1.9). In addition, *forest land remaining forest land* is subject to significant, non-anthropogenic natural disturbances including wildfires that are beyond control despite extensive efforts of emergency management organisations.

Consistent with guidance in the IPCC 2019 refinement (IPCC 2019) to the 2006 guidelines (IPCC 2006), to ensure transparency, two wildfire estimates are reported: net emissions including inter-annual variability from non-anthropogenic natural disturbances; and the long run trend in net anthropogenic greenhouse gas emissions from the wildfire disturbances and post-fire removals as the forest recovers.

In order to identify emissions from human activity, a statistical approach has been developed to identify non-anthropogenic natural disturbances on *forest land remaining forest land.* For these fires, carbon stock loss and subsequent recovery from non-anthropogenic natural disturbances are modelled to average out over time, leaving greenhouse gas emissions and removals from anthropogenic fires as the dominant result (Figure 6.1.10).

All prescribed fires are considered to be anthropogenic in nature. Disturbance areas are monitored for permanent changes in land use, in which case emissions are reported in the appropriate land conversion category, and salvage logging emissions are reported.

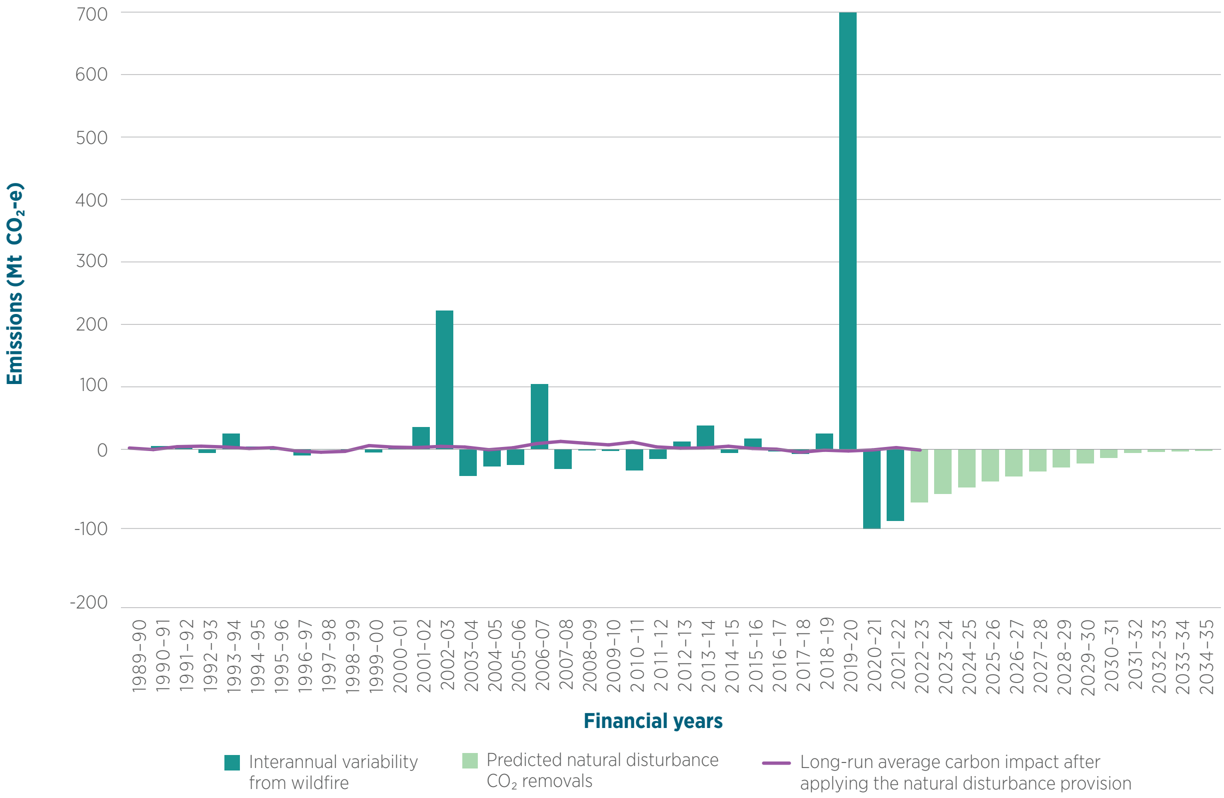
Figure 6.1.9 Annual area burnt by bushfires in Australian temperate forests



Source: Satellite data: DCCEEW using data supplied by Landgate. Note that 2020 areas also include data supplied by Emergency Management Spatial Information Network Australia (EMSINA).

Historical data: based on a range of sources, including a mixture of historical records, anecdotal evidence, and satellite imagery. Updated (with corrections) from (Roxburgh, Volkova, et al. 2015)

Figure 6.1.10 Net emissions from wildfire showing inter-annual variability and long-run trend in carbon impact after applying the natural disturbances provision



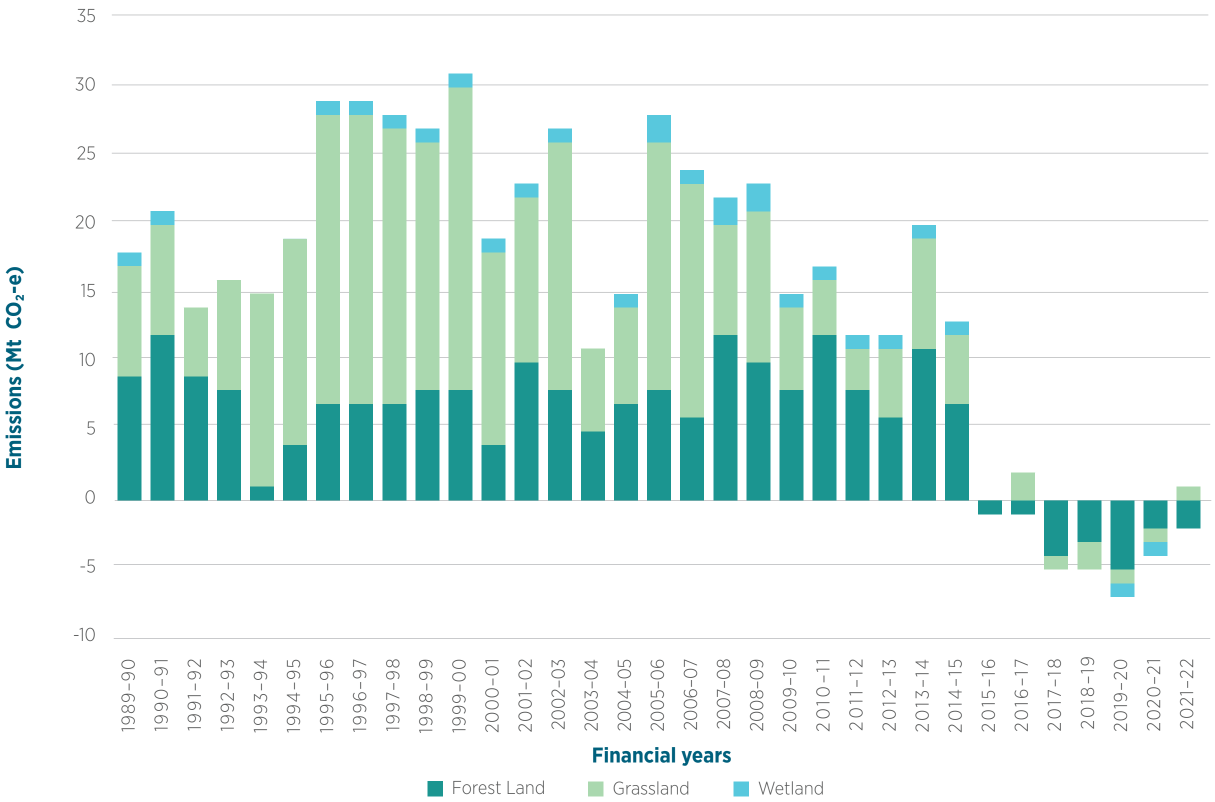
Savanna Fire

Australia reports savanna fire activity in forest land, grasslands, and wetlands based on the land use classification which has been burned by fire or is recovering from the effects of fire.

Tropical savannas represent a large proportion of the total fire affected area each year globally. Australia's tropical savannas cover approximately 26% of the national land mass. Between ~15% and ~35% of the land area in these landscapes can be fire affected each year. Many of these fires are anthropogenic, particularly in the higher rainfall regions where there is ongoing Indigenous and pastoral use of fire as a land management tool. As highly fire prone landscapes, if management fires are not employed the occurrence and extent of naturally ignited wildfires can be severe.

Strategic savanna burning involves lighting fires in the early dry season (EDS) when fine fuel loads, and resulting fire intensities, are low and fires can be controlled. Burning in this way decreases the occurrence and extent of large high intensity late dry season (LDS) fires, which are generally hotter fires that burn more fuel and can be difficult to control. A fire regime that includes strategic EDS fires can decrease greenhouse gas emissions, while the decrease in fire intensity and extent may also result in some sequestration of carbon in pools of dead and live biomass (Paul and Roxburgh (2022)).

Figure 6.1.11 Emissions from Australian tropical savannas by land-use category, 1989–90 to 2021–22



Cropland and Grassland management practices

On croplands, the uptake of reduced, minimum and no-till management techniques through the 1980s and 90s is reflected in decreasing emissions during this period as a new soil C state of equilibrium is reached. Further management changes in recent years and their impact on the soil C steady state can be detected in shifts later in the emissions trend.

Changes in carbon stocks in grasslands are largely driven by changes in land management practices and climate. These factors determine the amount of live biomass and dead organic matter (DOM) as well as the amount of residues, root and manure inputs to soil carbon. Management and climatic changes can be detected as the emissions trend moves to new equilibrium levels through time. In the arid and semi-arid rangelands of central Australia, soil carbon stocks under natural grass species are assumed to have reached a steady state.

Wetlands

Separate to emissions associated with forest conversions, emissions from Wetlands includes CH_4 emissions from *reservoirs* and *other constructed waterbodies,* net changes in sparse woody vegetation, loss of seagrass beds due to capital dredging and N_2O emissions from aquaculture operations. CH_4 emissions from *reservoirs* and *other constructed waterbodies* exert the dominant influence on both the level and trend in emissions reported over the time period.

6.2 Land-use definitions and the land representation approaches used and their correspondence to the land use, land-use change and forestry categories

6.2.1 Australia's National Circumstances

Australia has a land area of 769 million hectares containing unique land, water, vegetation and biodiversity resources. Australia is a dry continent where rainfall is highly variable and floods and droughts are a common feature. There are a number of distinct climatic zones, with summer dominant rainfall in the tropics/subtropics in the north, Mediterranean climates in the south, arid and semi-arid regions in the centre, and areas of high rainfall on the coastal fringes and in the ranges of the east (Figure 6.2.1 and Figure 6.2.2).

Figure 6.2.1 Long-term average annual rainfall

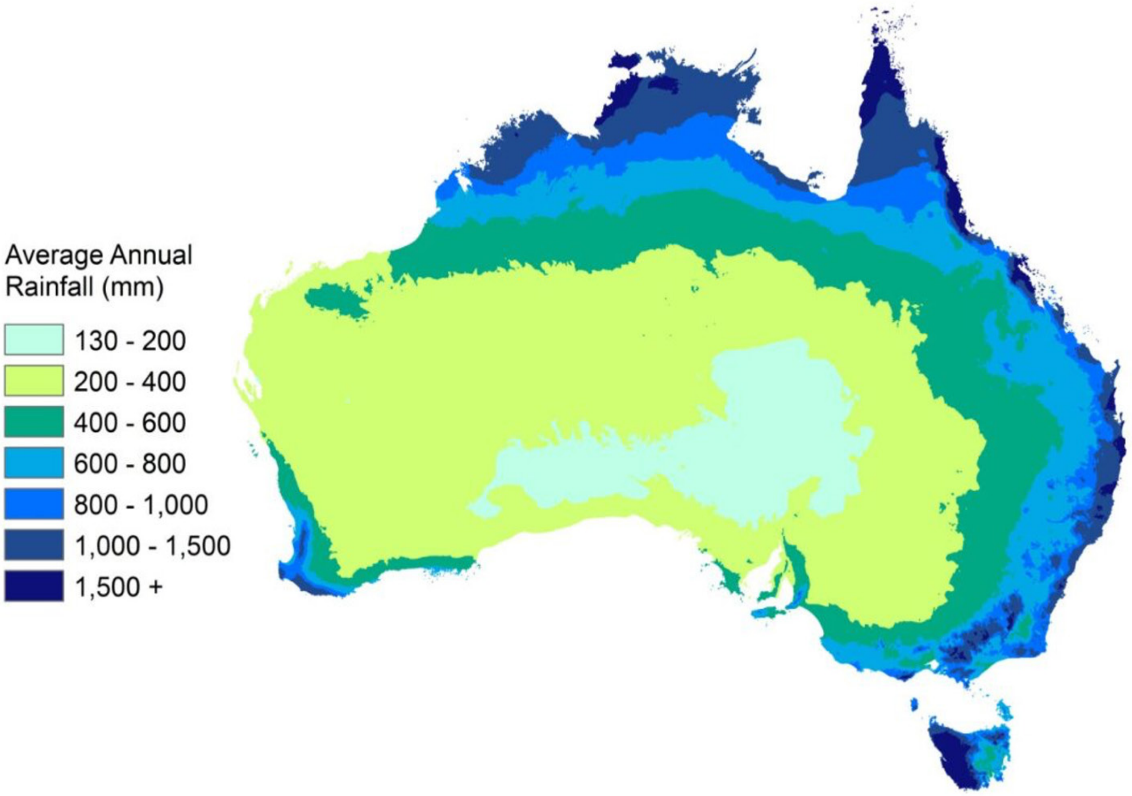
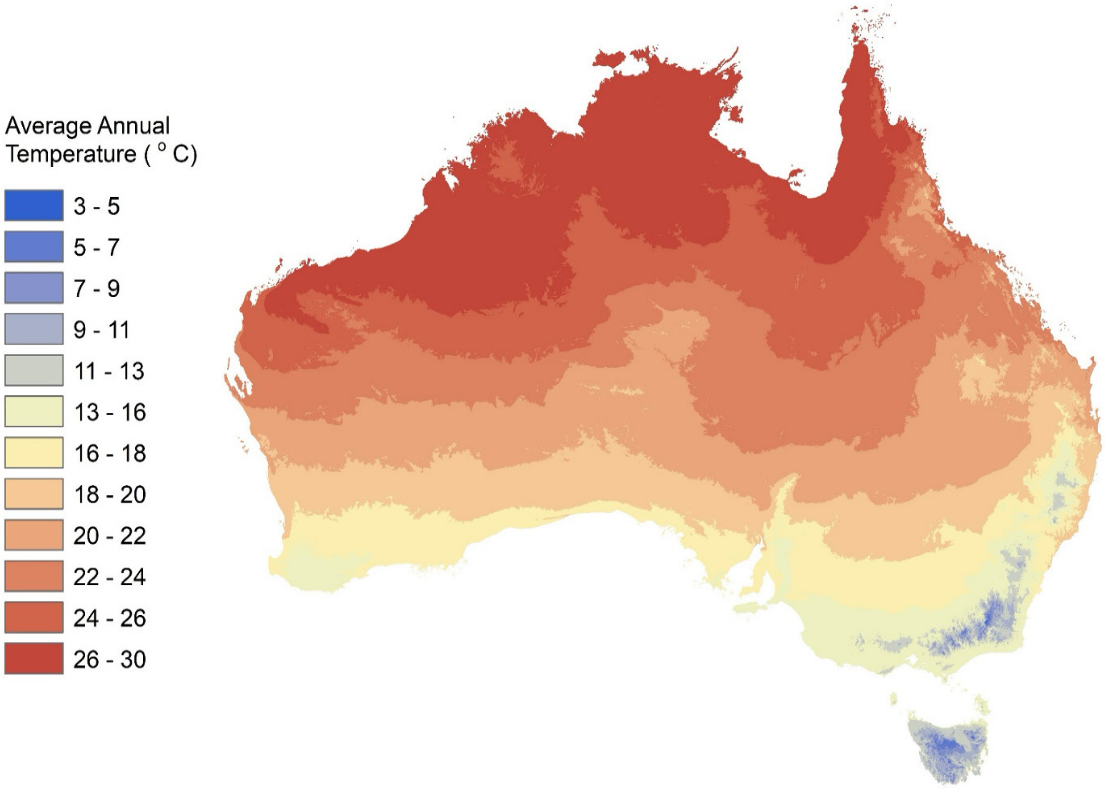


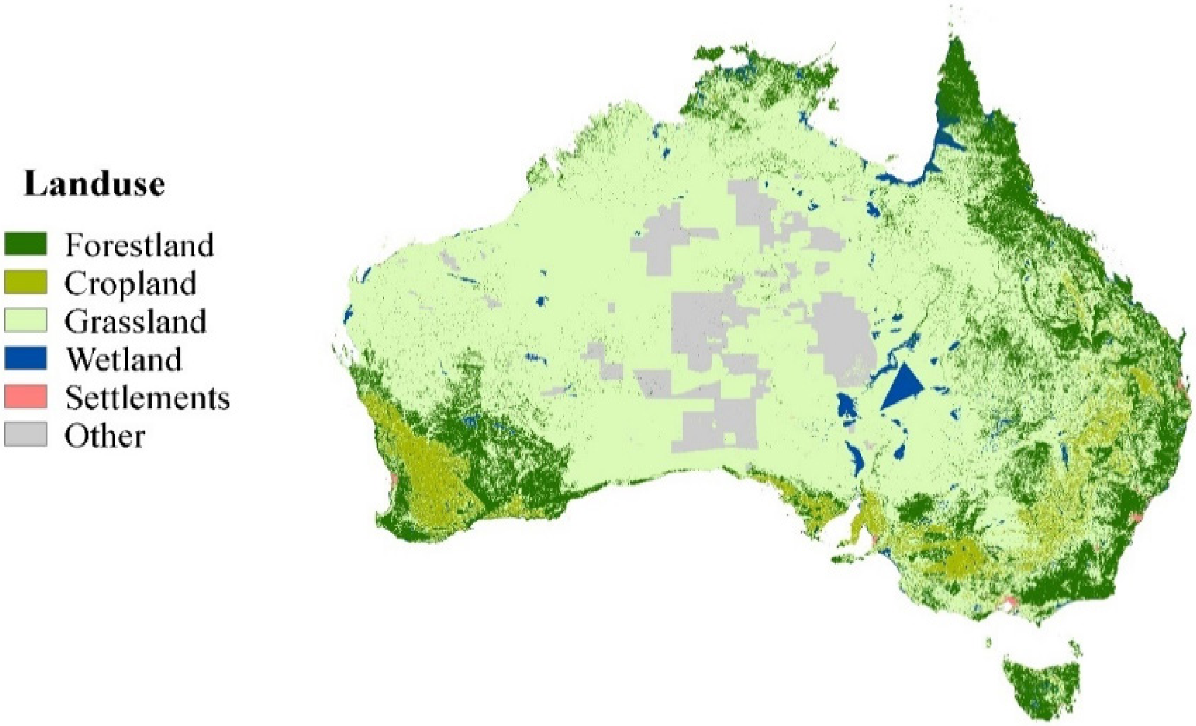
Figure 6.2.2 Long-term average annual temperature



Australia has a diversity of soil types ranging from old, highly weathered and infertile, to younger, more fertile soils derived from volcanic rocks and alluvium. Approximately 50 per cent are dominated by sandy surface soil horizons, 37 per cent are dominated by loam and sandy clay loams in the surface horizon and the remaining 13 per cent are dominated by light to medium clay textured soil in the surface horizon. Most of these soils have low levels of nitrogen, phosphorus and other nutrients.

The areas of the continent under different land uses are shown in Figure 6.2.3. Significant agricultural activities include wool, beef, wheat, cotton and sugar production. Australia is also an exporter of dairy produce, fruit, rice and flowers. Australia's forest resources consist of native forests (primarily dominated by *Eucalyptus* species), which are used for wood production, recreation and conservation, and plantations of native (primarily *Eucalyptus* species) and exotic species (primarily *Pinus* species).

Figure 6.2.3 Land use in Australia



Cropland is generally located along a broad inland fringe across the southern and eastern areas of Australia, with the highest yields commonly obtained in the southwest and eastern regions. In the southern regions, *cropland* is dominated by wheat production, with barley, oats, lupins and canola being the other dominant crops. In the north, wheat, sugarcane, sorghum and cotton production dominate.

The majority of *grassland* areas occur in inland Australia and are used for extensive grazing of both sheep and cattle. In Australia, grazing occurs across very diverse climates, ecosystems and management systems. The pasture types and associated management intensities range from highly improved to extensive rangeland systems in the semi-arid and arid regions of Australia. Native or naturalised pastures are the major pasture type, occupying approximately 17 per cent of Australia's land area with sown and fertilised pastures occupying only 4 per cent of the land area. Sown pastures are represented by mixed annual grasses and legumes as well as mixed perennial grasses and legume species depending upon rainfall and regional location. Irrigated pastures represent about 5 per cent of all pastures and are generally confined to the dairy and feedlot industries.

The three floristically diverse coastal wetland communities covered in the 2013 IPCC Wetlands Supplement (IPCC 2013), namely mangrove forests, tidal marshes and seagrasses are present in Australia's tidal and near coastal zones. Together they cover 8 to 12 million hectares of coastal wetlands around Australia's 60,000 kilometre coastline (mainland plus islands) and store an estimated 3 billion tonnes of carbon, mostly in the soil (mean value, range = 1.4 to 6 billion tonnes Lawrence et al. (2012)). Although relatively small in area, this thin veneer of coastal vegetation comprises some of Australia's densest carbon stores.

6.2.2 Land classifications

Forest land (Figure 6.2.4) includes:

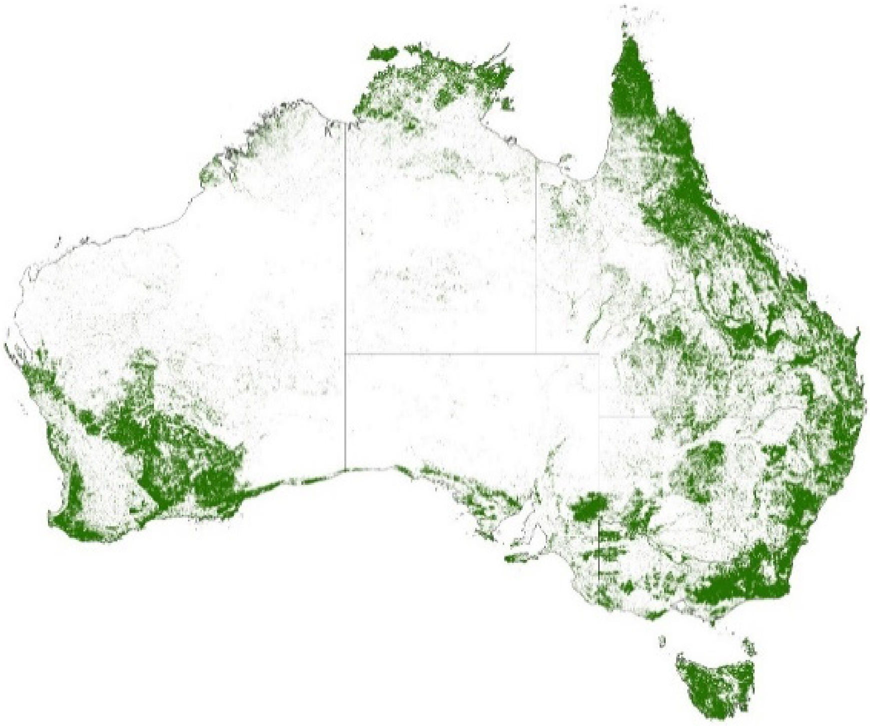
- All lands with a vegetation height of 2 metres or higher and crown canopy cover of 20 per cent or more over an area of at least 0.2 ha; and
- Lands with ecosystems with woody vegetation that currently fall below but which, *in situ,* could potentially[8] reach the threshold values of the definition of *forest land.*

Young natural stands and all plantations and environmental plantings that have yet to reach a crown density of 20 per cent or a tree height of 2 metres are included under *forest land,* as are areas normally forming part of the forest area which are temporarily unstocked as a result of either human intervention (e.g. harvesting) or natural causes, but which are expected to revert to forest.

Forest land does not include woody horticulture that meets the forest threshold parameters; this land is classified as croplands.

Australia has adopted a minimum forest area of 0.2 ha.

Figure 6.2.4 Forest extent in Australia



Cropland includes all land that is used for continuous cropping and those lands managed as crop-pasture (grassland) rotations (Figure 6.2.5) (ABARES 2017) as well as perennial woody horticulture that would otherwise reach the forest thresholds.

Non-CO_2 emissions from *cropland remaining cropland* are reported in the *Agriculture* sector.

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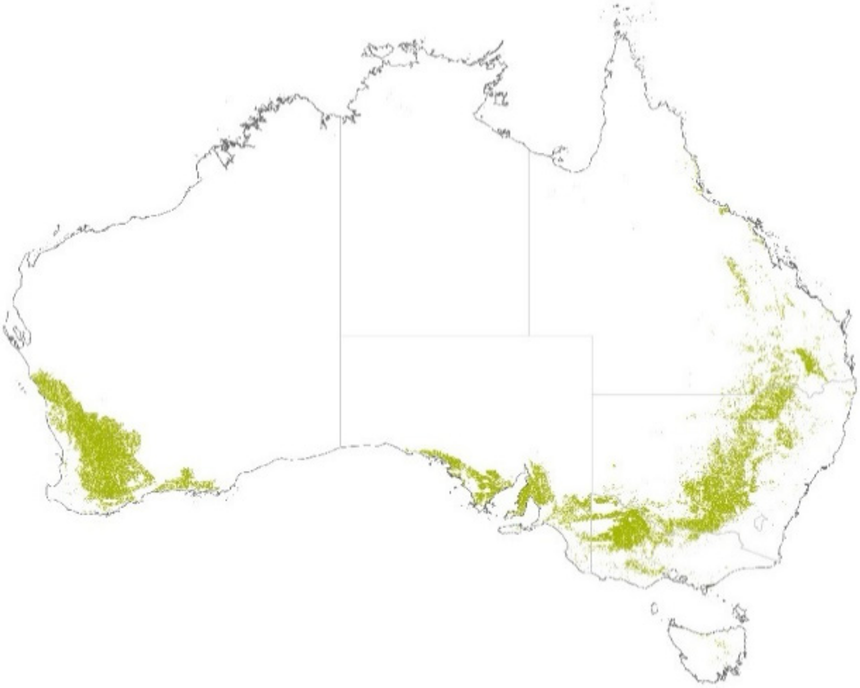
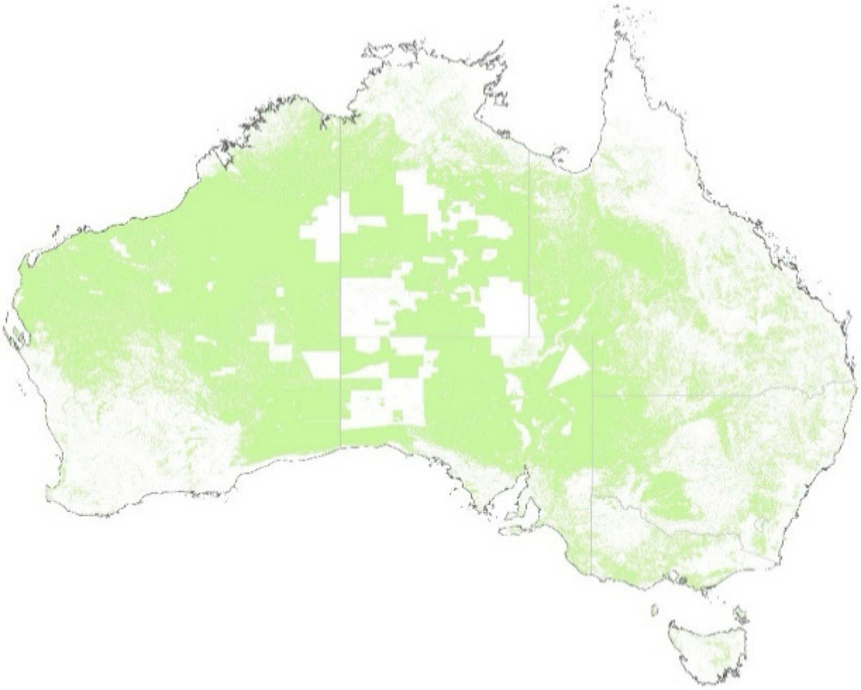
[8] This potential is evidenced from the remote sensing series that the land had previously supported forest.

Figure 6.2.5 Cropland remaining cropland distribution in Australia



The *grassland* category represents a diverse range of climate, management and vegetation cover (Figure 6.2.6) (ABARES, (2014)). The *grassland* category also includes sub-forest forms of woody vegetation (shrubs).

Figure 6.2.6 Grassland remaining grassland distribution in Australia



Settlements include areas of residential and industrial infrastructure, including cities and towns, and transport networks. The area of the *settlements* land use classification is based on information sourced from the 2017 ABARES catchment scale land use data (ABARES, (2017)). *Settlements* includes additional land use classes such as manufacturing and industry, commercial services, transport and communications including airports.

Wetlands include areas of perennial lakes, reservoirs, swamps and major water course areas derived from the Australian Hydrological Geospatial Fabric (AHGF) data published by the Australian Bureau of Meteorology, all existing wetlands as defined in the Directory of Important Wetlands in Australia (DIWA), and the extensive coastal wetlands of mangrove and tidal marsh ecosystems which circle the Australian continent. Land areas with wetland characteristics that meet the definition of *forest land,* such as mangroves, are reported under the *forest land* category.

The *other land* category includes bare soil, rock and other land areas that do not fall into any of the other five categories according to ABARES' catchment scale land use map of Australia (ABARES 2014).

The allocation of a particular forest conversion area to either *wetland (flooded land), settlement, cropland* or *grassland* is determined using the same criteria as outlined above for the location in which the conversion occurred. Where the regrowth of forest is observed on these lands, the land is re-assigned to the inverse category for conversion to forest.

6.2.3 Land representation matrix

Areas under each land-use are reported in Table 6.2.1 and Table 6.2.2 below.

Further detail is included in the Common Reporting Tables which are included with this document as a part of this Report.

Table 6.2.1 Area under land use, land use change and forestry classifications, 1988–89 to 2021–22 (kha)

Year	Forest remaining Forest	Land converted to Forest	Cropland remaining Cropland	Land converted to Cropland	Grassland remaining Grassland	Land converted to Grassland	Wetlands remaining Wetlands	Land converted to Wetlands	Settlements remaining Settlements	Land converted to Settlements	Other land
1988–89	136,162	2,675	37,698	1,843	508,926	6,270	13,447	23	960	134	60,692
1989–90	135,351	3,221	37,687	1,927	508,438	6,936	13,232	228	966	150	60,692
1990–91	134,421	3,877	37,688	1,982	508,112	7,464	13,209	244	972	166	60,692
1991–92	133,560	4,416	37,688	2,012	507,917	7,935	13,266	179	980	184	60,692
1992–93	133,013	4,842	37,689	2,028	507,722	8,222	13,306	132	985	196	60,692
1993–94	132,428	5,223	37,690	2,048	507,547	8,570	13,303	127	991	209	60,692
1994–95	131,996	5,611	37,690	2,065	507,367	8,771	13,321	101	996	218	60,692
1995–96	131,555	5,907	37,691	2,089	507,184	9,062	13,306	108	1,002	231	60,692
1996–97	131,111	6,209	37,692	2,115	507,007	9,345	13,300	105	1,008	244	60,692
1997–98	130,687	6,488	37,692	2,137	506,809	9,659	13,293	104	1,012	256	60,692
1998–99	130,113	6,770	37,693	2,157	506,653	10,076	13,277	108	1,017	271	60,692
1999–00	129,575	7,083	37,693	2,170	506,508	10,429	13,271	105	1,022	280	60,692
2000–01	128,940	7,327	37,694	2,189	506,382	10,921	13,262	105	1,028	289	60,692
2001–02	128,379	7,583	37,695	2,204	506,257	11,331	13,258	99	1,034	296	60,692
2002–03	127,896	7,823	37,695	2,219	506,104	11,702	13,256	93	1,039	310	60,692
2003–04	127,423	8,107	37,696	2,232	505,903	12,068	13,249	91	1,043	326	60,692
2004–05	126,804	8,339	37,697	2,251	505,686	12,631	13,245	83	1,050	351	60,692
2005–06	126,254	8,635	37,697	2,264	505,486	13,055	13,244	74	1,058	369	60,692
2006–07	125,760	8,910	37,698	2,276	505,319	13,420	13,233	75	1,063	383	60,692
2007–08	125,409	9,228	37,698	2,282	505,153	13,605	13,250	49	1,068	395	60,692
2008–09	125,112	9,684	37,699	2,285	504,974	13,617	13,238	50	1,073	404	60,692
2009–10	124,858	10,238	37,700	2,284	504,756	13,529	13,228	53	1,080	410	60,692
2010–11	124,577	10,786	37,700	2,285	504,556	13,456	13,225	49	1,088	414	60,692
2011–12	124,344	11,273	37,701	2,285	504,343	13,416	13,214	50	1,093	417	60,692
2012–13	124,120	11,762	37,702	2,288	504,085	13,410	13,203	50	1,098	419	60,692
2013–14	123,843	12,293	37,702	2,289	503,863	13,382	13,193	48	1,106	419	60,692
2014–15	123,646	12,896	37,703	2,285	503,568	13,281	13,179	48	1,113	416	60,692
2015–16	123,343	13,474	37,704	2,285	503,310	13,266	13,166	49	1,123	417	60,692
2016–17	123,041	13,962	37,704	2,280	503,119	13,280	13,158	48	1,128	416	60,692
2017–18	122,811	14,215	37,705	2,279	502,952	13,427	13,150	48	1,133	417	60,692
2018–19	122,635	14,444	37,705	2,280	502,788	13,541	13,144	48	1,136	415	60,692
2019–20	122,573	14,682	37,706	2,281	502,514	13,641	13,138	47	1,141	414	60,692
2020–21	122,343	15,088	37,707	2,281	502,272	13,709	13,132	47	1,144	414	60,692
2021–22	121,897	15,837	37,727	2,262	502,206	13,470	13,131	47	1,148	411	60,692

Table 6.2.2 All land use totals, 1988–89 to 2021–22 (kha)

Year ending June	Forest land	Cropland	Grassland	Wetland	Settlements	Other land
1988–89	138,836	39,542	515,196	13,469	1,094	60,692
1989–90	138,572	39,614	515,374	13,460	1,116	60,692
1990–91	138,298	39,670	515,576	13,453	1,139	60,692
1991–92	137,976	39,701	515,851	13,444	1,164	60,692
1992–93	137,856	39,717	515,944	13,438	1,181	60,692
1993–94	137,651	39,738	516,117	13,430	1,200	60,692
1994–95	137,607	39,755	516,138	13,422	1,214	60,692
1995–96	137,463	39,780	516,246	13,414	1,233	60,692
1996–97	137,320	39,806	516,353	13,405	1,251	60,692
1997–98	137,174	39,829	516,468	13,397	1,268	60,692
1998–99	136,884	39,850	516,729	13,385	1,288	60,692
1999–00	136,658	39,864	516,937	13,375	1,302	60,692
2000–01	136,267	39,883	517,303	13,366	1,317	60,692
2001–02	135,962	39,898	517,589	13,357	1,330	60,692
2002–03	135,718	39,914	517,807	13,348	1,349	60,692
2003–04	135,530	39,928	517,970	13,339	1,369	60,692
2004–05	135,144	39,947	518,317	13,328	1,401	60,692
2005–06	134,889	39,962	518,541	13,318	1,427	60,692
2006–07	134,670	39,974	518,738	13,308	1,446	60,692
2007–08	134,637	39,980	518,758	13,298	1,463	60,692
2008–09	134,796	39,984	518,591	13,289	1,477	60,692
2009–10	135,096	39,984	518,285	13,281	1,489	60,692
2010–11	135,363	39,985	518,011	13,274	1,502	60,692
2011–12	135,617	39,987	517,760	13,264	1,510	60,692
2012–13	135,882	39,989	517,495	13,252	1,518	60,692
2013–14	136,135	39,991	517,245	13,240	1,525	60,692
2014–15	136,542	39,988	516,849	13,228	1,530	60,692
2015–16	136,817	39,989	516,576	13,215	1,539	60,692
2016–17	137,003	39,984	516,399	13,207	1,544	60,692
2017–18	137,025	39,984	516,379	13,199	1,550	60,692
2018–19	137,078	39,985	516,330	13,192	1,551	60,692
2019–20	137,255	39,987	516,155	13,185	1,555	60,692
2020–21	137,431	39,988	515,981	13,178	1,558	60,692
2021–22	137,734	39,989	515,676	13,178	1,559	60,692

6.3 Country-specific approaches

6.3.1 Information on approaches used for representing land areas and on land-use databases used for the inventory preparation

Land monitoring system

Australia uses Approaches 1 and 3 as described in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) to monitor land use, land use change and forestry.

The principal monitoring system is a remote sensing programme used to identify *forest lands* and changes in forest cover (see Annex 5.6.1 for details).

The remote sensing programme is implemented by the Department of Climate Change, Energy, the Environment and Water. The system monitors national forest cover on an annual basis using Landsat satellite data (collected by MSS, TM, ETM+ and OLI sensors). The time series of national maps of forest cover extends from 1972 and has been assembled on an annual basis since 2004. These rasters are able to detect fine-scale changes in forest cover at 25 m by 25 m resolution.

Supplementary spatial information from the Land Use Mapping programme of Australia's Bureau of Agricultural Resource Economics and Sciences (ABARES 2014)) is used to identify land areas in the grassland, non-coastal wetlands and other land categories. Cropland and Settlements have been assessed based on the September 2017 revision of these areas (ABARES 2017), with settlements supplemented by spatial data from other unpublished sources. Land categories are expected to be updated over time. This information supports an Approach 1 representation of land, where only total areas are known for the areas under these land categories, not the prior land-use. Where the prior land-use is not known, emissions and removals associated with conversions to these land uses are estimated using the methods for land remaining in a land category. Further information on reporting of conversions between different land uses is included in Annex 5 (Completeness).

Identified changes in forest area from the remote sensing programme are assessed through a series of automated analytical tools and are quality controlled through inspection by trained operators to determine if these changes are due to human activity and are followed by land use change (e.g. forest clearing for agriculture, mining or urban development). The full details of the remote sensing and attribution analysis are provided in Annex 5.6.1.

Loss of forest cover

Human-induced land-use changes from forest land to other land uses are visually attributed by trained operators. In cases where there is a temporary loss of forest cover, due to a forest harvest or fire, the land remains in the *forest land* category unless a subsequent land use change is identified.

Losses in forest cover due to changes that occur within land tenures where it is expected that the land will revert to forest (e.g. harvested forest) are monitored for a period of time, depending upon the type of forest land use. In the absence of land use change, most of the areas without forest cover that have entered the monitoring system continue to be classified as "forest" provided that the time since forest cover loss is shorter than the number of years within which tree establishment is expected. After that time period, lands that have lost forest cover due to direct human-induced actions, have undergone land use change, and failed to regenerate are classified as converted to the appropriate non-forest land use classification. As an interim estimate for reporting purposes, a small proportion of the area being monitored within plantations is assumed to have undergone a land use change. This proportion is based on historical observations.

In Australia, land remains in the "conversion" sub-category for 50 years, unless specified otherwise for a particular type of conversion (for example, wetlands converted to croplands and grasslands). This period is longer than the IPCC default and reflects the long-term impacts of conversion on woody carbon dynamics in Australian systems.

Once classified as a forest conversion event, the land continues to be monitored for subsequent forest cover changes associated with regrowth and re-clearing. Where subsequent forest-cover changes occur within a period shorter than 50 years, the land is reported in each reporting year based on the end-use category of the land in that year (either land *converted to forest land* following regrowth, or to the relevant *"forest land converted to…"* subcategory following re-clearing).

Gain in forest cover

In cases where new forest cover is detected on land previously under another land use (cropland, grassland, wetland or settlement), the land enters the *land converted to forest land* subcategory. Land monitored for this cover gain includes:

- Establishment of new commercial plantations
- Environmental plantings
- Forest emerging through natural regeneration (from seed or rootstock) on previously not forested, protected lands (i.e. land that has vegetation which is protected or requires a permit to clear under the relevant state's or territory's vegetation management laws, including conservation areas)
- Forest re-emerging on land that has previously been converted from forest to a non-forest land use.

Incorporation of land monitoring data into emissions estimation

The land monitoring system supports Tier 3, Approach 3 spatial enumeration of emissions and removals calculations for the following sub-categories:

- Forest land remaining forest land
- Forest land converted to cropland, wetlands (Flooded Land), grassland, and settlements
- Grassland, cropland, wetland (tidal marsh) and settlements converted to forest land; and
- Cropland remaining cropland and grassland remaining grassland.

Spatial enumeration is achieved through the use of a time-series (since 1972) of Landsat satellite data to determine change in forest and sparse woody vegetation extent at a fine spatial disaggregation. The forest cover change information is coupled with spatially referenced databases of climate and land management practices which allows a comprehensive quantification of emissions (see Annexes 5.6.1 and 5.6.2).

FullCAM can also be configured to operate in a Tier 3, Approach 2 mode where spatially explicit data are unavailable. In this configuration, known as the 'Estate' module, FullCAM uses age-based growth data to estimate living biomass and dead organic matter (DOM) from both turnover and harvest residue. The 'Estate' module of FullCAM is used to scale regional models of carbon stock change by the areas of each forest type (see (Richards and Evans 2000)).

The other principal reporting elements, *wetlands remaining wetlands* and *settlements remaining settlements,* are reported using Tier 2 and Tier 3 methods.

6.3.2 Information on approaches used for natural disturbances

Fire (biomass burning) is the principal form of natural disturbance which impacts carbon stocks on the land in Australia.

Most Australian forests are adapted to fire, and fires, whether wildfires or prescribed fires, are generally not stand-replacing. Many eucalypt species continue growing, with burned leaves and twigs quickly regrowing from epicormic shoots with no effect on stand age-class. In most eucalypt forests, fires do not cause significant changes in the rate of turnover of living biomass to dead biomass, particularly following lower intensity fires which primarily burn only litter and deadwood (Raison and Squire et al. 2008, Bradstock et al. 2012, Fairman et al. 2015). Fire regimes differ widely in regard to fire frequency and intensity across Australia as shown in Figure 6.3.2, with implications for the estimation of carbon stocks.

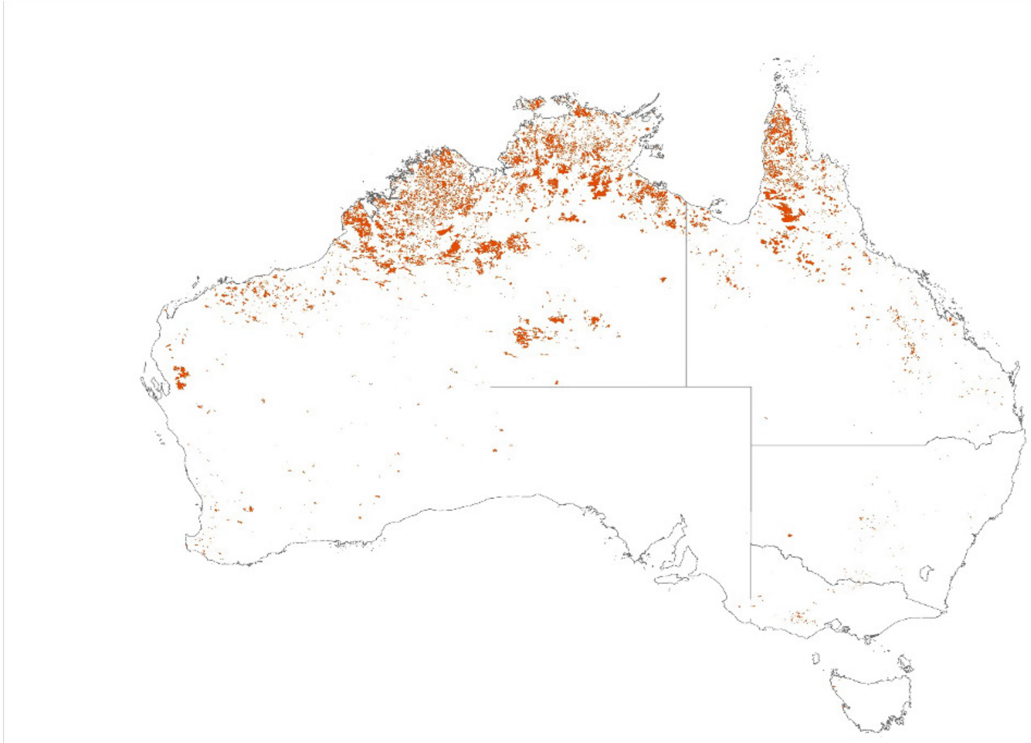
Fire is a very frequent occurrence in the northern and central Australian wet/dry tropical, subtropical and semi-arid forest ecosystems. Many fires are from anthropogenic sources due to ongoing indigenous fire management and the pastoral use of fire as a land management tool.

The seasonality of burning in this region has profound impacts on the fire behaviour and emissions associated with a fire event. Fires in the late dry season (LDS) are typically larger, more intense and consume more fuel than fires that occur during the early dry season (EDS). A primary aim of anthropogenic burning is to encourage more fires in the EDS to mitigate the impacts of the larger, more intense fires in the LDS. These strategic fires in the EDS can decrease net greenhouse gas emissions from these landscapes.

Australia's temperate forests are also highly adapted to fire although do not exhibit the same fire frequency as those in the north of the continent. Instead, the majority of these forests are characterised by fire intervals on the decadal scale.

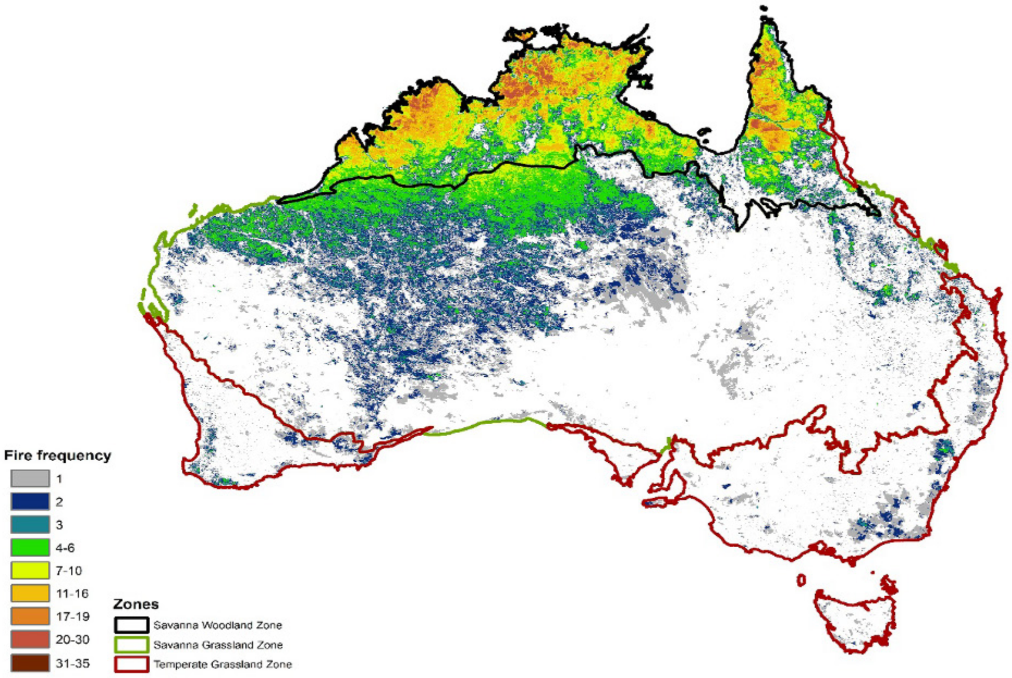
Figure 6.3.1 shows the incidence of fire activity in 2021-22. Figure 6.3.2 shows the reoccurrence of fire events since 1988, highlighting the frequency with which the semi-arid and tropical savannas of Northern Australia are burned and re-burned by fire.

Figure 6.3.1 Fire activity in Australia, 2021–22



Date sourced from Western Australian Land Authority (Landgate)

Figure 6.3.2 Forest and grassland wildfire, 2021–22



Date sourced from Western Australian Land Authority (Landgate)

Prescribed burning in temperate forests involves conducting managed fires that aim to mitigate the risk and severity of wildfires by reducing fuel loads. Prescribed burning is typically low intensity and performed during the cooler and wetter months, consuming only a proportion of the dead organic matter present in the forest.

Wildfires can range from moderate intensity burns through to high intensity wildfire, which can remove most debris as well as understorey vegetation, foliage, and small branches.

Some wildfires constitute non-anthropogenic natural disturbances as they are beyond the control of, and not materially influenced by, Australian authorities and occur despite costly and on-going efforts across regional and national government agencies and emergency services organisations to prevent, manage and control the fires.

In this inventory, in addition to reporting inter-annual variability from natural disturbances, the trend in net emissions from anthropogenic fires (which include prescribed fires and wildfires) is reported. In order to estimate the trend in anthropogenic fires, non-anthropogenic natural disturbances are modelled to average out over time, leaving anthropogenic emissions and removals as the dominant result.

The same methods, factors and data are used to estimate emissions and removals from fire in sparse woody vegetation in *grassland remaining grassland, forest converted to grassland* and *wetland remaining wetland* to ensure consistent estimation of emissions and removals across land classifications.

Stratification of forests

Other native forests are stratified into three geographic / climatic zones where fires demonstrate significantly different behaviour. The boundaries of these zones are shown in Figure 6.3.2.

- Tropical zone forests – the northern part of the Northern Territory (NT), Western Australia (WA) and Queensland (Qld), are characterised by wet/dry tropical woodland and higher rainfall than the arid centre and is known as the 'Top End'. The Top End corresponds to the Interim Biogeographic Regionalisation for Australia (IBRA)[9] version 4.1 zones AEZ 1, AEZ 2 and AEZ 3 which are predominantly woodland with smaller areas of open forest and grassland;
- The open woodlands and grasslands of the arid interior of central Australia ('the Centre') comprise AEZ 5, AEZ 6 and AEZ 11 of the NT, WA, Qld, South Australia (SA) and New South Wales (NSW) and these zones are used as the inventory definition of subtropical and semi-arid zone forests; and
- Temperate forests – comprising forests in zones AEZ4 and AEZ zones 7-10.

Tropical zone forests are further disaggregated into seven vegetation classes (Table 6.3.1). These classes are derived using a combination of validated vegetation, land use and geological data sets (Lynch et al. (2015); Meyer and Cook, (2015)).

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[9] IBRA is a framework used for sustainable resource management and conservation planning. The 80 IBRA regions in IBRA version 4.1 represent a landscape-based approach to classifying the land surface from a range of continental data on environmental attributes such as vegetation, geology, soils and climate. Background information and a map of the IBRA regions is available at https://www.dcceew.gov.au/environment/land/nrs/science/ibra

Table 6.3.1 Symbols used in algorithms for biomass burning of forest land

State (i)	Vegetation Class (j)	Rainfall Zone (k)	Fire Variant (l)	DOM size class (m)
1 = ACT	1 = Wet/dry tropical zone		1 = Early Dry Season (EDS)	1 = Fine
2 = NSW	1.1 = Woodlands (with either hummock or mixed grassland)	1 = High	2 = Late Dry Season (LDS)	2 = Coarse
3 = NT	1.2 = Shrubland with hummock grasses	1 = High	3 = Annual	3 = Heavy
4 = SA	1.3 = Open forest with mixed grasses	1 = High	4 = Temperate prescribed burning	4 = Shrub
5 = TAS	1.4 = Shrubland (heath) with hummock grass	2 = Low	5 = Temperate wildfire	5 = Aggregated
6 = QLD	1.5 = Woodland with tussock, hummock or mixed grasses	2 = Low		
7 = VIC	1.6 = Open woodland with mixed grass	2 = Low		
8 = WA	1.7 = Pindan	2 = Low		
	2 = Subtropical and semi-arid zone	3 = NA		
	3 = Temperate zone	3 = NA		

Carbon stock changes

A time series of monthly satellite data is used to identify the time and location of fires, which are simulated at the 25 m x 25 m resolution (Figure 6.3.2). The AVHRR burnt area product produced by the Western Australian Land Authority (Landgate), is tailored to Australian conditions and based on the visual interpretation of fire areas by experienced operators. The data was assessed by the Royal Melbourne Institute of Technology (RMIT, 2014), compared with a range of alternative datasets and was found to be the most suitable and highest quality time series data available.

The AVHRR burnt area product is not used for prescribed burning identification as it is limited in its ability to identify fires where the canopy remains intact. Areas of land where prescribed burns were conducted are identified through digitised, spatially explicit mapping of prescribed burning treatment areas from state or territory fire authorities.

When fires are detected, impacts on all pools excluding soil carbon are modelled (including live biomass, standing dead stem, branches bark and coarse woody debris, bark debris and grasses). Further research is required to estimate the impacts of fire on soil carbon.

Carbon stock changes in all pools are modelled using the spatially explicit (Approach 3) capabilities of the Tier 3 FullCAM modelling system. These were parameterised for typical fires, and not assumed to be highly intense stand-replacing fires which are unusual in most Australian eucalypt and dominated forests. Hence, for both woody and grass live biomass components, it was assumed that fire did not burn roots, with live root biomass assumed to continue at equilibrium conditions of growth and turnover regardless of the fire simulation. A full description of the modelling system is provided in Annexes 5.6.2 and 5.6.4, Waterworth et al. (2007); Waterworth and Richards, (2008); and Paul and Roxburgh, (2019).

Changes in live biomass are estimated using the gain-loss method. The *other native forests* component excludes areas subject to observed harvesting and deforestation, therefore are assumed to represent mature stands in equilibrium conditions, with annual increments in living biomass and soil carbon stocks balanced by annual losses in the absence of disturbances. The main processes leading to emissions and removals in these forests are related to fire management practices. For this reason, the loss of biomass due to wood removals (harvesting) is zero.

Biomass losses due to disturbances (as a percentage of pre-fire biomass) are shown in Annex 5.6.11, Table A5.6.11.6.

Live woody biomass is simulated as mature stands at equilibrium conditions. The model inputs of initial above-ground biomass of living woody vegetation were derived from the maximum site carrying capacity (Roxburgh et al. (2019)).

Simulations include short-term fire-induced impacts on the predicted relative allocation of woody biomass due to: (i) fires resulting in only partial burning of live woody biomass components, with the extent of impact varying between components, and; (ii) rates of post-fire re-sprouting or regeneration differing between components, e.g. relatively fast for foliage and relatively slow for stem wood.

Annual increments after fire events are calculated directly as recovery following the loss of live biomass from disturbances using the biomass recovery function described in Annex 5.6.2. Wildfires are not stand-replacing, and typically only affect 10 percent of initial live biomass. A typical time for live biomass recovery following temperate forest wildfires is between 10 and 15 years. For prescribed burning in temperate forests and management fires in savanna woodlands, the impact on live biomass is much lower such that it can take up to 5 years to recover.

Changes in dead organic matter stocks in *other native forests* are calculated in accordance with the gain-loss method in Equation 2.18 of the IPCC 2006 Guidelines (Volume 4) (IPCC 2006) for estimating annual change in carbon stocks in dead wood or litter for areas remaining in a land-use category:

$$\Delta C_{DOM} = \Sigma_{ijklm} (A \times (DOM_{in} - DOM_{out}) \times CF) \qquad (6.3.1)$$

Where Subscripts $_{ijklm}$ are the dimensions over which DOM is stratified for the purposes of this estimate (see Table 6.3.1)

ΔC_{DOM} = annual change in carbon stocks in the DOM pools

A = area of land remaining in land-use category

DOM_{in} = average annual transfer of biomass into the dead wood / litter pool due to annual processes and disturbances;

DOM_{out} = average annual carbon loss out of dead wood or litter pool

CF = carbon content (Table A5.6.11.8);

DOM stocks are modelled using the spatially explicit (Approach 3) capabilities of the Tier 3 FullCAM modelling system.

Table 6.3.2 Comparison of carbon pools modelled under the previous T2 model and the current T3 FullCAM implementation

Pool type	Fuel pools calculated using previous T2 method	Fuel pools simulated using FullCAM
Live biomass	Shrub	Live Above-Ground Biomass impacted by fire, but which recovers quickly
Fine DOM	Fine-grass	Decomposable grass litter + Resistant grass litter + above-ground biomass of grass
Fine DOM	Fine-woody	Standing Dead foliage + Decomposable foliage litter + Resistant foliage litter
Coarse DOM	Coarse-light	Standing dead bark + Bark litter + Deadwood < 5cm
Coarse DOM	Coarse-heavy	Standing Dead stem + Standing Dead branch + Deadwood > 5cm

FullCAM simulates turnover and decay processes for each pool (or sub-set of pools) based on site conditions (productivity and vegetation type) and monthly climate data, until a fire event is identified based on the Advanced Very High Resolution Radiometry (AVHRR) satellite data. Fire events were individually parameterized for each State (i), Vegetation Class (j), Rainfall Zone (k), Fire Variant / seasonality (l), and DOM size class (m) (Roxburgh et al. (2015)), with the resulting fuel dynamics being replicated by FullCAM as described by Paul and Roxburgh (2019).

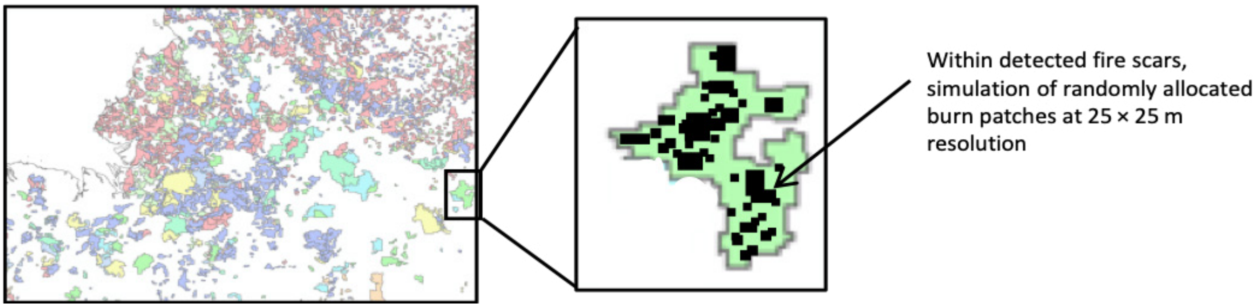
The savanna fire zone applied some differences in approach where there was additional empirical data (Paul and Roxburgh (2022)):

- Early Dry Season (EDS) and Late Dry Season (LDS) fire events were calibrated for each vegetation class (j);
- The default IPCC DOM classes of litter and dead wood are further disaggregated into fine (grass live biomass, grass litter, foliage on standing dead material, and foliage litter), coarse-light (standing dead bark, and bark litter), coarse-heavy (standing dead stem and branches, and coarse woody debris) and live woody biomass (Table A5.6.11.4);
- In order to initialise the model ahead of the reporting period, fires prior to 1988 are simulated based on available estimates of typical fire return intervals, time of year fires occur, area of the fire scar, and the proportion of EDS to LDS burns in the savanna fire zone, where available from previous studies and expert opinion (Meyer and Cook (2011); Murphy et al. (2013)). To introduce variation in the simulated fire events, uniform probability distribution functions were applied to vary these assumptions between what was deemed to be their upper and lower bounds.
- It was assumed that grasses were a component of the total live biomass within each fire zone. FullCAM has existing default inputs (e.g. yields, allocation of biomass, die-off, decomposition, etc.) for simulation of different perennial grass species (Table A5.6.11.3).

Burning efficiencies and Patchiness

Fires do not uniformly affect the landscape and will leave unburned patches at a finer scale than the resolution of the satellite data. In FullCAM, fire events are only applied to a proportion of model cells within the fire scar in accordance with the assumed Patchiness values *(P)*. Patchiness depends on fire intensity and varies based on State, Vegetation Type and Fire Variant (e.g. seasonality). Figure 6.3.3 shows fire patches (various colours indicate different year in which the fire occurred) in north-west Australia. As indicated in the panel to the right, within each fire scar detected, the patchiness assumption is applied such that a burning event is simulated within only a proportion of pixels within each fire scar.

Figure 6.3.3 Diagrammatic example indicating how spatial fire is implemented within FullCAM



In the wet/dry tropical zone, fires are classified by the season of burning as either early dry season (EDS) or late dry season (LDS). EDS fires are characterised by low intensity or severity, a high degree of patchiness, a greater propensity to extinguish spontaneously and reduced total fuel consumption. LDS fires are characterised by high intensity, low levels of patchiness, a greater propensity to spread and high total fuel consumption.

The average date of transition from EDS to LDS is the last day of July. This date is based on indigenous fire management practices and observations of the seasonal patterns of fire behaviour (C. Meyer, J. Russell-Smith pers. comm.). On average, changes in ambient humidity and wind speed at this time are sufficient to support fire propagation through the night; which allows fires to spread for several days and to reach high intensities (C. D. Haynes 1985); Russell-Smith et al. (1997)).

For subtropical and semi-arid forests, burning efficiencies are assumed to be constant from year to year and throughout the year. In temperate forests, while different burning efficiencies are applied for prescribed fires and wildfires, these are not further disaggregated based on seasonality.

Emission factors

FullCAM calculates area burned, the DOM stocks at time t, and the losses due to fire based on the burning efficiency, providing an output in terms of carbon flow to atmosphere due to fire for each State (i), Vegetation Class (j), Rainfall Zone (k), Fire Variant (l), and DOM size class (m). Using these calculations, emission factors derived from direct field measurements from fires across Australia (Meyer and Cook (2015); Roxburgh et al. (2015); Meyer et al. (2012); Hurst *et* al. (1994), (1994)) were then applied to calculated non-CO_2 emissions Table A5.6.11.9 to Table A5.6.11.11.

Non-CO_2 emissions

For CH_4, CO, and NMVOCs calculate emissions as:

$$E = \Sigma_{ijklm} \text{YSLB} (A \times DOM_{out\ ijklm} \text{YSLB} \times CC_{jkm} \times EF_{g,jkm} \times C_g). \qquad (6.3.2)$$

and for NO_X, N_2O:

$$E = \Sigma_{ijklm} \text{YSLB} (A \times DOM_{out\ ijklm} \text{YSLB} \times CC_{jkm} \times NC_{jkm} \times EF_{g,jkm} \times C_g). \qquad (6.3.3)$$

Where E = emissions from fires (kt);
A = Area of land remaining in land-use category
$DOM_{out\ ijklm}$ = average DOM losses in fire (kt)
CC_{jkm} = carbon content (Appendix A5.6.11.5)
NC_{jkm} = nitrogen:carbon ratio (Appendix A5.6.11.7)
EF_{gjkm} = emission factor (g N or C emitted as trace species / g DOM N or C emitted) (Tables A5.6.11.9-11);
C_g = elemental to molecular mass conversion factor (Appendix A5.6.11.8); and
YSLB = age class of DOM stocks based on the number of years since last burned.

1. *Definition of natural disturbances and types of disturbances identified in the inventory*

The fire-adapted ecology of Australian eucalypt-dominated temperate forests leads to infrequent, extreme wildfires. Natural 'background' emissions and removals caused by natural disturbance fires are considered to be caused by non-anthropogenic events and circumstances beyond the control of, and not materially influenced by, Australian authorities and occur despite costly and on-going efforts across regional and national government agencies and emergency services organisations to prevent, manage and control natural disturbances to the extent practicable. These fires are considered to be part of the 'natural background' of non-anthropogenic emissions and removals, which under the Managed Land Proxy (MLP) are understood to average out over time and space[10].

This national definition of natural disturbances applies to wildfires on temperate forests and does not apply to fires reported as controlled burning (e.g. in temperate forests or in wet-dry tropical forests and woodlands). All fires on *land converted to forest land* are treated as anthropogenic.

The impacts of human activities (e.g. salvage logging, prescribed burning, deforestation) are excluded from the identification of natural disturbances through the application of an Approach 3 representation of lands which is used to track lands subject to natural disturbances and separately identify and exclude land subject to human activities, as explained in section 6.3.

2. *Quantification of inter-annual variability due to all wildfire and natural disturbances (total Managed Land Proxy (MLP) flux)*

In Australia, all lands are considered managed lands. All carbon stock changes on managed land from anthropogenic and natural 'background' emissions and removals are reported, consistent with the MLP, including from wildfires.

Inter-annual variability in natural 'background' of emissions and removals is modelled as shown in Figure 6.3.4 below, along with the estimated trend in net emissions and removals associated with human activities.

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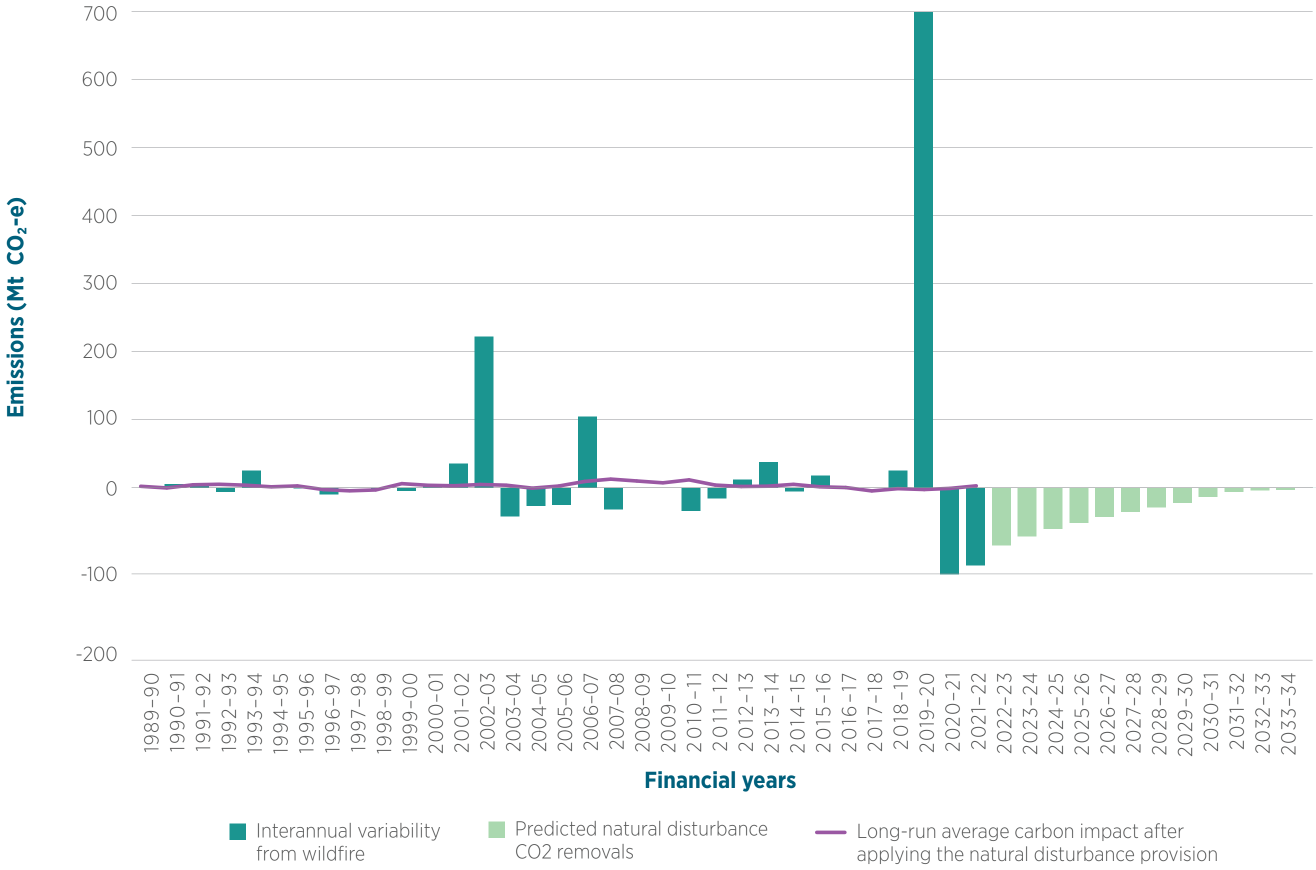
[10] IPCC 2006 Guidelines, Volume 4, Chapter 1 (p 1.5) states that, "…while local and short-term variability in emissions and removals due to natural causes can be substantial (e.g. emissions from fire, see footnote 1), the natural 'background' of greenhouse gas emissions and removals by sinks tends to average out over time and space."

Figure 6.3.4 Interannual variability from wildfire, including natural 'background' emissions and removals (total MLP flux)



3. Methods used for identification and quantification of emissions and removals due to natural disturbances

The quantification of emissions and subsequent removals from natural disturbances is done by identifying fires which meet the definition of natural disturbances both at the total (landscape-level) emissions and regional levels and tracking disturbed areas at fine spatial scales within the Tier 3, Approach 3 FullCAM modelling system.

In order to disaggregate emissions and removals due to natural disturbances under the Tier 3 method applied in this inventory, natural disturbances are explicitly identified in the activity data. Both initial carbon losses and subsequent recoveries in carbon stocks are modelled as part of the disturbance event, and carbon stocks are spatially tracked until pre-disturbance levels are reached to ensure completeness and balance in reporting. A modelling approach is then applied to ensure that emissions and subsequent removals from non-anthropogenic natural disturbances average out over time, leaving greenhouse gas emissions and removals of anthropogenic fires as the dominant result in the national inventory (IPCC 2006 Volume 4 1.5 (IPCC 2006)), consistent with the Managed Land Proxy (see footnote 10). The approach ensures that Australia's modelled implementation of the MLP is comparable with estimates generated using other methods, such as Tier 3 stock-difference approaches, that tend to average out interannual variability due to natural causes over space (scaling from plots to region) and time (averaging between periodic re-measurements). Natural disturbances evident in the activity data are identified in two steps, summarised in Table 6.3.3.

1. First, at the national level, emissions from the area burned are assessed on a year-by-year basis for extreme fire events where outcomes at the national level were beyond the control of authorities to manage. This is done by comparing each year's data with a threshold level or 'margin' based on two standard deviations above the mean of gross annual emissions from all fires and after iteratively excluding outliers. The national natural disturbance threshold is calculated for the calibration period of 1989-90 to 2019-20.
2. Second, once natural disturbance years are identified at a national level, natural disturbances are spatially identified and the area burnt tracked at the sub-national level. Natural disturbances at the State and Territory level were identified where the area burned during their local fire season exceeded a State or Territory natural disturbance threshold equal to the average area of the calibration period plus one standard deviation of the non-natural disturbance years.

Natural disturbance areas are identified at the level of each State or Territory for a year in which both the area burned exceeds the State or Territory natural disturbance threshold and the national emissions from total area burned exceeds the national natural disturbance threshold.

The methodology for identifying natural disturbance events does not preclude long-term changes in fire management practices (such as prescribed burning) affecting trends in anthropogenic emissions and removals.

Table 6.3.3 Calculations for the natural disturbance test in States and Territories, 1989–90 to 2021–22

	Calibration period	Calculation details	Threshold	Number of natural disturbance years 1989–90 to 2021–22
Step 1: National Level Test	1989-90 to 2019-20	Applied to: gross emissions (not including removals). Threshold calculation: mean plus two standard deviations of calibration period.	62,571 kt CO_2-e	6
Step 2: Regional test	1989-90 to 2019-20	Only applies in national outlier years (following Step 1 test). Applied to: annual area burned. Threshold calculation: mean area burned plus one standard deviation of background (non-outlier) years.		
ACT			0.56 kha	2
NSW			191.91 kha	3
Qld			145.16 kha	2
SA			32 kha	3
Tas			30.19 kha	4
VIC			90.9 kha	5
WA			322.04 kha	4

All fire areas are monitored for any permanent change in land use, which would trigger reporting of emissions in the appropriate land conversion category. Emissions from salvage logging are reported as part of *harvested native forests*.

4. *Disaggregation of emissions and removals due to natural disturbances and identification of the trend in emissions and removals associated with human activity*

After identifying lands subject to natural disturbances, and associated emissions and removals, anthropogenic emissions and removals are estimated using the remaining time-series of area burned in anthropogenic fire in each State or Territory. The 2019 Refinement (IPCC 2019) to the 2006 IPCC (IPCC 2006) guidelines note that even after disaggregating natural disturbances, "This remaining aggregate of emissions and removals associated with human activities might still include some effects of IAV [inter-annual variability] of natural disturbances and other natural effects on anthropogenic emissions and removals" (IPCC 2019 Refinement, Volume 4, Chapter 2.6.1.1 (IPCC 2019)). In order to control for this remaining inter-annual variability the long-run trend in carbon stocks is reported, reflecting the balance of the carbon lost in the fire and that re-absorbed by regrowth. This information is reported in Table 6.3.4 below.

To ensure transparency and to demonstrate complete reporting of anthropogenic and natural disturbance emissions and removals, the following additional information has been included:

- Identification of lands subject to natural disturbances and monitoring for forest recovery;
- Monitoring for land-use changes to ensure that no land-use change has occurred on lands subject to natural disturbances;
- Demonstrating practicable efforts to prevent, manage and control wildfires in Australia; and
- Inclusion of salvage logging emissions.

Table 6.3.4 Disaggregation of total managed land proxy flux into natural disturbances component and identification of trend in emissions associated with human activity

	Forest remaining Forest									
Years	Total MLP flux from wildfires					Natural disturbances component				
	Total area under the MLP (kha)	Annual area of wildfires including natural disturbances, reported in NIR (kha)	Carbon stock change (kt C)	Non-CO_2 fluxes (kt CO_2-e)	CO_2-e (kt)	Annual area of natural disturbances (in reporting year) (kha)	Cumulative area subject to natural disturbances (kha)	Carbon stock change (kt C)	Non-CO_2 fluxes (kt CO_2-e)	CO_2-e (kt)
1989-90	135,351	202	266	1,153	178	0	0	0	0	0
1990-91	134,421	490	-1,013	1,653	5,366	0	0	0	0	0
1991-92	133,560	199	-172	1,456	2,088	0	0	0	0	0
1992-93	133,013	85	1,752	439	-5,986	0	0	0	0	0
1993-94	132,428	789	-5,866	3,847	25,354	0	0	0	0	0
1994-95	131,996	283	-592	1,894	4,064	0	0	0	0	0
1995-96	131,555	152	743	1,458	-1,266	0	0	0	0	0
1996-97	131,111	43	2,740	229	-9,816	0	0	0	0	0
1997-98	130,687	271	208	1,340	578	0	0	0	0	0
1998-99	130,113	169	616	999	-1,259	0	0	0	0	0
1999-00	129,575	110	1,496	453	-5,032	0	0	0	0	0
2000-01	128,940	496	-973	1,564	5,131	0	0	0	0	0
2001-02	128,379	698	-8,457	5,065	36,074	0	0	0	0	0
2002-03	127,896	2,619	-53,741	26,780	223,831	2,583	0	-56,927	26,529	235,261
2003-04	127,423	89	11,879	792	-42,763	0	2,577	10,344	0	-37,926
2004-05	126,804	303	7,906	1,770	-27,220	0	2,568	8,611	0	-31,572
2005-06	126,254	223	7,226	1,224	-25,270	0	2,556	6,902	0	-25,307
2006-07	125,760	1,689	-24,525	15,801	105,727	1,298	2,429	-21,356	12,894	91,198
2007-08	125,409	314	9,238	1,967	-31,904	0	3,704	9,732	0	-35,684
2008-09	125,112	482	1,696	4,778	-1,440	0	3,673	8,226	0	-30,162
2009-10	124,858	863	2,016	4,605	-2,787	0	3,638	6,627	0	-24,300
2010-11	124,577	104	9,558	760	-34,285	0	3,612	5,617	0	-20,595
2011-12	124,344	472	4,878	2,274	-15,611	0	3,567	4,545	0	-16,665

Forest remaining Forest										
Years	Total MLP flux from wildfires					Natural disturbances component				
	Total area under the MLP (kha)	Annual area of wildfires including natural disturbances, reported in NIR (kha)	Carbon stock change (kt C)	Non-CO_2 fluxes (kt CO_2-e)	CO_2-e (kt)	Annual area of natural disturbances (in reporting year) (kha)	Cumulative area subject to natural disturbances (kha)	Carbon stock change (kt C)	Non-CO_2 fluxes (kt CO_2-e)	CO_2-e (kt)
2012-13	124,120	700	-2,002	4,872	12,212	0	3,482	3,624	0	-13,287
2013-14	123,843	1,121	-8,236	7,995	38,195	861	3,383	-11,134	6,562	47,386
2014-15	123,646	545	2,483	3,495	-5,609	0	4,160	4,565	0	-16,740
2015-16	123,343	862	-3,216	5,942	17,736	762	4,057	-6,630	5,079	29,389
2016-17	123,041	519	1,892	3,821	-3,118	0	4,741	4,835	0	-17,730
2017-18	122,811	495	2,828	3,284	-7,086	0	4,650	4,017	0	-14,731
2018-19	122,635	870	-5,083	6,529	25,168	735	4,485	-9,250	5,854	39,772
2019-20	122,573	7,969	-169,260	84,479	705,100	7,969	3,933	-172,977	84,479	718,729
2020-21	122,343	238	35,611	1,892	-128,683	0	11,857	36,472	0	-133,732
2021-22	121,897	157	31,836	1,072	-115,660	0	11,814	30,548	0	-112,009

Forest remaining Forest										
Years	Inter-annual variability in non-natural disturbance wildfires					Refined MLP flux				
	Remaining area of managed land (kha)1	Annual area of wildfires reported in NIR (kha)	Carbon stock change (kt C)	Non-CO_2 fluxes (kt CO_2-e)	CO_2-e (kt)	Remaining area of managed land (kha)1	Annual area of wildfires reported in NIR (kha)	Carbon stock change (kt C)	Non-CO_2 fluxes (kt CO_2-e)	CO_2-e (kt)
1989-90	135,351	202	266	1,153	178	135,351	202	-482	1,476	3,243
1990-91	134,421	490	-1,013	1,653	5,366	134,421	490	116	1,230	806
1991-92	133,560	199	-172	1,456	2,088	133,560	199	-1,007	1,710	5,400
1992-93	133,013	85	1,752	439	-5,986	133,013	85	-1,178	1,858	6,177
1993-94	132,428	789	-5,866	3,847	25,354	132,428	789	-827	1,819	4,851
1994-95	131,996	283	-592	1,894	4,064	131,996	283	-245	1,573	2,470
1995-96	131,555	152	743	1,458	-1,266	131,555	152	-554	1,753	3,783
1996-97	131,111	43	2,740	229	-9,816	131,111	43	743	1,184	-1,540
1997-98	130,687	271	208	1,340	578	130,687	271	1,160	896	-3,359

Forest remaining Forest										
Years	Inter-annual variability in non-natural disturbance wildfires					Refined MLP flux				
	Remaining area of managed land (kha)1	Annual area of wildfires reported in NIR (kha)	Carbon stock change (kt C)	Non-CO_2 fluxes (kt CO_2-e)	CO_2-e (kt)	Remaining area of managed land (kha)1	Annual area of wildfires reported in NIR (kha)	Carbon stock change (kt C)	Non-CO_2 fluxes (kt CO_2-e)	CO_2-e (kt)
1998-99	130,113	169	616	999	-1,259	130,113	169	817	917	-2,079
1999-00	129,575	110	1,496	453	-5,032	129,575	110	-1,422	1,884	7,099
2000-01	128,940	496	-973	1,564	5,131	128,940	496	-827	1,666	4,697
2001-02	128,379	698	-8,457	5,065	36,074	128,379	698	-643	1,625	3,982
2002-03	127,896	37	3,186	251	-11,429	127,896	37	-1,083	1,888	5,858
2003-04	127,423	89	1,535	792	-4,837	127,423	89	-823	1,821	4,840
2004-05	126,804	303	-704	1,770	4,353	126,804	303	234	1,389	530
2005-06	126,254	223	324	1,224	37	126,254	223	-502	1,732	3,572
2006-07	125,760	392	-3,169	2,907	14,528	125,760	392	-2,115	2,529	10,284
2007-08	125,409	314	-494	1,967	3,780	125,409	314	-2,896	3,096	13,716
2008-09	125,112	482	-6,530	4,778	28,722	125,112	482	-2,173	3,003	10,971
2009-10	124,858	863	-4,611	4,605	21,513	124,858	863	-1,472	2,877	8,276
2010-11	124,577	104	3,941	760	-13,690	124,577	104	-2,499	3,458	12,619
2011-12	124,344	472	333	2,274	1,053	124,344	472	-613	2,789	5,037
2012-13	124,120	700	-5,626	4,872	25,499	124,120	700	-107	2,567	2,960
2013-14	123,843	260	2,898	1,433	-9,191	123,843	260	-213	2,587	3,368
2014-15	123,646	545	-2,083	3,495	11,131	123,646	545	-868	2,897	6,080
2015-16	123,343	100	3,413	863	-11,653	123,343	100	19	2,579	2,509
2016-17	123,041	519	-2,943	3,821	14,612	123,041	519	273	2,428	1,426
2017-18	122,811	495	-1,189	3,284	7,645	122,811	495	1,433	1,729	-3,526
2018-19	122,635	135	4,167	676	-14,604	122,635	135	578	1,934	-185
2019-20	122,573	0	3,717	0	-13,629	122,573	0	1,424	1,385	-3,838
2020-21	122,343	238	-861	1,892	5,049	122,343	238	389	1,614	188
2021-22	121,897	157	1,288	1,072	-3,651	121,897	157	-556	1,848	3,887

5. *Identification of lands subject to natural disturbances and monitoring for forest recovery (expectation of balance between emissions and subsequent removals)*

The Tier 3, Approach 3, modelling system using FullCAM has been designed to comply with the following safeguard mechanisms:

- the use of geo-located time-series wildfire activity data,
- coverage of all forest lands,
- the ability to monitor if there is a permanent land use change on those lands following a wildfire event during the commitment period,
- the inclusion of emissions associated with salvage logging in the accounting, and
- identification of lands where the natural disturbance is followed by another disturbance event, in order to avoid double counting.

FullCAM uses two remote sensing data sources. The Advanced Very High Resolution Radiometer (AVHRR) is used identify and map natural disturbance impacts due to wildfire on forest lands, whereas Landsat data is used to map forest cover changes and identify permanent land-use changes across all forest lands.

FullCAM spatially tracks areas and carbon stocks at the 25m x 25m pixel-level on lands identified as experiencing natural disturbances in a particular year, until another anthropogenic activity occurs (e.g. non-natural disturbance fire, salvage logging or land-use change).

Further information to demonstrate the disaggregation and monitoring of recovery of carbon stocks lost during disturbances is included in Chapter 6.4.1.4 (Category-specific QAQC for *forest land remaining forest land).*

6. *Monitoring for land-use changes to ensure that no land-use change has occurred on lands subject to natural disturbances*

All forest land is monitored for harvesting and land-use change events. Where forest cover loss events are identified, these areas visually attributed by experienced operators to either direct, human-induced land-use change, or a temporary forest loss which does not constitute land-use change such as harvesting, fire and other non-anthropogenic disturbance.

7. *Demonstrating practicable efforts to prevent, manage and control wildfires in Australia (how the requirements of natural definition of disturbances have been met)*

In Australia, wildfires threaten life and property, and are addressed in disaster response plans and management arrangements in each state and territory. Common frameworks for national, state and territory fire management policies include: reducing the likelihood of fires occurring, for example through fuel reduction burning and fire bans; managing or controlling the fire during its occurrence; monitoring programs and early warning systems; and firefighting operations. In addition to such disaster management policies, there is also a significant research effort into understanding and better managing wildfires, and following many significant fire events, inquests or enquiries are held to assess the disaster response and potential for improvement.

There are fire management policies and plans in place at the national and the state and territory level to control for the risks, events and consequence of wildfire to the extent that this is possible. These policies and plans are periodically updated by jurisdictional governments and set out frameworks for:

- Reducing the likelihood of a wildfire occurring, for example, through the use of prescribed burning;
- Managing or controlling the disturbance during its occurrence;
- Monitoring programs and early warning systems; and
- Firefighting operations.

8. Inclusion of salvage logging emissions

Emissions from salvage logging are included in estimates for *harvested native forests* and *pre-1990 plantations.* Estimates of forest harvesting are based on log production information that includes the products of salvage logging. These production statistics do not differentiate between material sourced from conventional clear felling and salvaging activities following wildfire or other natural disturbances.

A review of salvage harvesting by ABARES (Finn et al. 2015) identified that this is a very minor activity compared to either total harvesting activity or total areas burned. Salvage harvesting is generally opportunistic, determined as much by commercial factors as biophysical factors.

Demonstrating balance of emissions and subsequent removals associated with natural 'background' fires

Over time, average net emissions of CO_2 from non-anthropogenic emissions and subsequent removals will approach zero. Therefore the disaggregation of natural disturbance emissions will neither over- nor under-estimate net emissions in the long term. This can be further demonstrated when simulating a fire event at the plot level – over the long-term the average net carbon dioxide emissions from natural disturbances is zero.

Natural disturbance emissions and removals are not in exact balance over the period since 1989-90 due to a number of recent disturbances from 2006-07 to 2019-20, recovery from which is ongoing. Given the recovery rates for a typical disturbance event, it is projected to take an extended period without further disturbance for average net emissions to equal zero. For this reason, a modelling approach is used to ensure that these natural disturbances' net emissions and removals average out within the reporting timeframes.

Net emissions and removals from wildfires prior to 1989-90 are included in reporting. However no natural disturbances have been identified which affect net emissions and removals during the reporting period.

Table 6.3.5 Balancing of natural disturbance CO_2 emissions and removals

Year	Natural disturbance CO_2 emissions	Natural disturbance CO_2 removals
	Mt CO_2	
1989-90	0.00	0.00
1990-91	0.00	0.00
1991-92	0.00	0.00
1992-93	0.00	0.00
1993-94	0.00	0.00
1994-95	0.00	0.00
1995-96	0.00	0.00
1996-97	0.00	0.00
1997-98	0.00	0.00
1998-99	0.00	0.00
1999-00	0.00	0.00
2000-01	0.00	0.00
2001-02	0.00	0.00
2002-03	208.73	0.00
2003-04	0.00	-37.93
2004-05	0.00	-31.57
2005-06	0.00	-25.31

Year	Natural disturbance CO_2 emissions	Natural disturbance CO_2 removals
	Mt CO_2	
2006-07	98.48	-20.18
2007-08	0.00	-35.68
2008-09	0.00	-30.16
2009-10	0.00	-24.30
2010-11	0.00	-20.59
2011-12	0.00	-16.66
2012-13	0.00	-13.29
2013-14	50.31	-9.48
2014-15	0.00	-16.74
2015-16	38.23	-13.92
2016-17	0.00	-17.73
2017-18	0.00	-14.73
2018-19	45.61	-11.69
2019-20	648.34	-14.09
2020-21	0.00	-133.73
2021-22	0.00	-112.0
2022-23 (projected)	0.00	-85.4
2023-24 (projected)	0.00	-72.3
2024-25 (projected)	0.00	-61.4
2025-26 (projected)	0.00	-51.9
2026-27 (projected)	0.00	-43.5
2027-28 (projected)	0.00	-35.9
2028-29 (projected)	0.00	-29.1
2029-30 (projected)	0.00	-22.5
2030-31 (projected)	0.00	-13.5
2031-32 (projected)	0.00	-6.0
2032-33 (projected)	0.00	-4.4
2033-34 (projected)	0.00	-3.0
2034-35 (projected)	0.00	-2.5
Total (to 1990-2035)	1089.70	-1031.42
1990-2023 net average to	0.63	
1990-2023 net standard deviation	77.21	

No systematic bias is introduced into the inventory by the disaggregation of natural disturbances from anthropogenic fires. The approach does not introduce any artificial trend in reported emissions and removals (that is, it avoids the expectation of credits or debits).

The approach also improves the quality, accuracy and time series consistency of annual estimates by reducing the high levels of inter-annual variability in the time series.

6.3.3 Information on approaches used for reporting harvested wood products

Australia applies Approach 1 from the 2019 Refinement (IPCC 2019) to the 2006 IPCC Guidelines (IPCC 2006), also known as the stock-change approach. For transparency and comparability, information is also provided regarding estimates under Approach 2, also known as the production approach.

Further information is provided in Chapter 6.10.

6.4 **Forest Land** (CRT category 4.A)

6.4.1 Forest Land Remaining Forest Land

6.4.1.1 Category Description

There are four broad sub-divisions to *forest land remaining forest land*: harvested native forests, plantations, other native forests and fuelwood.

Harvested native forests are those forests comprised of native species subjected to harvesting practices and natural regrowth. Various silvicultural techniques may be applied to initiate and promote particular growth characteristics. The areas included in this sub-division include multiple-use public forests and public forest areas which have been available for harvesting at any time since 1990 (Mutendeuzi et al. (2014)) and private native forests subject to harvest or regrowing from prior harvest.

Plantations included within *forest land remaining forest land* are commercial plantations (hardwood and softwood) established in Australia up to the end of 1989. Softwood plantations make up the vast majority of these pre-1990 plantations with hardwood plantations (primarily eucalypt species) making up only a minor part of the plantation estate. Until the mid-1960s, most new areas of softwood plantation were derived from clearing of native forest or scrublands. In later years, some of the hardwood plantations were also established after clearing native forest (Snowdon and James 2008). By the mid-1980s, clearing of native forests for the establishment of plantations had ceased in most states, and most new plantations were established on farmland.

Other native forests include those forests that are comprised of native species, which are not *harvested native forests* or *plantations.* The *other native forests* sub-division includes protected areas (such as wilderness areas and national parks) not previously subject to harvesting and extensive areas of forests including woodlands.

The main processes affecting emissions and removals from these forests include fire management practices and wildfires. Accordingly net emissions are estimated for the following activities:

- prescribed burning of temperate forests;
- wildfire in temperate forests; and
- management fires and wildfire in tropical, sub-tropical and semi-arid forests.

Harvested wood products are not reported in this category. Carbon stocks in wood products are transferred to *harvested wood products* and are discussed further in Chapter 6.10.

As for all forests, the *harvested native forests* sub-category is monitored for forest conversions. Areas that are identified as direct human induced forest conversions are excluded from *forest land remaining forest land* from the time of the conversion event, and any harvesting losses associated with the conversion event are also excluded and reported only under the new land use category to avoid double-counting.

Anthropogenic emissions and removals from forest land remaining forest land are shown in Table 6.4.1.

Table 6.4.1 Emissions and removals from forest land remaining forest land, kt CO_2-e

			Other native forests				
Year	Harvested native forests	Plantations	Fuelwood consumed	Wildfires	Prescribed burning of temperate forests	Non-temperate forest fires	Total
1989-90	-4,743	-7,585	446	3,243	211	9,387	960
1994-95	-3,239	-9,354	501	2,470	136	3,585	-5,901
1999-00	-3,593	-4,844	244	7,099	-1,820	8,058	5,144
2004-05	-20,645	-4,931	-419	530	1,709	6,952	-16,803
2005-06	-21,310	-3,063	-491	3,572	2,032	8,284	-10,975
2006-07	-20,543	-5,634	-555	10,284	1,812	5,876	-8,759
2007-08	-19,926	-2,431	-612	13,716	1,703	11,938	4,389
2008-09	-7,702	-1,334	-662	10,971	1,274	10,108	12,654
2009-10	-4,068	3,892	-711	8,276	776	8,176	16,340
2010-11	-7,498	6,135	-757	12,619	654	11,644	22,797
2011-12	-10,597	4,272	-577	5,037	-298	8,359	6,197
2012-13	-13,500	-244	-439	2,960	60	6,256	-4,907
2013-14	-28,000	1,174	-415	3,368	788	10,798	-12,287
2014-15	-34,930	3,271	-465	6,080	989	7,265	-17,791
2015-16	-37,324	-931	-403	2,509	923	-1,324	-36,551
2016-17	-40,520	3,349	-342	1,426	948	-755	-35,894
2017-18	-46,054	1,885	-304	-3,526	120	-4,370	-52,250
2018-19	-37,349	3,188	-278	-185	-364	-3,495	-38,484
2019-20	-32,973	5,003	-249	-3,838	-771	-5,302	-38,129
2020-21	-32,177	7,472	-164	188	-1,717	-2,372	-28,770
2021-22	-24,175	8,742	-110	3,887	-1,592	-1,630	-14,878

6.4.1.2 Methodological issues

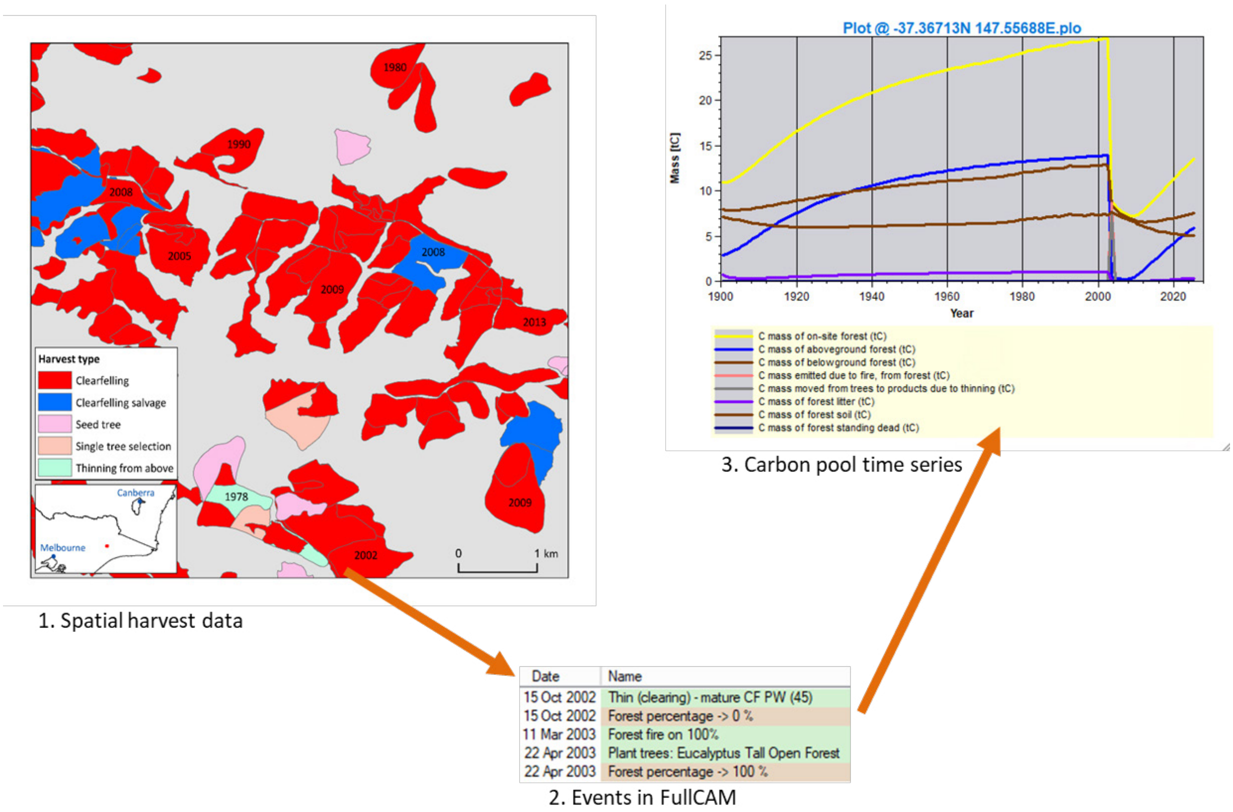
Both spatially explicit and non-spatially explicit models have been implemented in the estimation of emissions and removals from *harvested native forests.* For public forests in Victoria, New South Wales, Tasmania and Queensland, a spatially explicit Tier 3 FullCAM model for *harvested native forests* has been used. The non-spatially explicit estate modelling capability of FullCAM is used for both public and private forests in Western Australia, and for private native forests only in Victoria, New South Wales, Tasmania and Queensland.

Harvested native forests – Spatial Method

The spatially explicit Tier 3 FullCAM model for *harvested native forests* has been applied to publicly managed forests in the states of Victoria, New South Wales, Tasmania and Queensland.

The FullCAM spatial method for *harvested native forests* simulates carbon stock changes due to tree growth, timber harvesting and associated management, and fire. The general operation of FullCAM spatial simulations is described in Annex 5.6.2. In the spatial method for *harvested native forests,* the type, location and date of timber harvesting activities are drawn from historical harvest data provided by state forestry agencies. This is illustrated in Figure 6.4.1, in which harvest areas drawn from the spatial harvest data trigger events in the FullCAM simulation and resulting changes to the forest carbon pools. The yellow line represents the on-site carbon mass at one site increasing with tree growth, decreasing with timber harvesting in 2002, and again increasing with regrowth.

Figure 6.4.1 Overview of the spatial method for harvested native forests



1. Spatial harvest data

Date	Name
15 Oct 2002	Thin (clearing) - mature CF PW (45)
15 Oct 2002	Forest percentage -> 0 %
11 Mar 2003	Forest fire on 100%
22 Apr 2003	Plant trees: Eucalyptus Tall Open Forest
22 Apr 2003	Forest percentage -> 100 %

2. Events in FullCAM

3. Carbon pool time series

Estimating changes in living biomass

The annual change in living biomass in *harvested native forests* is the net result of uptake due to forest growth (above and below ground as determined by the growth models) and losses due to forest harvesting and post-harvest fire where this occurs. Losses occur with the removal of forest products (transferred to *harvested wood products)* and movement of residue material (including belowground biomass) to dead organic matter (DOM) and soils.

Harvested native forests are modelled based on Major Vegetation Groups of the National Vegetation Information System (NVIS, see (NLWRA 2001)). The changes in carbon stock are estimated using FullCAM for areas defined as Multiple Use Forest (Annex 5.6.5.3), with the model run separately for each 25m x 25m grid cell within these areas. Growth of living biomass in each cell is calculated according to the Tree Yield Formula (TYF), as described in Annex 5.6.3.2, using biomass increments which are defined as a function of the:

- age of the tree stand;
- the maximum aboveground biomass (M), predicted by the model for a mature forest at each location (Annex 5.6.4); and
- estimated constant that determines the rate of biomass accumulation towards M.

Post-harvest regrowth is modelled according to the type of harvest that took place. Areas subject to clearfell harvest regrow from age zero according to the TYF.

After disturbance events which leave living biomass, such as partial harvesting or fire, a biomass recovery function determines the rate of regrowth in the post-disturbance recovery phase. The biomass recovery function is based on the calculated amount of biomass lost from disturbances, which then grows back as an addition to the annual increment over a number of years, until the 'target biomass' is reached (see *Biomass recovery function* in Annex 5.6.2.2).

Partitioning of biomass among tree components

FullCAM calculates below-ground biomass (coarse and fine roots) and the partitioning of above-ground biomass (stems, branches, bark and leaves), using empirically determined proportions of biomass to each component as outlined by Paul et al. (2017). This method allows allocation to vary between tree species based on vegetation classes (Table 6.4.2).

Table 6.4.2 Partitioning of biomass between the tree components in different vegetation groups

	Fraction of biomass allocated to:					
Major Vegetation Group	Stems	Branches	Bark	Leaves	Coarse Roots	Fine Roots
Woodlands <500mm rainfall	0.28	0.22	0.08	0.07	0.27	0.08
Forests >= 500mm rainfall	0.49	0.11	0.09	0.04	0.24	0.03

Carbon fraction of biomass

The carbon fractions of the tree components (Table 6.4.3) are based on studies of Australian vegetation Gifford (2000a) and (2000b)).

Table 6.4.3 Carbon Fraction of biomass for each tree component based on Gifford (2000a and 2000b)

Tree component	% Carbon
Stems	50
Branches	47
Bark	49
Leaves	52
Coarse roots	50
Fine roots	48

Forest harvest

Harvest events are applied at the locations and dates specified in the spatial data for harvest history provided by state government agencies (currently Victoria, New South Wales, Tasmania and Queensland) which also specifies the harvest type used in each case. The harvest history data is described in Annex 5.6.5.3. The characteristics of each harvest type used in FullCAM, are the proportion of above ground tree biomass harvested, the proportion of tree stem mass which is removed from the site as product, and management associated with the harvest type, such as a post-logging regeneration burn. These harvest characteristics were determined based on advice provided by organisations responsible for managing timber production on public land (VicForests, Forestry Corporation of New South Wales, Sustainable Timber Tasmania and the Queensland Department of Agriculture and Fisheries). The characteristics of each harvest type are listed in Table 6.4.4.

The amount of carbon affected by each harvest event is determined for each 25 x 25 m pixel by characteristics of the harvest type, and the size of each carbon pool at that location at the time of harvest, resulting from past growth and disturbance over time.

Table 6.4.4 Harvest types used in the spatial model for harvested native forests, and their parameters

State	Harvest type	Major Vegetation Group	Percentage harvested	Pulpwood taken	Percentage of stem to product	Post-harvest fire
Vic	Clearfell (including salvage)	Eucalyptus Tall Open Forest; Eucalyptus Open Forest; Eucalyptus Low Open Forest; Low Closed Forest & Closed Shrublands	100%	Yes	95%	Yes
		Other forest types	100%	No	35%	Yes
Vic	Group (or Gap) selection	Eucalyptus Tall Open Forest	100%	No	67%	No
		Eucalyptus Tall Open Forest	50%	Yes	95%	No
		Other forest types	50%	No	45%	No
		Other forest types	50%	Yes	55%	No
Vic	Regrowth retention harvesting	Eucalyptus Tall Open Forest	100%	Yes	95%	Yes
		All forest types	100%	No	35%	Yes
Vic	Dangerous tree removal / road alignment	Eucalyptus Tall Open Forest; Eucalyptus Open Forest	100%	Yes	95%	No
		All forest types	100%	No	35%	No
Vic	Seed tree	Eucalyptus Tall Open Forest; Eucalyptus Low Open Forest; Low Closed Forest and Closed Shrublands	85%	Yes	90%	No
		All forest types	85%	No	50%	No
Vic	First Shelterwood	Eucalyptus Tall Open Forest; Eucalyptus Open Forest; Eucalyptus Low Open Forest	85%	Yes	55%	No
		All forest types	85%	No	50%	No
Vic	Second Shelterwood	All forest types	100%	-	65%	No
Vic	Single tree selection	All forest types	20%	-	90%	No
Vic	Thinning from above / below	Eucalyptus Tall Open Forest; Eucalyptus Open Woodland	50%	-	90%	No
		Other forest types	40%	-	90%	No
Vic	Variable Retention 1	Eucalyptus Open Forest, Eucalyptus Open Woodland, Eucalyptus Tall Open Forest, Eucalyptus Woodland, Low Closed Forest and Closed Shrublands, Rainforest and vine thickets	75%	No	35%	Yes, usually
				Yes	95%	Yes, usually
Vic	Variable Retention 1 (recovery)	Eucalyptus Open Forest, Eucalyptus Tall Open Forest, Eucalyptus Woodland, Other Forests and Woodlands, Other Shrublands, Rainforest and vine thickets	75%	No	35%	No
				Yes	95%	No
Vic	Variable Retention 2	Eucalyptus Open Forest, Eucalyptus Tall Open Forest, Rainforest and vine thickets	65%	No	35%	Yes, usually
				Yes	95%	Yes, usually
Vic	Variable Retention 2 (recovery)	Eucalyptus Tall Open Forest	65%	No	35%	No
				Yes	95%	No

State	Harvest type	Major Vegetation Group	Percentage harvested	Pulpwood taken	Percentage of stem to product	Post-harvest fire
Vic	Fallen Product Recovery	Acacia Forest and Woodlands, Eucalyptus Open Forest, Eucalyptus Tall Open Forest, Eucalyptus Woodland, Low Closed Forest and Closed Shrublands, Other Forests and Woodlands	100%	No	35%	No
				Yes	95%	No
NSW	Australian group selection	All forest types	25%	-	90%	No
NSW	Plantation clearfell	All forest types	65%	Yes	85%	Yes
NSW	Salvage – roadline & storm	All forest types	100%	-	90%	No
NSW	Salvage – fire & other	All forest types	50%	-	90%	No
NSW	Alternate coupe	All forest types	80%	Yes	90%	Yes
NSW	Miscellaneous	All forest types	10%	No	90%	No
NSW	Non-commercial harvest	All forest types	100%	No	0%	No
NSW	Thinning	All forest types	40%	No	90%	No
NSW	Single tree selection – light	All forest types	20%	No	90%	No
NSW	Single tree selection – mix	All forest types	30%	No	90%	No
NSW	Single tree selection – moderate	All forest types	30%	No	90%	No
NSW	Single tree selection – release	All forest types	30%	No	90%	No
NSW	Single tree selection – heavy	All forest types	40%	No	90%	No
NSW	Single tree selection – regeneration	All forest types	60%	No	90%	No
Tas	Clearfell	All forest types	95%	-	80%	Yes
Tas	Clearfell native for plantation	All forest types	100%	-	80%	Yes
Tas	Salvage – roadline, quarry & dam	All forest types	95%	-	80%	No
Tas	Salvage – fire & other	All forest types	50%	-	65%	No
Tas	Variable retention	All forest types	85%	-	80%	Yes
Tas	Seed tree retention	All forest types	80%	-	80%	Yes
Tas	Advanced growth retention	All forest types	75%	-	80%	No
Tas	Potential sawlog retention	All forest types	70%	-	80%	No
Tas	Commercial thinning	All forest types	60%	-	80%	No
Tas	Shelterwood retention	All forest types	60%	-	80%	No
Tas	Shelterwood removal	All forest types	80%	-	80%	No

State	Harvest type	Major Vegetation Group	Percentage harvested	Pulpwood taken	Percentage of stem to product	Post-harvest fire
Tas	Wattle removal	All forest types	60%	-	35%	No
Tas	Special species sawlogs	All forest types	5%	-	70%	No
Tas	Craftwood	All forest types	5%	-	80%	No
Qld	Carbon Regime 1	All forest types	19%	-	76%	No
Qld	Carbon Regime 2	All forest types	14%	-	76%	No
Qld	Carbon Regime 3	All forest types	8%	-	88%	No
Qld	Carbon Regime 4	All forest types	3%	-	78%	No
Qld	Carbon Regime 5	All forest types	5%	-	65%	No
Qld	Carbon Regime 6	All forest types	40%	-	76%	No
Qld	Carbon Regime 9	All forest types	27%	-	91%	No
Qld	Carbon Regime 10	All forest types	32%	-	91%	No
Qld	Carbon Regime 11	All forest types	36%	-	91%	No
Qld	Carbon Regime 12	All forest types	25%	-	84%	No
Qld	Carbon Regime 21	All forest types	7%	-	76%	No
Qld	Carbon Regime 22	All forest types	5%	-	91%	No
Qld	Carbon Regime 23	All forest types	3%	-	88%	No
Qld	Carbon Regime 24	All forest types	1%	-	78%	No
Qld	Carbon Regime 25	All forest types	2%	-	65%	No
Qld	Carbon Regime 26	All forest types	14%	-	76%	No
Qld	Carbon Regime 29	All forest types	10%	-	91%	No
Qld	Carbon Regime 210	All forest types	12%	-	91%	No
Qld	Carbon Regime 211	All forest types	13%	-	91%	No
Qld	Carbon Regime 212	All forest types	9%	-	84%	No

Pulpwood taken is not specified where it does not affect percentage harvested or percentage stem to product. Once harvested, in the model, the removal of products is assumed to result in a transfer of carbon to *harvested wood products* based on production statistics.

Estimating changes in debris

The annual change in DOM in *harvested native forests* is the net result of additions from turnover and harvest residue, and losses due to decay and turnover into soils. Losses are caused by decomposition of both natural accumulation and harvest residue and burning of residues as part of some silvicultural systems. The turnover rates applied for each plant component in the model are shown in Table 6.4.5. The decomposition rates used for standing dead pools are shown in Table 6.4.6, and for debris in Table 6.4.7. Along with the initial amount of forest debris, these values were derived from Paul et al. (2017).

Table 6.4.5 Turnover for tree components

Tree component	Turnover % per month
Branches	0.74
Bark	0.41
Leaves (rainfall >500mm)	2.96
Leaves (rainfall <500mm)	1.28
Coarse Roots	0.87
Fine Roots	12.55

Table 6.4.6 Decomposition rates for standing dead pools used in the harvested native forests model

Standing Dead component	Breakdown % per month
Stems, branches and coarse roots	0.83
Bark	1.25
Leaves and fine roots	1.67

Table 6.4.7 Decomposition rates for debris pools used in the harvested native forests model

	Breakdown % per month	
Debris component	**Decomposable**	**Resistant**
Deadwood	-	1.25
Bark litter	-	1.44
Leaf litter	81.2	2.70
Coarse dead roots	-	2.93
Fine dead roots	81.2	81.2

Breakdown rates are not given for decomposable deadwood, bark litter and coarse dead roots because these pools are treated as entirely resistant.

Estimating changes in soil carbon

Soil carbon is estimated using FullCAM with a national soil carbon map (Viscarra-Rossel et al. (2014)) (Annex 5.6.5) as the base input data. FullCAM simulates changes in soil carbon using Roth-C soil carbon model. Roth-C model computes turnover of organic carbon in soils, taking into account clay content, temperature, moisture content, plant material inputs and plant cover. A mean incremental value for the transitions between SOC near steady states is derived, in this case from the simulated annual data, consistent with the method applied in croplands and grasslands.

Harvested native forests – biomass burning

Wildfires and prescribed fires on *harvested native forests* are modelled in FullCAM as temperate forest fires consistent with *Other native forests.*

The CO_2 emissions associated with slash burning which follows some harvest types (see Table 6.4.4) in *harvested native forests* are similarly modelled in FullCAM as part of the *harvested native forests* model. The mass of carbon burnt annually (FC_{jk} in equations 4.A.1_1 and 4.A.1_2) is taken directly from FullCAM and is used to estimate the CO_2 and non-CO_2 gas emissions associated with slash burning.

Harvested native forests – Estate Method

The non-spatially explicit estate method of FullCAM is used for both public and private forests in Western Australia, and for private native forests only, in Victoria, New South Wales, Tasmania and Queensland. For private native forests in New South Wales, an estate model has been developed drawing on the parameters and settings used in spatial modelling of public native forests in that state. For the other estate models for public and private forests, the following methods and parameters apply.

Estimating changes in living biomass

The annual change in living biomass in *harvested native forests* is the net result of uptake due to forest growth (above and below ground as determined from the growth models) and losses due to forest harvesting. Losses occur with the removal of forest products (transferred to *harvested wood products)* and movement of residue material (including belowground biomass) to dead organic matter (DOM) and soils.

Public and private *harvested native forests* in Western Australia, and private harvested native forests in Victoria, Tasmania and Queensland are modelled based on forest types which are consistent with reporting used under the Montreal Process National Forest Inventory (ABARES 2023) and National Vegetation Information System Major Vegetation Groups (NVIS, see (NLWRA 2001)). A comparison with the inventory forest classes is shown in Table 6.4.8 (Waterworth et al. (2015)). Age classes and growth rates (t C ha^{-1} yr^{-1}) for each forest type in multiple-use public forests were reported by Lucas et al. (1997) (Table 6.4.9 and Table 6.4.10).

The changes in carbon stock are estimated using FullCAM, which is configured using the area of each forest type and age class in Table 6.4.9 and biomass increments based on the growth rates reported in Table 6.4.10. Forests of unknown age, or those containing two or more age classes, were assumed to be equivalent to the 'Mature' age class.

Post-harvest growth is modelled according to the type of harvest that took place. Areas subject to clearfell harvest regrow from age zero. Areas subject to partial harvest continue to grow at the same rate as they were growing prior to the harvest (i.e. there is no thinning effect at the stand level, either positive or negative, on the rate of biomass accumulation despite the reduction in stem numbers).

Table 6.4.8 Forest classification comparison table

Inventory forest class (Lucas et al. 1997)	NVIS Major Vegetation Groups	National Forest Inventory (SOFR 2023)
Rainforest	Rainforest and vine thickets	Rainforest
Tall dense eucalypt forest	Eucalyptus tall open forest	Eucalypt tall closed
		Eucalypt tall open
Medium dense eucalypt forest	Eucalyptus open forest	Eucalypt medium closed
		Eucalypt medium open
Low dense eucalypt forest	Low Closed Forests and	Eucalypt low closed
	Tall Closed Shrublands	Eucalypt low open
Tall sparse eucalypt forest	Eucalypt Open Forests	Eucalypt tall woodland
Medium sparse eucalypt forest	Eucalypt medium woodland	
Low sparse eucalypt forest	Eucalyptus woodland	Eucalypt low woodland
	Eucalyptus open woodland	
	Other Open Woodlands	
	Tropical woodlands and grasslands	
	Eucalypt Low Open Forests	
Eucalypt Mallee	Mallee Woodlands and Shrublands	Eucalypt Mallee open
	Mallee Open Woodlands and Sparse Mallee Shrublands	Eucalypt Mallee woodland
Callitris forests	Callitris Forest and Woodlands	Callitris
Acacia forests	Acacia forest and woodlands	Acacia
Other forests	Casuarina Forests and Woodlands	Casuarina
	Melaleuca Forests and Woodlands	Melaleuca
	Mangrove	Mangrove
	Acacia Open Woodlands	
	Eucalypt Woodlands	

Waterworth et al. (2015)

Table 6.4.9 Areas by forest type and age classes in 1989–90 in multiple-use public forests (ha) (Estate method, Australia-wide)

Forest Type	Establishment 1-10yrs	Juvenile 11-30yrs	Immature 31-100yrs	Mature 100-200 yrs	Senescent > 200 yrs	Forests of unknown age [(a)]	Two Aged	Three or More Aged	Total
Rainforests				842,580					842,580
Tall Dense Eucalypt Forests	46,728	95,470	234,898	292,095	230,102	641,646	115,683	388,188	2,044,810
Medium Dense Eucalypt Forests	14,576	97,742	173,424	829,088	168,152	1,659,839	273,720	1,022,136	4,238,677
Medium Sparse Eucalypt Forests					345,153	274,270		663,366	1,282,789
Cypress pine Forests						42,258		144,182	186,440
Other Forests						673,019		141,686	814,705
Totals	**61,304**	**193,212**	**408,321**	**1,963,7633**	**743,407**	**3,291,031**	**389,404**	**2,359,558**	**9,410,000**

(a) The unknown and mixed age classes were represented in the model consistent with the 'Mature' age class.

Table 6.4.10 Aboveground growth rates by forest type and age class (t C ha^{-1} yr^{1})

	Establishment	Juvenile	Immature	Mature	Senescent
Forest Type	**1–10 yrs**	**11–30 yrs**	**31–100 yrs**	**100–200 yrs**	**> 200 yrs**
Rainforests	-	-	-	0.58	0
Tall Dense Eucalypt Forests	6.44	4.41	2.23	0.74	0
Medium Dense Eucalypt Forests	4.24	2.80	0.99	0.18	0
Medium Sparse Eucalypt Forests	0.24	0.24	0.24	0.24	0
Cypress pine Forests	0.25	0.25	0.25	0.25	0
Other Forests	0.23	0.23	0.23	0.23	0

Partitioning of biomass to tree components

The ratios used to partition biomass to the different tree components (Table 6.4.11) are drawn from a synthesis of available data compiled by(Snowdon, Eamus, et al. 2000) and the results of (Ximenes and Gardner 2005) and Ximenes et al. (2005).

Table 6.4.11 Partitioning of biomass to each of the tree components

	Fraction of biomass allocated to:					
Forest Type	**Stems**	**Branches**	**Bark**	**Leaves**	**Coarse roots**	**Fine roots**
Rainforest	0.60	0.08	0.09	0.03	0.17	0.03
Tall Dense Eucalypt Forest	0.55	0.12	0.10	0.03	0.17	0.03
Medium Dense Eucalypt Forest	0.50	0.15	0.12	0.03	0.17	0.03
Medium Sparse Eucalypt Forest	0.47	0.15	0.12	0.03	0.20	0.03
Cypress pine Forest	0.47	0.15	0.12	0.03	0.20	0.03
Other forest	0.47	0.15	0.12	0.03	0.20	0.03

Carbon fraction of biomass

The carbon fractions of the tree components (Table 6.4.12) are based on studies of Australian vegetation (Gifford, (2000a) 2000a and (2000b)).

Table 6.4.12 Carbon fraction of biomass for each tree component based on Gifford (2000a) and (2000b)

Tree component	% Carbon
Stems	52
Branches	47
Bark	49
Leaves	52
Coarse roots	49
Fine roots	46

Forest harvest

The amount of carbon removed as products in a harvest is dependent upon age class, forest type and the type of harvest. The area of *harvested native forests* harvested in each broad forest type and age class was derived from roundwood log volumes removals for each state (ABARES 2023) using a historical relationship between roundwood removals and harvest area data collated by state agencies.

The broad silvicultural systems applicable to each state are reported in Table 6.4.13. Information on the forest type and silviculture method applied also varied in the level of detail available. Where the information was not explicitly reported, it was inferred from the best available information, including information within the state agency reporting, publications from state agencies (e.g., Forestry Tasmania, (2008); FPA, (2007); Forests NSW, (2008); Vic Forests, (2008)) and from Raison and Squire (2008). It is assumed that no harvesting occurred in the Establishment (1-10 years) and Juvenile (11-30 years) phases as these are generally too young to produce forest products in Australia's native forests.

Most states began phasing out logging of rainforests in the 1980s, and for the most part, logging was entirely phased out prior to 1990 (Raison and Squire, (2008)). It was not possible to separate cool temperate rainforest logging from logging in wet temperate eucalypt forests in Tasmania. The harvested area for rainforests in Tasmania was therefore modelled as tall and medium dense eucalypt forests, which are closest to cool temperate rainforests spatially and in successional sequence (Hickey 1994).

Table 6.4.13 Broad silvicultural systems used in the Estate model for harvested native forests

Forest type	Silviculture	% of trees harvested	Post-harvest management
Tall dense eucalypt forest	Clearfell with pulpwood	100%	Regeneration burn
	Clearfell without pulpwood	100%	Regeneration burn
	Partial harvest with pulpwood	35-50%	Slash left on-site
	Partial harvest without pulpwood	25%	Slash left on-site
Medium dense eucalypt forest	Clearfell with pulpwood	100%	Regeneration burn
	Clearfell without pulpwood	100%	Regeneration burn
	Partial harvest with pulpwood	35-75%	Slash left on-site
	Partial harvest without pulpwood	40%	Slash left on-site
Medium sparse eucalypt forest	Partial harvest without pulpwood	30%	Slash left on-site
Callitris forest	Partial harvest without pulpwood	40%	Slash left on-site

Once harvested, in the model, the removal of products at harvest is assumed to result in a transfer of carbon to *harvested wood products* (see Chapter 6.10) based on production statistics.

Estimating changes in debris

The annual change in DOM in *harvested native forests* is the net result of additions from harvest residue and turnover, and losses due to decay and turnover into soils. Losses are caused by decomposition of both natural accumulation and harvest residue and burning of residues as part of some silvicultural systems.

The initial amount of forest debris for each forest type and age class combination is based upon model simulations, cross checked with published estimates of debris in Australian forests. For each forest type, a clearfell event was simulated using initial debris levels. This simulation was then run to equilibrium over 200 years. The final debris pools from this simulation were then used as the initial conditions for a final simulation. The results of the final simulation were used to define the initial debris for each age class for each respective forest type. This method produced debris quantities that are comparable with published estimates of debris in Australian forests (e.g., Woldendorp and Keenan 2005, Hingston, F.J.; Dimmock, G.M.; Turton, A.G. 1980).

The turnover rates applied for each plant component in the model are shown in Table 6.4.14. There is limited information on decomposition rates in the *harvested native forests* of Australia. The decomposition rates for the different debris pools were drawn from the best available information including Mackensen et al. (2003), Mackensen and Bauhaus (1999), O'Connell (1997) and Paul and Polglase (2004). The rates used are shown in Table 6.4.15.

Table 6.4.14 Turnover for tree components

Tree component	Turnover per year
Branches	0.05
Bark	0.07
Leaves	0.50
Coarse Roots	0.10
Fine Roots	0.85

Table 6.4.15 Decomposition rates for debris pools used in the harvested native forests model

Debris component	**Breakdown per year**	
	Decomposable	**Resistant**
Deadwood	0.05	0.05
Bark litter	0.50	0.50
Leaf litter	0.80	0.80
Coarse dead roots	0.40	0.10
Fine dead roots	1.00	1.00

The amount of residue produced by a harvest is also dependent upon the harvest type, forest age and forest type. Information on the production of harvest residue by broad forest type, harvest type and forest age was sourced from Raison and Squire, 2008 and studies of residue production (Ximenes and Gardner, (2005); Ximenes et al. (2005)).

Estimating changes in soil organic carbon

Soil carbon is estimated using FullCAM operating in estate mode with a national soil carbon map (Viscarra-Rossell et al. (2015b)) (Annex 5.6.5) as the base input data. FullCAM simulates changes in soil carbon using the Roth-C soil carbon model. The Roth-C model computes turnover of organic carbon in soils, taking into account clay content, temperature, moisture content, plant material inputs and plant cover.

Harvested native forests – biomass burning

Wildfires and prescribed fires on *Harvested native forests* are modelled as temperate forest fires consistent with the methods for natural disturbances described in Chapter 6.3.2.

The CO_2 emissions associated with slash burning in *harvested native forests* are estimated by FullCAM. The mass of carbon burnt annually (FC_{jk}) is taken directly from FullCAM and is used to estimate the CO_2 and non-CO_2 gas emissions associated with slash burning.

There are no direct measurements of trace gas emissions from slash burning in Australia; however it is considered that these fires will have similar characteristics to hot prescribed fires and wildfires (Hurst et al. 1996).

The algorithms for total annual emissions of CH_4, CO and NMVOCs are:

$$E_{ijk} = FC_{jk} * EF_{ijk} * C_i \qquad (6.4.1)$$

and for total annual emissions for NO and N O are:

$$E_{ijk} = FC_{jk} * NC_{jk} * EF_{ijk} * C_i \qquad (6.4.2)$$

Where FC_{jk} = annual carbon burnt in slash burning (obtained from FullCAM) (kt),
EF_{ijk} = emission factor for gas i from vegetation (Tables A5.6.11.10-12),
NC_{jk} = nitrogen to carbon ratio in biomass (Annex 5.6.11.8)
C_i = factor to convert from elemental mass of gas species *i* to molecular mass (Annex 5.6.11.9).

Harvested Native Forests Activity Data

Table 6.4.16 Area of harvesting activity by year and modelling method

Year	Area harvested (ha)		
	Estate method (WA public forests, private native forests in all states)	Spatial method (public forests in Vic, NSW, Tas, Qld)	Total
1989-90	47,686	120,052	167,738
1994-95	55,868	124,332	180,200
1999-00	48,380	55,373	103,753
2004-05	34,037	78,045	112,082
2005-06	25,259	76,846	102,105
2006-07	26,219	69,235	95,455
2007-08	28,895	69,023	97,918
2008-09	24,011	66,712	90,723
2009-10	17,984	63,286	81,270
2010-11	16,964	45,773	62,737
2011-12	12,930	42,716	55,646
2012-13	10,658	60,170	70,829
2013-14	8,767	46,334	55,101
2014-15	8,498	49,344	57,842
2015-16	10,072	33,278	43,350
2016-17	10,827	40,957	51,785
2017-18	9,876	47,236	57,112
2018-19	9,900	33,694	43,595
2019-20	12,979	34,645	47,624
2020-21	12,164	23,765	35,929
2021-22	10,595	18,508	29,102

Source: Estate method areas derived from Australian Forest and Wood Products Statistics (ABARES 2023). Spatial method activity data from Department of Jobs, Skills, Industry and Regions Victoria (obtained 2023), Forestry Corporation of New South Wales (2023) Sustainable Timber Tasmania (2023) and the Queensland Department of Agriculture and Fisheries (2023).

Pre-1990 Plantations

Plantations included within *forest land remaining forest land* are commercial plantations (predominantly softwood) established in Australia up to the end of 1989.

Pre-1990 plantations are simulated using a fully spatial FullCAM simulation. Spatial layers based on information obtained from ABARES are constructed for plantings and harvesting is identified from Landsat satellite imagery.

The carbon pools considered for *plantations* include above and below ground biomass, DOM and soil.

Estimating changes in carbon stocks

Plantation forest growth and changes in debris in *forest land remaining forest land* is estimated in a manner fully consistent with that described for plantations in *land converted to forest* (Chapter 6.4.2.2).

Fires on *Plantations* are modelled as temperate forest fires consistent with *Other native forests.*

Activity data

Activity data for *plantations* establishment is sourced from the National Plantation Inventory (NPI) (ABARES 2016), which provides spatial information on areas planted during 1939-40 to 1988-89, years of planting and plant type/species. The plantation area is spread over the 15 NPI regions (Figure 6.4.2) in three broad classes defined as Short Rotation Hardwood (SRH), Long Rotation Hardwood (LRH) and Softwood (SW). Table 6.4.17 shows the plantation establishment activity data.

As explained above, the timing of harvesting is based on satellite imagery while the timing of thinning is based on region and species specific management practices.

Figure 6.4.2 The National Plantation Inventory regions

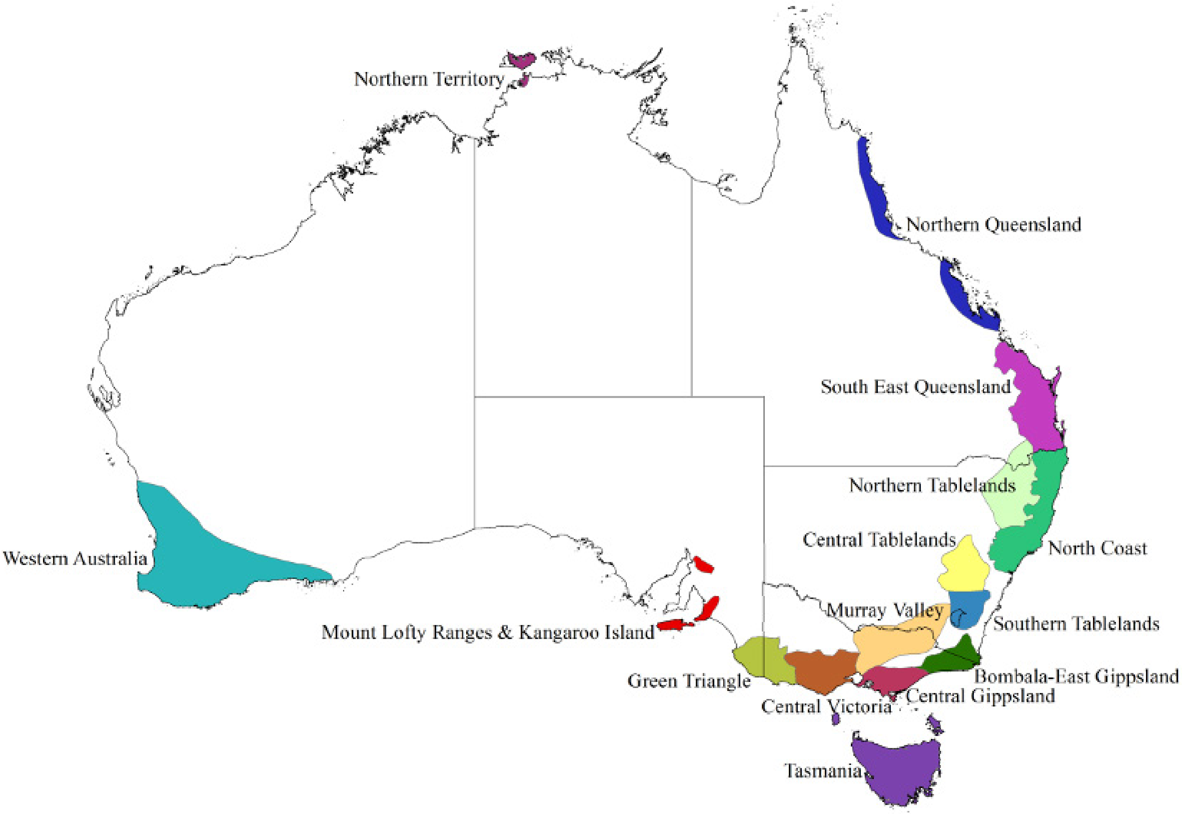


Table 6.4.17 Cumulative area of land converted to plantation from 1939-40 to 1988–89

Year	Area (ha)	Year	Area (ha)
1939-40	818	1964-65	88,111
1940-41	1,476	1965-66	101,189
1941-42	2,440	1966-67	117,217
1942-43	2,977	1967-68	132,600
1943-44	4,126	1968-69	152,958
1944-45	5,946	1969-70	174,337
1945-46	7,756	1970-71	197,355
1946-47	9,945	1971-72	221,677
1947-48	11,876	1972-73	246,389
1948-49	14,600	1973-74	271,855
1949-50	17,184	1974-75	297,202
1950-51	19,837	1975-76	324,016
1951-52	22,484	1976-77	349,761
1952-53	25,204	1977-78	376,550
1953-54	27,926	1978-79	403,158
1954-55	30,686	1979-80	427,484
1955-56	33,588	1980-81	453,817
1956-57	36,493	1981-82	477,122
1957-58	39,580	1982-83	504,146
1958-59	44,191	1983-84	531,896
1959-60	49,777	1984-85	559,649
1960-61	55,519	1985-86	589,023
1961-62	61,354	1986-87	619,993
1962-63	68,662	1987-88	651,390
1963-64	77,839	1988-89	681,460

Other native forests

Wildfire emissions and removals in temperate and tropical zone forests are estimated using a Tier 3, Approach 3 spatial simulation using FullCAM, consistent with the methods described for natural disturbances in Chapter 6.3.2.

Emissions of CO_2 from the consumption of *fuelwood* are estimated using data on the residential consumption of wood and wood-waste obtained from the Australian Energy Statistics. Carbon stocks lost through emissions from consumption of fuelwood from the residential sector are assumed to be collected from DOM in forests. To ensure no double counting with modelled decay or fires affecting the DOM pool, these instant losses through fuelwood consumption are offset against an Olson fuel accumulation curve (T95 per cent = 11 years).

6.4.1.3 Uncertainty assessment and time-series consistency

Uncertainties for the *forest land remaining forest land* sub-category are estimated to be ±33.5 per cent for CO_2. The majority of this uncertainty is due to the *other native forest* sub-division. Uncertainty in the *plantations* is expected to be less than 10 per cent. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to methodology.

6.4.1.4 Category-specific QA/QC and verification

Harvested native forests

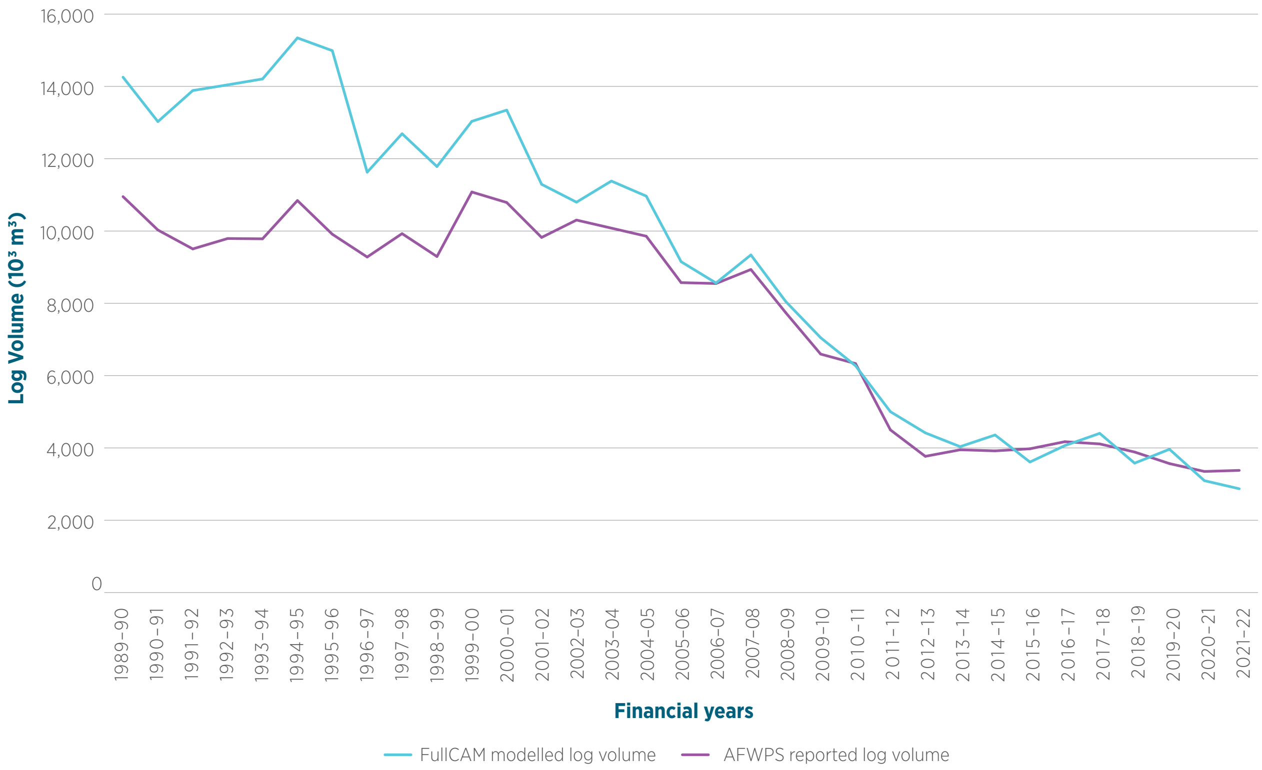
For the Estate method for *harvested native forests,* data on harvesting is derived from roundwood log volumes for each state. Roundwood log volumes are published by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) in the biannual Australian Forest and Wood Products Statistics report (ABARES 2023) , a comprehensive dataset relating to Australia's forestry sector, including time series data on forest and wood products resources, production, consumption, trade and employment. Historical harvest area data was obtained from a combination of annual reports of Australian state agencies, financial statements, and spatial harvest area data. These datasets have been subject to review processes and financial auditing and are the basis for Australia's reporting to the Food and Agriculture Organisation of the United Nations.

Data on stem to whole tree conversions, carbon content and wood densities are within the ranges published in Gifford, (2000a); Gifford, (2000b); Ilic et al. (2000); and Snowdon et al. (2000). The estimated slash produced by forest harvesting is in line with independent studies of slash production from forest harvesting for major Australian harvested forests (Snowdon et al. (2000); Ximenes et al. (2008a)).

For the Spatial method for *harvested native forests,* data on harvesting is provided directly by state forest management agencies. These data on the location, type and date of harvesting, along with parameters for tree growth, debris and soil processes are used to generate the estimate of net emissions and also of the carbon mass removed from the harvested areas as product. Conversion of this carbon mass to wood volume provides a model output which can be compared directly to the roundwood log volumes published by ABARES.

The overall *harvested native forests* model is verified by comparing the log volume, calculated using the FullCAM harvested native forest model for emissions estimation, with national statistics of round wood production in native forests (ABARES 2022) (Figure 6.4.3). The log volume from the *harvested native forest* model was estimated by converting the carbon removed from forests as forest products to stem volume, assuming a stemwood carbon percentage of 50 per cent and average wood basic density of 730 kg/m^3. The modelled log volumes closely track the published statistics over time.

Figure 6.4.3 Estimated removals in Harvested Native Forests, FullCAM outputs compared to national harvesting statistics (ABARES 2022)



Pre-90 Plantations

The calibration and validation of FullCAM, along with the associated quality assurance and quality control program are described in Annex 5.6.2. An independent review of the models used to estimate emissions and removals in the *plantations* category was undertaken by CSIRO in 2001. Recent updates to the parameters for forest plantation used in modelling are provided in Annex 5.6.2.

Other native forests

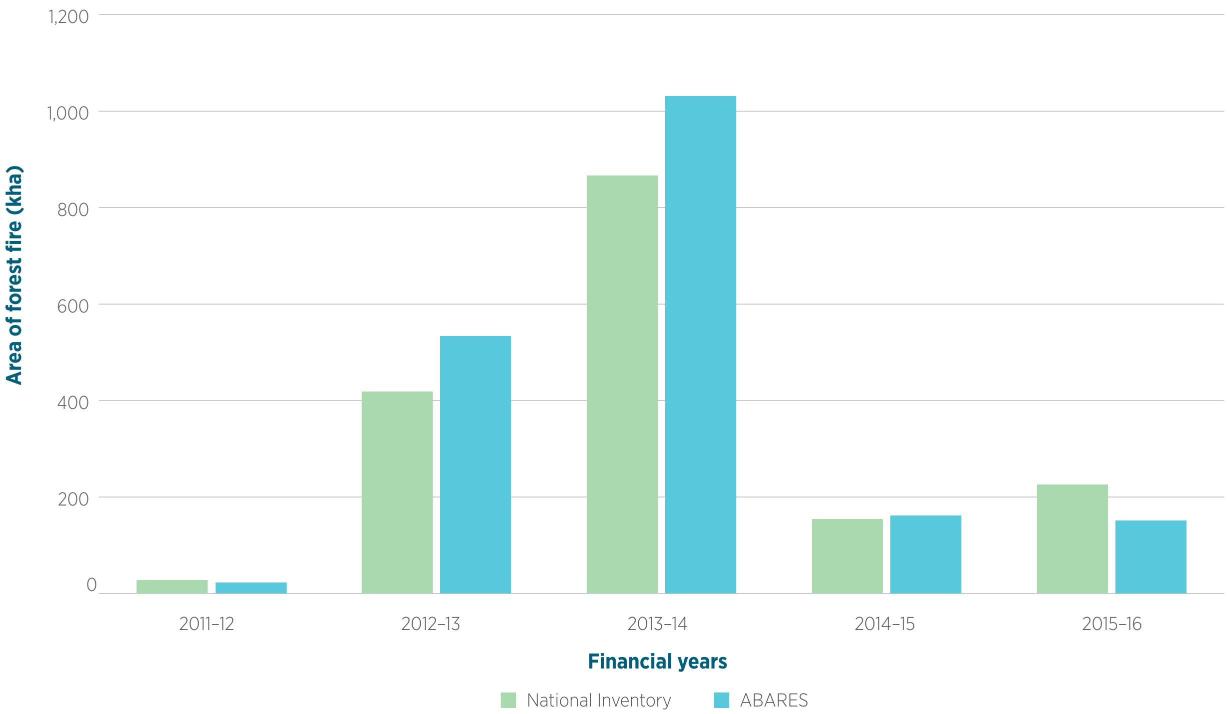
The activity data for wildfire was assessed by the Royal Melbourne Institute of Technology (RMIT) (K. Lowell 2014), and compared with a range of alternative datasets, and was found to be the most suitable and highest quality time series data available. The datasets considered by the RMIT included:

1. Monthly AVHRR burnt area products (1990 to 2014), obtained from the Western Australian Land Information Authority (Landgate);
2. Monthly MODIS burnt area 500m products (2000 to 2013), obtained from the global database maintained by the University of Maryland, USA;
3. Limited coverage of wildfire data from the Landsat series of satellites; and
4. Reference bushfire history data supplied by state agencies.

The overall quality of the post-2000 AVHRR burnt area products had a low commission error (5.4 per cent) which indicates that 94.6 per cent of the wildfire detected in the Landgate AVHRR burnt area product were correctly classified. The omission error was around 11 per cent after accounting for the undetected low-intensity prescribed burns (22 per cent) and smaller fires below the minimum mapping unit (9 per cent) which the 1km resolution AVHRR optical sensors were not expected to detect.

The data reported in the NIR also aligns with reporting to FAO forest resources assessment in the ABARES State of the Forests Report 2018 covering data up to 2016 (Figure 6.4.4).

Figure 6.4.4 Comparison of annual forest area experiencing wildfire, Australia, 2011–12 to 2015–16 (kha)



The reporting of net emissions from *other native forests,* and the identification and disaggregation of non-anthropogenic natural disturbances in temperate forests, results in both carbon dioxide emissions and removals from natural disturbances averaging out over time without impacting anthropogenic net emissions. This methodology and outcomes have been subjected to independent review (Federici 2016a).

6.4.1.5 Category-specific recalculations

The recalculations reported in the current submission are shown in Table 6.4.18 and include:

A. Refinements to crop and grass sub-models in FullCAM

Significant improvements have been made to the way the FullCAM model reflects climate impacts on crop and grass production and soil carbon. This is described in more detail in Chapters 6.5.1.5 and 6.6.1.5.

B. FullCAM database and parameter updates including for croplands and grasslands

Refinements have been made to a range of parameters used in FullCAM, including updates to grazing pressure, crop and grass regimes and crop yield tables, as well as minor enhancements including for implementation of savanna fire model parameters. These are outlined in further detail in Chapters 6.5.1.5 and 6.6.1.5.

C. Activity data updates

Activity data updates implemented in this submission include addition of:

- activity data and climate data covering 2021-22;
- annual updates to spatial datasets (Woody Change, Plantation Type, Fire time series and Land Use spatial layers) based on recent satellite observations.

D. Refinements to harvested native forest modelling

The spatial methodology introduced in the 2019 inventory to estimate emissions from native forestry on public lands has been extended in this report to include the state of Queensland. The changes in reported emissions have two causes. Firstly, using a spatial model with specific, reported timber harvesting events and locations changed reported emissions for public multiple use forests. These changes also reflect the effects of the weather record on tree growth, and particularly on the soil carbon pool which responds strongly to inter-annual variability in rainfall.

Secondly, revisions to the activity data have been received from the publicly owned NSW Forestry Corporation, resulting in higher harvesting rates prior to 2000. The multiple use forest extent in New South Wales has been updated using published forest tenure information, improving completeness of spatial harvesting activity data captured within the modelling.

Table 6.4.18 Forest land remaining forest land: recalculation of total CO_2-e emissions, kt CO_2-e

	2023 submission	2024 submission	Change	Reasons for recalculation (kt CO_2-e)			
Year	(kt CO_2-e)	(kt CO_2-e)	(kt CO_2-e)	A	B	C	D
1989-90	-972	960	1,932	258	662	1,995	-983
1994-95	-1,458	-5,901	-4,442	-31	283	1,083	-5,778
1999-00	5,396	5,144	-252	374	914	-530	-1,010
2004-05	-15,077	-16,803	-1,725	286	1,461	-1,905	-1,567
2005-06	-9,140	-10,975	-1,835	232	949	-1,896	-1,119
2006-07	-5,139	-8,759	-3,620	-574	-0	-1,282	-1,764
2007-08	8,800	4,389	-4,411	132	621	-2,225	-2,939
2008-09	9,571	12,654	3,083	-148	334	-1,920	4,817
2009-10	12,360	16,340	3,981	173	932	-1,794	4,669
2010-11	18,934	22,797	3,863	-6	345	-1,657	5,180
2011-12	523	6,197	5,675	-349	141	1,616	4,266
2012-13	-9,744	-4,907	4,837	5	925	-497	4,405

Year	2023 submission	2024 submission	Change	Reasons for recalculation (kt CO_2-e)			
	(kt CO_2-e)	(kt CO_2-e)	(kt CO_2-e)	A	B	C	D
2013-14	-10,205	-12,287	-2,082	731	-159	-1,884	-770
2014-15	-16,776	-17,791	-1,015	174	1,400	-943	-1,646
2015-16	-31,669	-36,551	-4,882	70	-417	-1,550	-2,986
2016-17	-33,363	-35,894	-2,531	486	1,852	-1,734	-3,135
2017-18	-45,777	-52,250	-6,473	20	476	-1,324	-5,645
2018-19	-35,868	-38,484	-2,616	249	327	-815	-2,376
2019-20	-40,972	-38,129	2,842	1,721	1,503	3,269	-3,651
2020-21	-38,930	-28,770	10,160	452	-908	13,554	-2,938

6.4.1.6 Category-specific planned improvements

Harvested native forests

Australia plans to complete the transition to a comprehensive Tier 3, Approach 3 fully spatial model for the *harvested native forests* sub-category. This approach has already been implemented for four states: Victoria, New South Wales, Tasmania and Queensland. This enables the ongoing incorporation of the most recent empirical research into aboveground biomass, allometrics, turnover and decay factors into the *harvested native forests* sub-category. The inclusion in this method of Western Australian native forest harvesting remains a priority.

The estate model method for private forests will also be updated drawing on data and factors drawn from the spatial model for public forests.

Improved calibrations for forest growth and disturbance

Work is in progress to compile additional field measurements for growth and disturbance in forests and rangelands. This will result in revision of parameters including those relating to tree growth, turnover and decay, loss of biomass due to fire and timber harvesting, and the rate at which biomass recovers from disturbances. A revised vegetation classification in development will refine the association of these parameters to vegetation types.

6.4.2 Land Converted to Forest Land

6.4.2.1 Category description

Land converted to forest land includes the sub-categories *grassland converted to forest land, cropland converted to forest land, settlements converted to forest land* and *wetlands converted to forest land.*

Grassland converted to forest land contains forest established on land that was previously non-forest. These conversions include commercial plantations and environmental plantings, forest that has regrown on land that was previously converted from a forest to grassland, and regeneration from natural seed sources on land protected by State or Territory vegetation management policies.

Cropland converted to forest land and *settlements converted to forest land* contains forest that has regrown on land that was previously converted from forest land to the land use identified.

Wetlands converted to forest land comprises land on which mangrove forest has been detected to emerge on tidal marshes.

The annual net emissions for the *land converted to forest land* category are shown in Table 6.4.19.

Table 6.4.19 Annual net emissions for land converted to forest land, kt CO_2-e

Year	Cropland converted to forest land	Grassland converted to forest land	Settlements converted to forest land	Wetlands converted to forest land	Total
1989-90	-81	-2,356	-7	-2,745	-5,188
1994-95	-166	-7,639	-64	-3,365	-11,234
1999-00	-288	-17,378	-138	-3,525	-21,328
2004-05	-224	-13,104	-200	-3,993	-17,521
2005-06	-225	-18,259	-195	-3,556	-22,234
2006-07	-215	-16,961	-190	-3,716	-21,082
2007-08	-219	-18,714	-172	-4,285	-23,390
2008-09	-202	-20,775	-166	-3,668	-24,811
2009-10	-204	-22,293	-170	-4,181	-26,848
2010-11	-247	-38,101	-147	-4,542	-43,037
2011-12	-286	-31,376	-162	-4,393	-36,218
2012-13	-268	-27,175	-208	-4,209	-31,861
2013-14	-289	-30,876	-239	-4,145	-35,549
2014-15	-324	-28,957	-233	-4,284	-33,798
2015-16	-380	-38,711	-330	-3,890	-43,312
2016-17	-451	-37,228	-310	-4,348	-42,336
2017-18	-435	-31,944	-347	-4,320	-37,046
2018-19	-371	-25,003	-309	-3,946	-29,629
2019-20	-423	-27,371	-318	-4,347	-32,459
2020-21	-544	-40,760	-380	-4,707	-46,391
2021-22	-627	-42,391	-371	-4,661	-48,050

6.4.2.2 Methodological issues

Plantations

Each individual 25m x 25m pixel identified as being a *plantation* is modelled through time from the time of establishment. Each 25m x 25m model takes into account the age, plantation type, management (including time of harvesting as detected from satellite imagery) and site conditions to estimate emissions and removals. Precise pixel areas are adjusted for the curvature of the earth to ensure the most accurate representation of areas and emissions for each location. Further information on the parameters used in modelling is provided in Annex 5.6.2.

The activity data for plantations in the *grassland converted to forest land* classification is drawn from the remote sensing program (see Annex 5.6.1) (Table 6.4.20).

Table 6.4.20 Cumulative area of plantations in grassland converted to forest land

Year	Area (ha)
1989-90	19,170
1994-95	211,103
1999-00	415,642
2004-05	805,700
2009-10	1,129,497
2010-11	1,185,706
2011-12	1,235,189
2012-13	1,273,272
2013-14	1,308,884
2014-15	1,337,444
2015-16	1,362,428
2016-17	1,378,503
2017-18	1,391,347
2018-19	1,400,229
2019-20	1,410,379
2020-21	1,424,701
2021-22	1,439,655

Native Vegetation

The emissions and removals arising due to the regrowth of native vegetation on previously-cleared land, and due to the emergence of forest in protected areas, are estimated using the spatially explicit (Approach 3) capabilities of the Tier 3 FullCAM modelling system. A full description of the modelling system is provided in Annexes 5.6.2 and 5.6.4, and Waterworth et al. (2007); Waterworth and Richards, (2008).

Reporting includes carbon in living biomass, dead organic matter (DOM) and soil pools. The areas are drawn from remotely sensed data.

Most areas will be classified as *grassland converted to forest land. Cropland converted to forest land* and *settlements converted to forest land* are identified where forest has regrown on land that was previously converted from forest land to the land use in question. These conversions do not always mean that the land has ceased being used for its converted purpose, but that a canopy of trees has been detected as re-emerging above the identified land use. For example, a canopy may emerge due to the urban landscaping of parks and gardens, or the restoration of riparian vegetation along waterways in cropping regions. The re-emergence of sufficient trees as would meet the definition of a forest requires that these lands to be recognised as converted to forest for the purposes of the national inventory.

Table 6.4.21 Cumulative areas of land converted to forest land with native vegetation, ha

Year	Regrowth on grasslands	Regrowth on croplands	Regrowth on settlements	Forest emerging in protected areas
1989-90	782,463	34,281	13,722	2,084,364
1994-95	1,447,497	63,673	32,131	3,429,061
1999-00	1,732,389	63,683	42,150	4,335,240
2004-05	1,788,299	56,619	46,547	5,097,827
2009-10	2,334,598	62,943	50,300	6,038,632
2010-11	2,558,729	68,152	53,111	6,259,184
2011-12	2,752,705	71,944	57,452	6,462,064
2012-13	2,956,345	75,491	60,044	6,676,805
2013-14	3,168,661	79,819	63,055	6,937,365
2014-15	3,429,800	87,743	68,987	7,202,248
2015-16	3,612,734	91,820	71,773	7,528,253
2016-17	3,755,192	99,871	74,875	7,823,713
2017-18	3,750,406	103,534	75,297	8,056,342
2018-19	3,747,062	105,590	78,524	8,264,538
2019-20	3,750,115	106,768	80,672	8,465,848
2020-21	3,777,440	108,626	81,805	8,769,716
2021-22	4,030,737	116,504	85,208	9,163,686

Mangrove forests

Australia's continental expanse incorporates a wide range of climate zones and coastal features that together determine the character of its coastal wetlands, including their carbon emissions and removal capacity. Mangrove forests are one of eight native forest types. They are found in the intertidal zones of tropical, subtropical and sheltered temperate coastal rivers, estuaries and bays. They grow in fine sediments deposited by rivers and tides, where they are regularly exposed to tidal inundation and lack of oxygen in the soil. They occupy an estimated 1,110,000 hectares around the Australian coastline (ABARES 2023). Mangroves meet Australia's definition of forests.

Tidal marshes comprise salt tolerant succulent herbs, sedges and grasses covering an estimated area of 1.4 million hectares in Australia. They are typically situated higher in the intertidal zone than mangrove, with the highest areas of tidal marsh only inundated at the highest spring tides (Metcalfe 1999). They are often subject to hypersaline conditions. Tidal marsh species diversity increases with increasing latitude in Australia; an association that appears strongly linked to mean minimum daily temperature 0.

The emergence of mangrove forest is identified using satellite imagery, as for other native forest. Given mangrove forests are generally bordered by seawater on the lower side and by salt marsh on the higher side, it is assumed that any emerging coastal mangrove forest does so on land which was previously tidal marsh or bare tidal flat and is therefore allocated to *wetland converted to forest land.*

Carbon dioxide emissions and removals are modelled using FullCAM, a spatially explicit Tier 3 modelling system calibrated, in this model, to mangrove ecosystems around Australia's coastal land area (Annex 5.6.10 with reference to Annexes 5.6.1 and 5.6.2).

Table 6.4.22 Cumulative area of mangrove establishment

Year	Area (ha)
1989-90	94,620
1994-95	109,452
1999-00	123,701
2004-05	135,028
2009-10	149,435
2010-11	151,742
2011-12	155,745
2012-13	158,853
2013-14	160,985
2014-15	163,833
2015-16	165,239
2016-17	169,777
2017-18	172,200
2018-19	174,150
2019-20	174,266
2020-21	173,715
2021-22	175,625

6.4.2.3 Uncertainty assessment and time-series consistency

Uncertainty in the *land converted to forest land* sub-category is expected to be 17.3 per cent. Further details are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to methodology.

Under *wetland converted to forest land* the confidence intervals associated with 2013 IPCC guidance (IPCC 2013) values for parameters associated with land use, land use change involving coastal wetlands are moderate. This inventory applies the spatially explicit FullCAM calibrated to available field data, sourced from scientific literature, to reduce uncertainty. Although a formal uncertainty analysis is not yet available, the level of uncertainty is anticipated to be 30-40% or the lower end of the guidance values and is considered to be within the medium range.

While there is a higher uncertainty in *wetlands converted to forest land* than in *grassland converted to forest land* estimates, the former category makes only a small contribution to the overall uncertainty of *land converted to forest land* due to its lower emissions.

6.4.2.4 Category-specific QA/QC and verification

Tier 1 quality control checks are complimented by an analysis of forest establishment rates, as shown in Figure 6.1.5. Trends in historic establishments provide context to present sequestration rates and provide confidence that the strong sinks being estimated in the most recent years are realistic.

See Annex 5.6 for evaluation of the model processes used for Land Converted to Forest Land.

6.4.2.5 Category-specific recalculations

The recalculations due to the reasons listed below, are reported in the Table 6.4.23 and include:

A. **Refinements to crop and grass sub-models in FullCAM**

   Significant improvements have been made to the way the FullCAM model reflects climate impacts on crop and grass production and soil carbon. This is described in more detail in Chapters 6.5.1.5 and 6.6.1.5.

B. **FullCAM database and parameter updates including for croplands and grasslands**

   Refinements have been made to a range of parameters used in FullCAM, including updates to grazing pressure, crop and grass regimes and crop yield tables, as well as minor enhancements including for implementation of savanna fire model parameters. These are outlined in further detail in Chapters 6.5.1.5 and 6.6.1.5.

C. **Activity data updates**

   Activity data updates implemented in this submission include addition of:

   - activity data and climate data covering 2021-22; and
   - annual updates to spatial datasets (Woody Change, Plantation Type, Fire time series and Land Use spatial layers) based on recent satellite observations.

Table 6.4.23 Land converted to forest land: recalculation of total CO_2-e emissions (kt)

	2023 submission	2024 submission	Change		Reasons for Recalculations	
Year	kt CO_2 -e	kt CO_2 -e	kt CO_2 -e	A	B	C
1989-90	-7,045	-6,050	995	-78	1,066	6
1994-95	-11,982	-12,515	-533	333	-920	54
1999-00	-24,232	-23,275	957	897	-41	102
2004-05	-22,585	-18,097	4,488	0	3,877	610
2005-06	-26,766	-24,598	2,168	1,562	507	99
2006-07	-23,589	-21,418	2,171	14	1,546	612
2007-08	-26,518	-22,624	3,894	956	2,221	718
2008-09	-25,638	-24,297	1,341	706	152	483
2009-10	-29,304	-27,179	2,125	1,174	698	253
2010-11	-39,746	-44,522	-4,775	2,155	-6,562	-369
2011-12	-36,960	-33,101	3,859	293	2,771	795
2012-13	-34,517	-29,363	5,153	-389	4,035	1,507
2013-14	-36,456	-36,411	45	1,373	-2,048	720
2014-15	-38,255	-32,851	5,404	1,057	3,326	1,021
2015-16	-45,740	-44,106	1,634	770	-293	1,157
2016-17	-48,622	-43,904	4,718	2,597	1,339	781
2017-18	-39,860	-36,624	3,236	-21	1,807	1,449
2018-19	-34,165	-30,466	3,699	1,546	516	1,638
2019-20	-36,747	-35,539	1,209	714	-381	875
2020-21	-50,980	-48,842	2,137	1,251	1,906	-1,019

6.4.2.6 Category-specific planned improvements

Improved calibrations for forest growth and disturbance

Work is in progress to compile additional field measurements for growth and disturbance in forests and rangelands. This will result in revision of parameters including those relating to tree growth, standing dead, turnover and decay, loss of biomass due to fire and timber harvesting, and the rate at which biomass recovers from disturbances. A revised vegetation classification in development will refine the association of these parameters to vegetation types.

Improved parameters for soil carbon will also be applied, with a run-in process to begin models with soil at equilibrium for the prevailing conditions.

Forest cover change

The remote sensing programme to detect forest cover change is being updated from the Landsat time series at 25m resolution to use Sentinel 2 satellite imagery at 10m resolution. It is expected that this significant improvement will be included in the next submission.

Systems for the estimation of areas of forest conversion and related assessments of the gains and losses of sparse woody vegetation will continue to be updated to enable consumption of information contained in datasets obtained from the NSW and Queensland State Governments' Statewide Landcover and Trees Study programs and similar products as they develop. The new systems will continue to build on experience gained in the use of these datasets during the finalisation of the area estimates for this inventory.

Specifically, the remote sensing programme is further advancing the methods to enable:

- ongoing improvements and development of rule-based methods for change detection and attribution;
- processing of remaining areas of vegetation monitoring for parts of central Australia to complete the national coverage; and
- estimation of above-ground biomass from remote-sensed canopy cover.

Mangrove modelling

Improvements will be made to the FullCAM Wetlands – coastal sub-model. These will involve updates to spatial inputs for mangrove and tidal marsh extents, and to Australia's tidal extent, as these become available. Future use of an upgraded change detection (CPN) in three vegetation classes may better define areas of mixed mangrove and tidal marsh, also known as 'scrub mangrove'. Calibration of the model will be refined with addition of new field data for mangrove and tidal marsh ecosystems.

6.5 **Cropland** (CRT category 4.B)

6.5.1 Cropland Remaining Cropland

6.5.1.1 Category Description

The *cropland remaining cropland* sub-category includes continuous cropping lands and lands that are cropped in rotation with pastures. Croplands are considered to be of high land value with a high return on production and moderate to high soil nutrient status and are therefore not generally converted to *forest land* or *grassland* but remain as *cropland.*

Anthropogenic emissions and removals on croplands occur as a result of changes in management practices from changes in crop type and from changes in land use. Permanent changes in management practices generate changes in the levels of soil carbon or woody biomass stocks over the longer term. Changes in carbon stock levels during the transition period to a new stock equilibrium are recorded under croplands.

Emissions and removals from *grassland converted to cropland* are reported under *cropland remaining cropland* because annual variations in area under cropping in Australian agricultural systems do not constitute a permanent land-use change. Activity data for crop-pasture rotations based on Australian national statistical information includes permanent conversions to croplands. This is appropriate for national circumstances and Australian agricultural systems which apply predominantly rain-fed cropping practices and respond to market fluctuations, resulting in seasonal variations in the lands under cropping rather than permanent land-use changes. The IPCC 2006 guidelines (IPCC 2006) permit such an approach where appropriate based on the activity data (for example where prior land use is not known, see *IPCC 2006 Guidelines,* Vol 4, Ch 5.3.3 (IPCC 2006)).

Anthropogenic emissions and removals from croplands are estimated from changes in specified management practices on croplands including:

- Total cropping area;
- Crop type and rotation (including pasture leys);
- Stubble management, including burning practices;
- Tillage techniques;
- Irrigation; and
- Application of green manures (particularly legume crops).

Conversion of pasture to cropping activities is included within the *cropland remaining cropland* estimates.

Carbon dioxide emissions from the application of lime are reported under *Agriculture.* Nitrous oxide emissions from the application of fertiliser are also reported under *Agriculture.*

Climate has important cyclical effects throughout the time series. The uptake of reduced, minimum and no-till management techniques through the 1980s and 90s is reflected in the tendency towards decreasing emissions during this period as a new soil C state of equilibrium is reached. The decreasing emissions trend is also inversely correlated with the increasing crop production over this period. The most recent years, 2021 and 2022, had the lowest emissions and highest crop production.

Figure 6.5.1 Net CO_2 emissions from cropland remaining cropland

Table 6.5.1 Net emissions and removals from cropland remaining cropland sub-categories (kt CO_2-e)

Year	Soil carbon	Perennial woody crops (biomass)	Total
1989-90	17,699	-58	17,641
1994-95	6,653	-87	6,566
1999-00	2,310	-48	2,262
2004-05	5,837	-170	5,667
2005-06	6,559	-180	6,379
2006-07	5,674	34	5,708
2007-08	4,436	-107	4,329
2008-09	4,064	-146	3,918
2009-10	3,925	-277	3,648
2010-11	3,582	-345	3,237
2011-12	962	-105	857
2012-13	-3,680	93	-3,587
2013-14	-4,278	15	-4,263
2014-15	-4,066	-85	-4,151
2015-16	-4,430	-207	-4,637
2016-17	-3,895	-256	-4,152
2017-18	-6,379	-123	-6,502
2018-19	-8,825	-183	-9,008
2019-20	-10,026	-315	-10,341
2020-21	-11,455	-418	-11,873
2021-22	-11,200	-530	-11,730

6.5.1.2 Methodological issues

Carbon dioxide emissions and removals from the *cropland remaining cropland* soils component are estimated using FullCAM (Annex 5.6.2). The CO_2 emissions and removals associated with changes in the area of perennial woody crops are estimated using a Tier 2 approach outlined below.

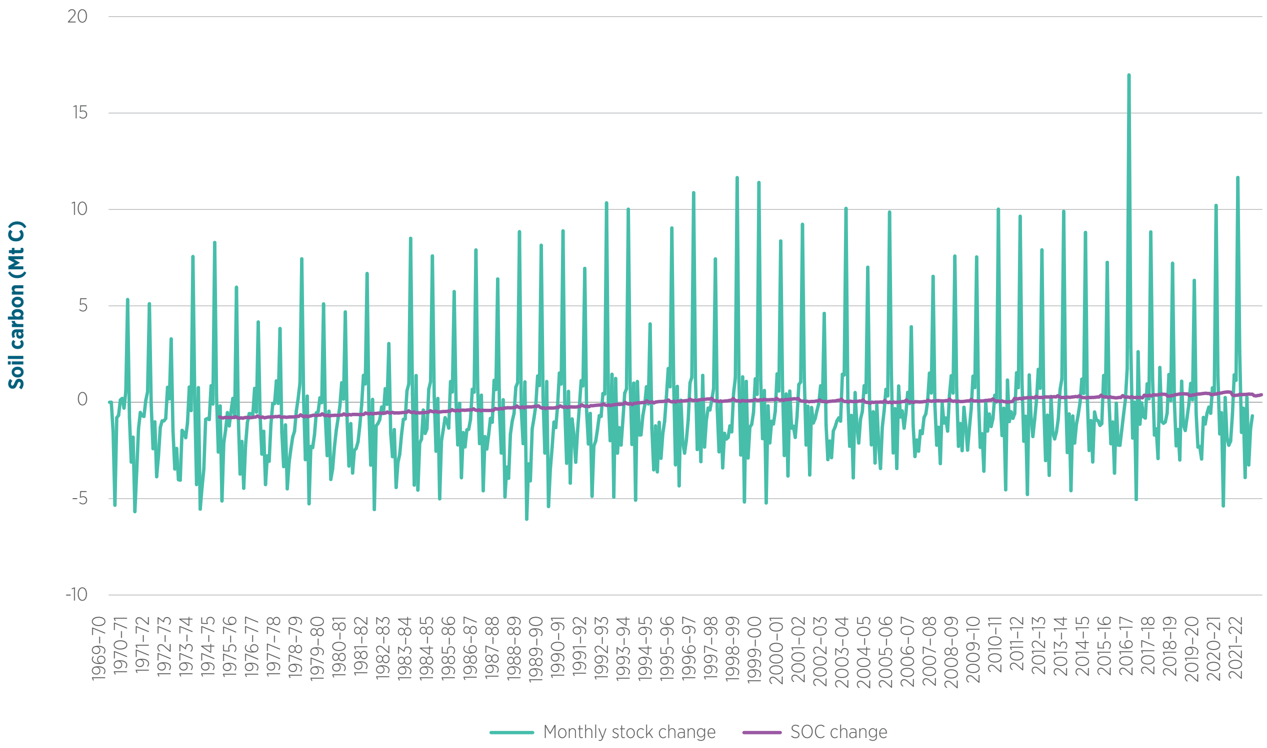
The area of *cropland* is estimated using the Catchment Scale Land Use of Australia dataset provided by ABARES (2017 version) at the mapping scale of 1:5000 to 1:250 000. Where a transition to or from forest within the preceding 50 years has not been identified, these lands are categorised as *cropland remaining cropland.*

Herbaceous crops

FullCAM is simulated in monthly time steps commencing at the time of first planting in 1970. When configured for cropland remaining cropland, FullCAM uses the same climate, site and management datasets as those used in the *forest land converted to cropland* estimates and as described in Annexes 5.6.2 and 5.6.5.

All on-site carbon pools (living biomass, dead organic matter (DOM) and soil) are estimated. For non-woody crops in *cropland remaining cropland* the changes in the soil carbon pool are reported. Carbon stock changes from living biomass and DOM of non-woody annual crops are reported to be zero, consistent with the guidance in the *2006 IPCC Guidelines* (IPCC 2006) that indicates that the increase in biomass stocks in a single crop year may be assumed equal to biomass losses from harvest and mortality in that year – thus there is no net accumulation of biomass carbon stocks (IPCC 2006, p5.7 (IPCC 2006)). In general, croplands will have little or no dead wood, crop residues or litter (IPCC 2006, p5.12 (IPCC 2006)). A mean incremental value for the transitions between SOC near steady states is derived, in this case from the simulated monthly data, as shown in Figure 6.5.2.

Figure 6.5.2 Monthly carbon stock change from cropland remaining cropland



Management practice change has been monitored in the ABS Land Management and Farming (ABS 2017) which provides information on management practices being adopted and utilised by Australian agricultural business. Further details on changes in management practices are provided in Annex 5.6.5.

Perennial woody crops

The carbon dioxide emissions and removals from changes in the area of perennial woody crops are estimated using a country-specific Tier 2 approach. The Tier 2 method retains the basic Tier 1 approach from the *2006 IPCC Guidelines* (IPCC 2006), but with differences to the period over which biomass accumulates (harvest/maturity cycle) and use of more accurate crop-specific coefficients.

Crop-specific coefficients were sourced from literature to calculate CO_2 emissions and removals. The coefficients required are: total biomass carbon stock at harvest (tonnes C ha^{-1}), years to maturity (M), biomass accumulation rate (tonnes C ha^{-1} yr^{-1}) and plot density (trees ha^{-1}). The mathematical relationships between these coefficients are displayed in Table 6.5.2. Additionally, root to shoot ratios were sourced from the literature and biomass accumulations associated with fruit production were excluded from all calculations. Where parameters were derived from other countries, corrections were made to account for local conditions. For example, for olives, carbon accumulation rates were sourced from Spain where plot density was 408 trees per hectare, whereas in Australia plot density of olives is reported to be 250 trees per hectare. The Spanish carbon accumulation rate was adjusted relative to the Australian plot density factor.

Table 6.5.2 Calculations used to develop tier 2 coefficients for perennial woody crops

	total biomass carbon stock at harvest (t C ha^{-1})	harvest cycle (yr)	biomass accumulation rate (t C ha^{-1} yr^{-1})
calculations	M x y	M	y
e.g. (oranges)	5	10	0.5

In total, 27 perennial woody crop types are grouped by major crop-type. The coefficients applied to each group were based on the dominant crop type (Table 6.5.3). The four main crop-types and dominant crops are: 1) citrus, with crop coefficients represented by orange data, 2) Nuts, with crop coefficients represented by macadamia data, 3) pomes, with crop coefficients represented by apple data and 4) stone fruit, with crop coefficients represented by peach data. Other smaller crops modelled included: olives, grapes, kiwifruit, avocados and mangoes. Grape crop coefficients were used to model kiwifruit, and avocado coefficients were used to model mangoes. Regarding nuts, while macadamias were used as the representative crop, almonds were estimated separately as almond-specific coefficients were available.

Estimates of changes in area of perennial woody crops are taken from the *ABS agricultural commodities statistics* (ABS 2022), which also account for planting and clearing events. Most crop data are provided as tree number values and subsequently were converted to area statistics using crop-specific plot density coefficients.

Table 6.5.3 Perennial woody crop Tier 2 coefficients

Crop type	total biomass carbon stock at harvest (t C ha^{-1})	harvest cycle (yr)	biomass accumulation rate (t C ha^{-1} yr^{-1})	plot density (trees ha^{-1})	root: shoot
Citrus					
Oranges	5	10[n]	0.5[a]	417[b]	0.17[c]
Nuts					
Macadamias	45	15[n]	0.82[e]	312[e]	0.25[e]
Almonds	9.6	8[n]	1.2[a]	222[f]	
Pomes					
Apples	4.9[g]	7[n]	0.7	1500[g]	0.17[c]
Stone fruit					
Peaches	5.2	4[n]	1.3[a]	740[h]	0.17[c]
Grapes	1.2	4[n]	0.3[a]	N/A	0.5[c]
Kiwifruits	1.5	5[n]	0.3[a]	N/A	0.5[c]
Olives	6.7	10[n]	0.67[j]	250[k]	0.145[c]
Avocados	6[l]	10[n]	0.6	210[l]	0.125[l]
Mangoes	13[l]	10[n]	1.3	185[m]	0.125[l]
IPCC default	63		2.1		

Source and location of study is: *a* = (Kroodsma and Field 2006) USA California, *b* = (Morgan, et al. 2006) USA Florida, *c* = (Federal Environment Agency 2013), (Ministerio de Agricultura 2013) *d* = Australian Macadamia Society website, *e* = (Murphy, et al. 2013) Australia, *f* = (Fernández-Puratich 2013) Spain, *g* = (Haynes and Goh 1980) New Zealand, *h* = (Marini and Sowers 2000) USA, *i* = (San Felipe Olives 2014) USA California, *j* = (Villalobos, et al. 2006) Spain, *k* = (Olives Australia 2014), *l* = (Lovatt 1996) USA California, *m* = (Department of Primary Industries and Regional Development 2017), and *n* = (Department of Agriculture and Fisheries, Queensland 2014). Note that plot density is represented by N/A for Grapes and Kiwifruit as reported in hectares by ABS. All figures not referenced were determined using calculations in Table 6.5.2.

6.5.1.3 Uncertainty assessment and time-series consistency

Based on a qualitative assessment the uncertainties for *cropland remaining cropland* were estimated to be medium. Further details are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to the methodology.

There are a number of gaps in the time series of *ABS commodities statistics* (ABS 2022) for perennial woody crops, in particular for the 2021-22 financial year, the ABS Rural Environment and agricultural commodities survey received a very low response rate and statistics were not available for most perennial woody crops. All data-gaps were filled using extrapolation and interpolation techniques consistent with the *2006 IPCC Guidelines* (IPCC 2006).

6.5.1.4 Category-specific QA/QC and verification

Extensive QA/QC of FullCAM shows that the results closely align to the Tier 2 steady-state soil carbon model (T2SSM) provided in Volume 4, Chapter 5 of the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2006). This work is described in Annex 5.6.2.

In relation to crop yields, CSIRO Agriculture and Food has tested the performance of the crop growth model against a database of crop yields (see Annex 5.6.5).

The calibration, validation and verification of FullCAM, along with the associated quality assurance and quality control programme are fully described in Annex 5.6.2.

6.5.1.5 Category-specific recalculations

The recalculation of the *cropland remaining cropland* time series is presented in Table 6.5.4, and an explanation of the key influences on the change in estimates follows:

A. Refinements to crop and grass sub-models in FullCAM

Changes to FullCAM this year include the revision of yield model. Yield response to rainfall has been revised through improvements to the water balance sub-model used in calculation of yields. The ranges of crop yields aligned better with those reported in ABS Agricultural Commodities statistics, especially in wetter climates. Annual grass growth was also modified to accept input yields as monthly growth increments rather than a single yearly value; this captured better the pasture growth and its response to climate. Minor modifications were also made to the handling of turnover, which is included in growth increments.

These changes have led to large recalculations in some years, particularly over 2020–2022 where the onset of La-Nina brought more rain, lower evaporation and temperatures; overall this increased crop production and as a result more carbon was retained within the soil.

B. FullCAM database and parameter updates including for croplands and grasslands

Updates and refinements were made to a range of parameters used in FullCAM, including updates to grazing pressure, crop and grass regimes and crop yield tables. Grazing pressure tables now reflect revised yields. Grazing is handled as a fraction of the crop mass. Annual grasses regimes were modified so the growth season is a minimum of 9 months to better reflect trends in annual pasture cultivations. Crop and grass yield tables were updated according to the revised yield model.

C. Activity data updates

Activity data updates implemented in this submission include addition of:

- activity data and climate data covering 2021-22; and
- annual updates to spatial datasets (Woody Change Plantation Type, Fire time series and Land Use spatial layers) based on recent satellite observations.

New activity data for the year 2021-22 affects the mean incremental value in earlier years for soil carbon stock change between steady states.

As noted above the most recent years, 2021 and 2022, had the lowest emissions and highest crop production.

Table 6.5.4 Cropland remaining cropland: Recalculation of CO_2-e emissions

	2023 submission	2024 submission	Change	Reasons for Recalculation (kt CO_2-e)		
	(kt CO_2-e)	(kt CO_2-e)	(kt CO_2-e)	A	B	C
1989-90	27,086	17,641	-9,445	-8,739	-940	234
1994-95	7,072	6,566	-507	175	-863	182
1999-00	-1,077	2,262	3,339	4,097	-906	148
2004-05	7,277	5,667	-1,610	-555	-1,101	46
2005-06	4,927	6,379	1,451	2,611	-1,184	24
2006-07	6,582	5,708	-875	664	-1,573	35
2007-08	6,282	4,329	-1,953	-299	-1,688	34
2008-09	7,386	3,918	-3,468	-1,990	-1,522	44
2009-10	1,648	3,648	2,000	3,296	-1,318	23
2010-11	2,044	3,237	1,193	2,139	-972	26
2011-12	2,521	857	-1,664	-675	-1,005	16
2012-13	1,195	-3,587	-4,782	-3,855	-990	63
2013-14	2,238	-4,263	-6,501	-5,646	-909	54
2014-15	-1,423	-4,151	-2,728	-1,965	-789	26
2015-16	-4,903	-4,637	266	886	-629	9
2016-17	-5,217	-4,152	1,065	1,455	-366	-24
2017-18	-4,101	-6,502	-2,402	-730	-163	-1,508
2018-19	-5,709	-9,008	-3,299	-564	1,037	-3,773
2019-20	897	-10,341	-11,238	-8,115	1,010	-4,133
2020-21	3,085	-11,873	-14,958	-11,481	1,013	-4,490

6.5.1.6 Category-specific planned improvements

Refining the spatial allocation of crop species is being investigated. It is envisaged that by incorporating additional covariate data, the accuracy of spatial allocation of crop types can be improved to better reflect national and regional trends.

Investigations into using pixel-based climate data to derive crop yields at finer resolution than statistical area 2 are progressing. It is hoped that this will better reflect the impact of regional differences in climate on crop yields.

The handling of the below-ground debris pool within FullCAM is being investigated to determine the optimal behaviour of the relationship of the Roth-C implementation and changing management practices. Handling of turnover and debris breakdown rates are being investigated. The initialisation of soil carbon pools within FullCAM is being investigated to determine the optimal starting values that more accurately reflect the measured carbon soil fractions at any given period in time.

The calibration of the impact of tillage activities within the FullCAM modelling framework is being refined. This will improve the estimation of the impact that varying tillage practices, such as minimum and no till, have on soil decay functions. Additionally, investigating the timing and parameters associated with pre- and post- harvest management events will enable more accurate modelling of their impacts to better reflect the entry of crop residues into the soil. Stubble management allocations and persistence are being reviewed to ensure they reflect up to date regional practices.

6.5.2 Land converted to cropland

6.5.2.1 Category description

Within the *land converted to cropland* subcategory, Australia reports emissions for *forest land converted to cropland* and *wetlands converted to cropland* subcategories. Net emissions from conversions between croplands and grasslands are included in *croplands remaining croplands* as it is common for cropping systems to include pasture/grazing rotations.

The *wetland converted to cropland* subcategory includes the conversion of wetlands to cropping, irrigated cropping and perennial horticulture, and involves mineral and organic hydrosols.

As Table 6.5.5 below indicates, *forest land converted to cropland* is the dominant contributor to both the level and trend in net emissions in this sub-category.

Table 6.5.5 Net emissions from land converted to cropland by sub-category, kt CO_2-e

Year	Forest land converted to cropland	Wetlands converted to cropland	Total
1989-90	17,450	241	17,690
1994-95	5,149	241	5,390
1999-00	3,104	241	3,345
2004-05	3,297	241	3,538
2005-06	6,512	241	6,753
2006-07	3,225	241	3,466
2007-08	3,164	241	3,405
2008-09	2,326	241	2,567
2009-10	3,439	241	3,680
2010-11	3,333	241	3,574
2011-12	-2,007	241	-1,766
2012-13	6,347	241	6,588
2013-14	3,717	241	3,958
2014-15	3,627	241	3,868
2015-16	1,484	241	1,725
2016-17	1,656	241	1,897
2017-18	106	241	347
2018-19	2,161	241	2,402
2019-20	1,232	241	1,473
2020-21	1,746	241	1,986
2021-22	-193	241	47

6.5.2.2 Methodological issues

Forest land converted to cropland

The methodology for the subcategory *forest land converted to cropland* is consistent with that used for native vegetation systems in *forest land converted to grassland,* which is described in more detail in Chapter 6.6.2.2. An area of land is identified as being converted to cropland rather than to grasslands if it would otherwise fall within cropland areas as identified for *cropland remaining cropland* (see chapter 6.5.1.2). Within the FullCAM framework, a database of cropland-relevant species is used in place of the database of grassland-relevant species for non-forest land use.

The activity data for the *forest land converted to cropland* classification is drawn from the remote sensing program (see Annex 5.6.1).

Wetlands converted to cropland

Areas of *wetlands converted to cropland* were estimated using IPCC Approach 2 using activity data for 1996 and 2010 acquired from *Australian Collaborative Land Use and Management Program* (ACLUMP) (ABARES 2016). Spatial information on final land uses, including grazing on native, improved and irrigated pastures, and cropping, irrigated cropping and perennial horticulture, was used in conjunction with available wetlands spatial data to estimate conversions to cropland and grazing land. In addition, expert opinion was provided by C. Meyer (personal communication, 2019) that identified 4,000 ha of histosols associated with cropping or grazing in Queensland and Victoria, based on the CSIRO Australian Soil Classification System (Isbell 2002) .

Following IPCC guidance (Volume 1, Chapter 2.2.3) extrapolation and interpolation methods were used to calculate an average annual rate of conversion of wetlands to cropland or grassland over the required time period for each state and territory. The default IPCC time period of 20 years was used for land remaining in transitional categories so that emissions from organic and mineral soils on converted lands continue to be estimated over this time.

With respect to biomass and dead organic matter, only non-woody biomass is assumed to be present in the wetlands prior to conversion – noting that conversions of forested wetlands are already accounted for in the inventory. Therefore, the IPCC tier 1 assumption, that no net change in biomass or dead organic matter stocks from conversion of wetlands to cropland occurs, was applied in this model.

Wetland converted to cropland on organic soils is distributed between Queensland, where 2,250 ha of coastal organic hydrosols were drained for sugar cane farming, and a further 750 ha in Victoria where highland organic hydrosols were drained for cropping. The remaining wetland to cropland conversions involved mineral hydrosols. Several soil-related emission factor values are applied based on stratification with respect to soil type (mineral or organic) and climate zone.

For organic soils, Equation 2.26 from IPCC 2006 Guidelines Vol 4 (IPCC 2006) was used to estimate the annual emissions:

$$L_{organic} = A \times EF \qquad (6.5.1)$$

Where L = emissions from draining organic soils organic
A = area converted
EF = emission factor

The tropical and temperate/boreal IPCC default emission factors were applied based on the tropical north Queensland and Victorian highland locations of the relevant croplands. Emission factor values for tropical and temperate/boreal croplands on drained organic soils are 14 and 7.9 tonnes CO_2-C/ha/year respectively (Table 2.1, 2013 Wetlands Supplement).

Conversions involving wetlands on mineral soils were dispersed over several climate zones. A tier 1 approach was used to estimate annual change in organic carbon stock in mineral soils over a 20-year transition period, based on Equation 2.25 (IPCC 2006) Volume 4, p 2.30. The exact distribution of the conversions within each state and territory was not known. Consequently, averaged climate zone and soil reference values were applied at a state and territory level; Queensland and the Northern Territory comprise Tropical wet and dry climate zones, Tasmania was considered cool temperate moist, and all other states were warm temperate (moist or dry). Australia's soils were generally weathered (Low activity clay), and were long term cultivated with (on average) reduced tillage and medium inputs. Based on these assumptions the following average annual changes in carbon stocks were derived and applied to their respective states to estimate annual emissions:

- Queensland/ Northern Territory: 2.97182 tonnes C / ha / year,
- Tasmania: 0.882 tonnes C / ha / year,
- All other States/Territories: 3.031063 tonnes C /ha / year.

Emissions from each state and territory were calculated, based on area, and then aggregated to give the annual national totals.

Activity data

The activity data for the *forest land converted to cropland* classification is drawn from the remote sensing program (see Annex 5.6.1), and that for the *wetlands converted to cropland* is described above. Table 6.5.6 below shows the cumulative areas of *forest land* and *wetlands* that were *converted to croplands* over the period since remote sensing commenced in 1971-72.

Table 6.5.6 Cumulative area of land converted to cropland, kha

Year	Forest land converted to cropland	Wetlands converted to cropland	Total
1989-90	1,914	13	1,926
1994-95	2,052	13	2,064
1999-00	2,157	13	2,170
2004-05	2,238	13	2,251
2005-06	2,251	13	2,264
2006-07	2,263	13	2,276
2007-08	2,269	13	2,282
2008-09	2,272	13	2,284
2009-10	2,272	13	2,284
2010-11	2,272	13	2,284
2011-12	2,273	13	2,285
2012-13	2,275	13	2,287
2013-14	2,276	13	2,288
2014-15	2,272	13	2,285
2015-16	2,272	13	2,285
2016-17	2,267	13	2,280
2017-18	2,266	13	2,279
2018-19	2,267	13	2,280
2019-20	2,268	13	2,280
2020-21	2,268	13	2,281
2021-22	2,262	13	2,274

6.5.2.3 Uncertainty assessment and time-series consistency

Uncertainties for *forest land converted to cropland* at the national scale were estimated to be ±27.3 per cent for CO_2. Further details are provided in Annex 2. Time series consistency is ensured using consistent methods and full recalculations in the event of any refinement to the methodology.

The current Tier 1 method for *wetlands converted to cropland* relies on interpolation and extrapolation with respect to two observational years. ABARES does not report on uncertainty about the land use estimates. However, these likely fall in the medium to high range.

While there is a higher uncertainty in *wetlands converted to cropland* than in *forest land converted to cropland,* the former category makes only a small contribution to the overall uncertainty of *land converted to cropland due to its lower emissions.*

6.5.2.4 Category-specific QA/QC and verification

The category specific QA/QC for the subcategory *forest land converted to cropland* is carried out together with that for *forestland converted to grassland* (see Chapter 6.6.2.4).

Quality control measures for *wetlands converted to cropland* involve internal reviews of data entry and model outputs, including a check on the consistency of land use statistics across Australian jurisdictions.

6.5.2.5 Category-specific recalculations

The recalculation of the *land converted to cropland* time series is presented in Table 6.5.7, and an explanation of the key influences on the change in estimates follows:

A. Refinements to crop and grass sub-models in FullCAM

Significant improvements have been made to the way the FullCAM model reflects climate impacts on crop and grass production and soil carbon. This is described in more detail in Chapters 6.5.1.5 and 6.6.1.5.

B. FullCAM database and parameter updates including for croplands and grasslands

Refinements have been made to a range of parameters used in FullCAM, including updates to grazing pressure, crop and grass regimes and crop yield tables. These are outlined in further detail in Chapters 6.5.1.5 and 6.6.1.5.

C. Activity data updates

Activity data updates implemented in this submission include addition of:

- activity data and climate data covering 2021–22; and
- annual updates to spatial datasets (Woody Change, Plantation Type, Fire time series and Base Land Use spatial layers) based on recent satellite observations

Table 6.5.7 Land converted to cropland: Recalculation of CO$_2$-e emissions (kt)

	2023 submission	2024 submission	Change	Reasons for recalculation (Kt CO$_2$-e)		
Year	**(kt CO$_2$-e)**	**(kt CO$_2$-e)**	**(kt CO$_2$-e)**	**A**	**B**	**C**
1989-90	18,570	17,450	-1,120	-917	-56	-147
1994-95	5,812	5,149	-663	-732	28	41
1999-00	4,309	3,104	-1,205	-1,115	-164	74
2004-05	4,195	3,297	-898	-952	68	-14
2005-06	5,413	6,512	1,099	1,432	-252	-81
2006-07	3,698	3,225	-473	-544	79	-9
2007-08	3,884	3,164	-720	-564	-79	-76
2008-09	3,554	2,326	-1,227	-1,046	-240	58
2009-10	3,285	3,439	154	130	55	-31
2010-11	3,864	3,333	-530	-418	-51	-61
2011-12	723	-2,007	-2,729	-2,581	-243	95
2012-13	4,181	6,347	2,167	2,235	43	-112
2013-14	3,564	3,717	153	225	9	-81
2014-15	2,916	3,627	711	926	-92	-123
2015-16	1,788	1,484	-304	-478	81	93
2016-17	1,821	1,656	-165	-188	53	-30
2017-18	995	106	-889	-775	-103	-11
2018-19	2,383	2,161	-222	-87	-189	54
2019-20	1,547	1,232	-314	-269	97	-142
2020-21	1,802	1,746	-57	-121	-10	74

6.5.2.6 Category-specific planned improvements

Please see Chapter 6.6.2.6 for planned improvements for the subcategory *forest land converted to grassland* which are directly relevant to *forest land converted to cropland.*

Future work will also build on the current spatial and temporal analysis of the relevant activities involved in wetland to cropland conversions, and better resolve the distribution of associated organic and mineral hydrosols. This will improve the stratification of the model and therefore the calculation of the regional emission factors applied.

6.6 **Grassland** (CRT category 4.C)

6.6.1 Grassland Remaining Grassland

6.6.1.1 Category description

The *grassland remaining grassland* category includes all areas of *grassland* that are not reported under *land converted to grassland.* Areas that are in rotational use between *grassland* and *cropland* are reported under either *forest land converted to cropland* or *cropland remaining cropland.*

Anthropogenic emissions and removals on grasslands result from changes in management practices on grasslands, particularly from changes in pasture and grazing; changes in savanna fire management practices; and changes in sparse woody vegetation that do not meet the definition of a forest. *Grassland remaining grassland* is reported in three components which align with each of these practices.

Permanent changes in management practices generate changes in the levels of soil carbon or woody biomass stocks over the longer term. As changes occur, carbon may be released as emissions or sequestered to the landscape. These impacts are transitory and are not permanent. After a time, the rate of net emissions or removals associated with the changed management practice will approach an equilibrium of approximately zero emissions until disturbed by another change in management practices.

The distribution of land areas in the *grassland remaining grassland* sub-category is estimated using the ABARES Catchment Scale Land Use of Australia 2017 at the mapping scale of 1:5000 to 1:250 000. The presence of sparse woody vegetation is identified from the remote sensing program (Annex 5.6.1).

Emission estimates for the components of *grassland remaining grassland* are reported in Table 6.6.1.

Table 6.6.1 Emissions and removals from grassland remaining grassland, by sub-category (kt CO_2-e)

	Herbaceous grasslands	Perennial woody biomass		
Year	Soil Carbon and Nitrogen mineralisation and run-off	Sparse Transitions	Savanna fire	Total
1989-90	-9,544	-3,085	8,207	-4,422
1994-95	-13,881	646	15,191	1,956
1999-00	-9,524	1,252	21,872	13,599
2004-05	6,845	2,839	7,120	16,804
2005-06	10,448	2,624	17,835	30,907
2006-07	3,538	2,549	16,691	22,778
2007-08	-2,237	1,831	7,822	7,416
2008-09	1,733	-581	10,937	12,088
2009-10	5,160	-2,740	6,338	8,758
2010-11	5,162	-4,574	4,205	4,794
2011-12	-408	-5,701	3,041	-3,068
2012-13	-3,673	-5,244	5,005	-3,912
2013-14	-1,370	-5,128	7,460	963
2014-15	878	-4,455	4,443	866
2015-16	1,544	-4,217	140	-2,533
2016-17	5,884	-4,190	2,515	4,208
2017-18	3,184	-4,242	-1,315	-2,373
2018-19	-6,233	-4,229	-1,673	-12,135
2019-20	-9,799	-4,382	-698	-14,880
2020-21	-13,710	-4,867	-590	-19,167
2021-22	-12,104	-5,227	590	-16,741

6.6.1.2 Methodological issues

Herbaceous Grasslands

Emissions and removals for herbaceous grasslands component are estimated using spatial simulations in the FullCAM framework.

Anthropogenic emissions and removals from grasslands are estimated from changes in specified management practices including:

- the area under grasslands;
- the area under grazing and changes in grazing intensity;
- woody biomass management; and
- fire management.

FullCAM estimates emissions from all on-site carbon pools (living biomass, dead organic matter (DOM) and soil). For the herbaceous grass component only the changes in the soil pool are reported. Carbon stock changes from living biomass and DOM of non-woody annual crops are reported to be zero, consistent with the guidance in *2006 IPCC Guidelines* (IPCC 2006) that indicates that the increase in biomass stocks in a single year may be assumed equal to biomass losses from harvest and mortality in that year – thus there is no net accumulation of biomass carbon stocks for non-woody biomass over the long term.

There are two main agro-ecological categories in grasslands:

- native arid grasslands which may include sparse woody vegetation and woodlands, and remain as primarily native grasses; and
- high-rainfall improved pastures.

The key management practices relevant to estimating changes in carbon stocks in the high rainfall pastures include: grazing intensity; and pasture composition. For the native arid and semi-arid grasslands, the key drivers include grazing intensity, fire management and the presence of woody vegetation.

Stratification of grasslands is undertaken based on climate and vegetation type. For the high rainfall pastoral regions, where cropping also occurs, the impacts of pasture composition and grazing have been modelled (Annex 5.6.5). In the arid rangelands areas it is assumed that these lands have remained native pastures and as such no stock changes are identified on these lands.

Initial soil carbon values are taken from the baseline map of soil organic carbon (R. Viscarra Rossel, C. Chen, et al. 2015). Management practice change has been monitored in the ABS Land Management and Farming (ABS 2017) which provides information on management practices being adopted and utilised by Australian agricultural business.

Grazing pressure for each ABS Statistical Area 2 region across Australia is derived from the ABS Commodity Statistics. Published beef cattle, dairy cattle, and sheep population and age data from the Australian Bureau of Statistics Agriculture Commodities (ABS 2022) are used to derive average feed amounts for these livestock types. This data is combined to calculate the grazing pressure for each statistical area 2 (SA2) which is then inserted into FullCAM as a fraction of standing dry matter eaten (t/ha) relative to the amount of dry matter produced (t/ha) each day across grassland areas. For *croplands* the managed grazing method is applied to pasture lands in a crop rotation.

Figure 6.6.1 Grazing pressure by animal type Australia

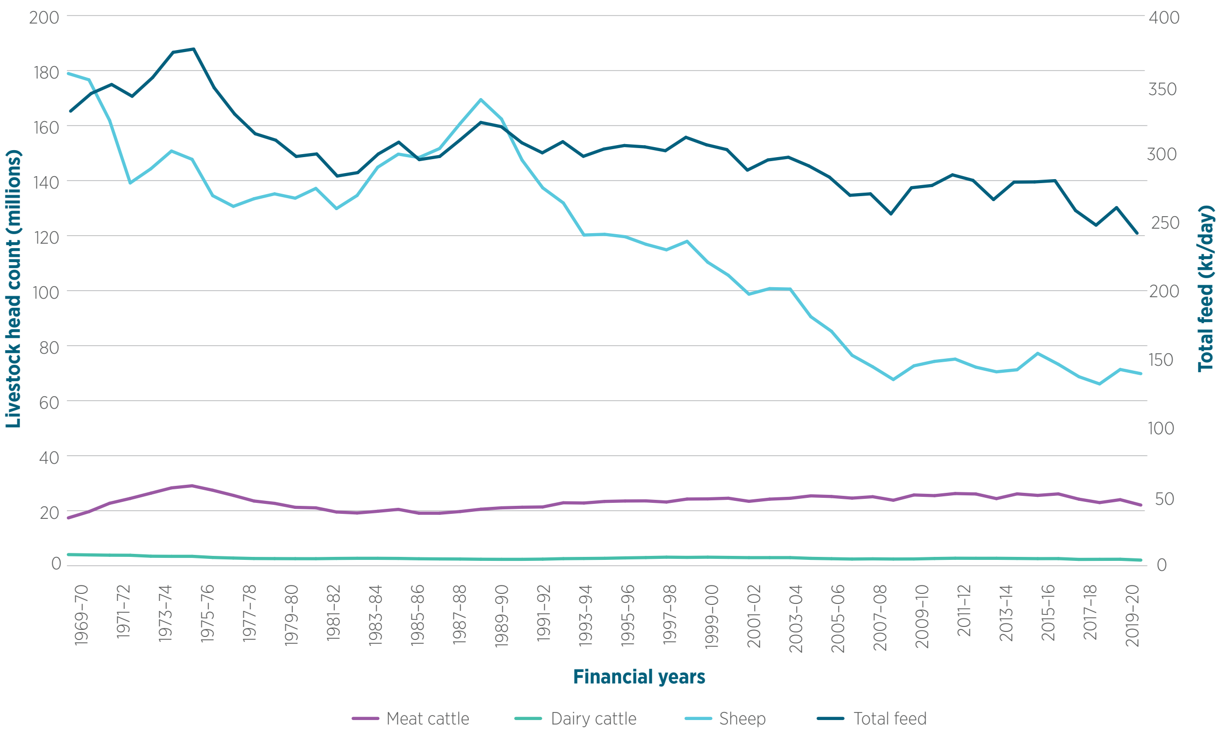


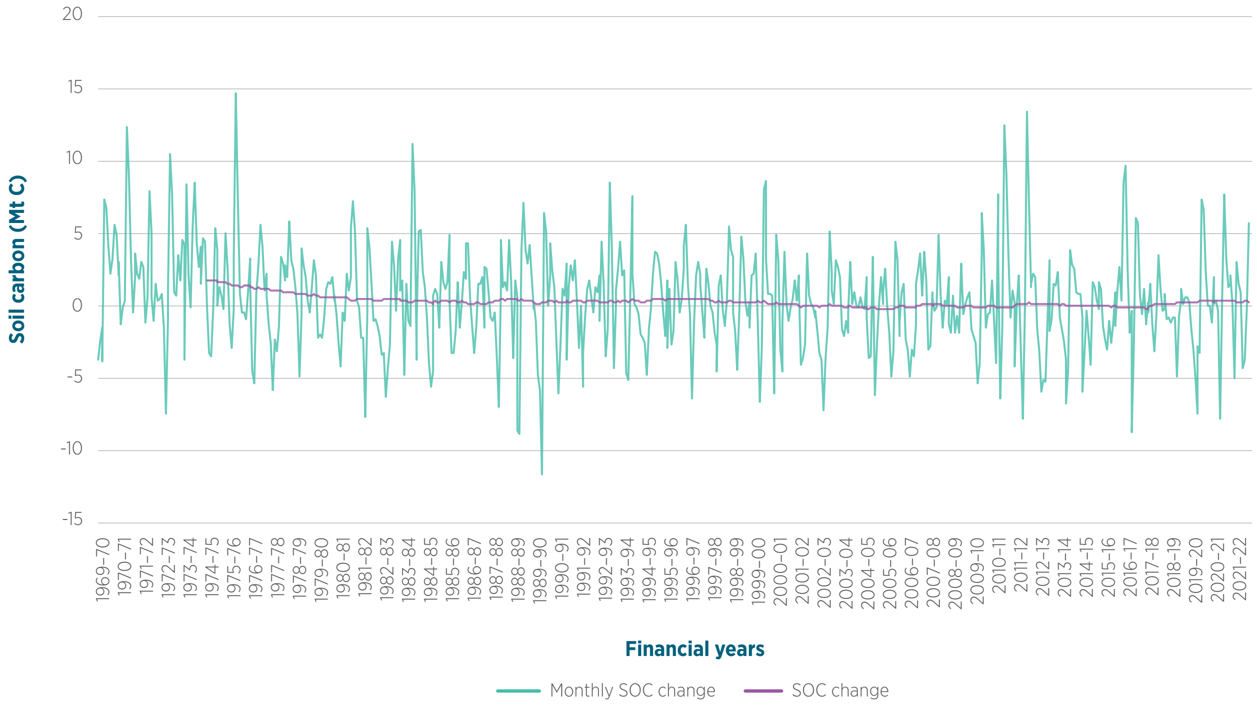
Figure 6.6.2 shows the spatial distribution and levels of biomass eaten.

Figure 6.6.2 Livestock grazing pressure levels for Australia (2021–22) at the SA2 level

Additional details on data sources and changes in management practices are provided in Annex 5.6.5.

The estimation of emissions from soil carbon from *grassland remaining grassland* (Figure 6.6.3) is modelled in the same way as for *cropland remaining cropland.* See the discussion on the methodology for herbaceous crops in Chapter 6.5.1.2.

Figure 6.6.3 Monthly carbon stock change from grassland remaining grassland



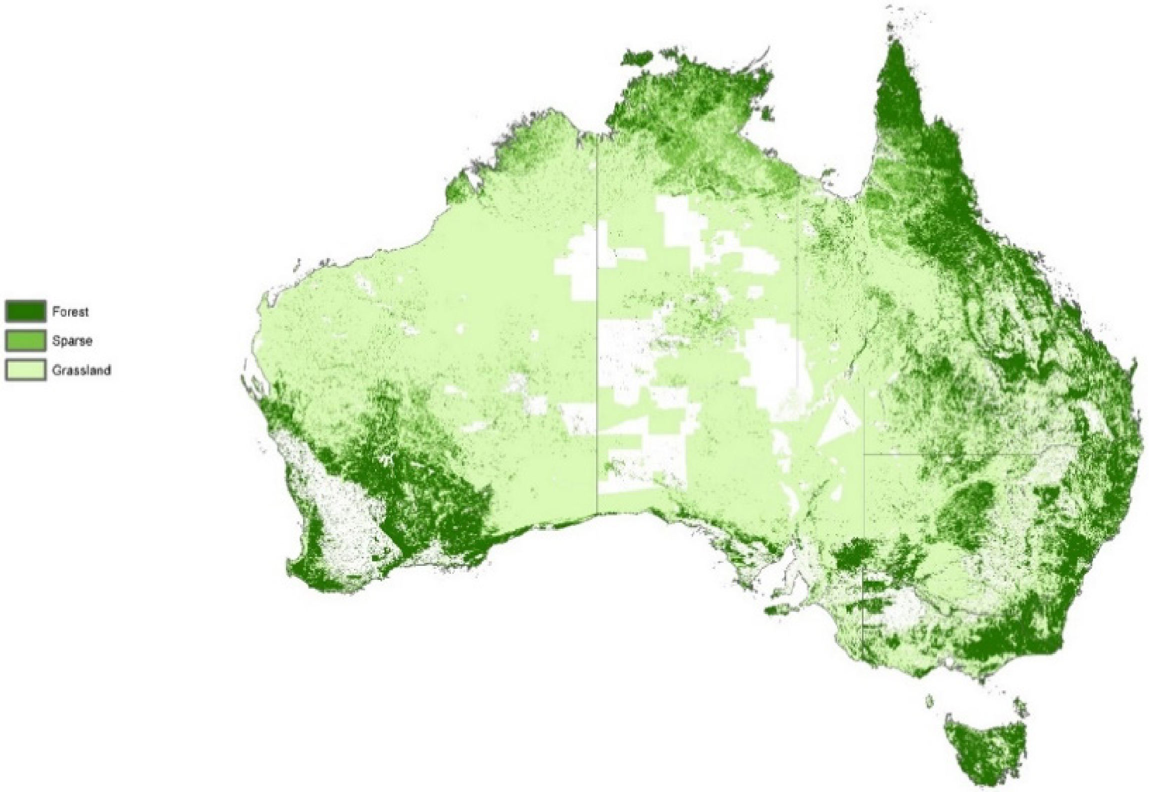
Sparse woody vegetation

Landsat TM, ETM+ and OLI data for the years from 1988 to 2022 (Caccetta and Furby 2004) are used to detect and map 3 land cover classes for woody vegetation: non-woody (<5% cover), sparse woody vegetation cover (5 per cent to <20 per cent canopy cover) and the forest cover (>20 per cent canopy cover). Figure 6.6.4 shows the extent of sparse vegetation in Australia as distinct from forest vegetation.

Data on sparse woody vegetation extends for the period since 1988. For the period 1970-1985, the net gain in area of sparse woody vegetation has been back-cast using the El Nino Southern Oscillation index (Bureau of Meteorology) as a proxy variable.

To estimate the change in woody biomass due to the change in sparsely woody areas, the net annual change in area was placed in a Tier 2 model. The model uses an average woody biomass of 10 t DM ha^{-1} (Raison et al. 2003) and where vegetation cover is observed to have been lost it presumes a linear loss of that amount over a period of 20 years. Where the area of sparse vegetation increases it is assumed that these will regrow to 10 t DM ha^{-1} over twenty years (i.e. a growth rate of 0.5 t DM ha^{-1} yr^{-1}) (Fensham, Fairfax and Dwyer 2012) and (Witt, et al. 2011).

Figure 6.6.4 Extent of forest and sparse woody vegetation



Savanna Fire

Emissions and removals on *grasslands remaining grasslands* associated with the burning and subsequent regrowth of biomass and debris are modelled using the same methods, factors and data as described in Chapter 6.3.2.

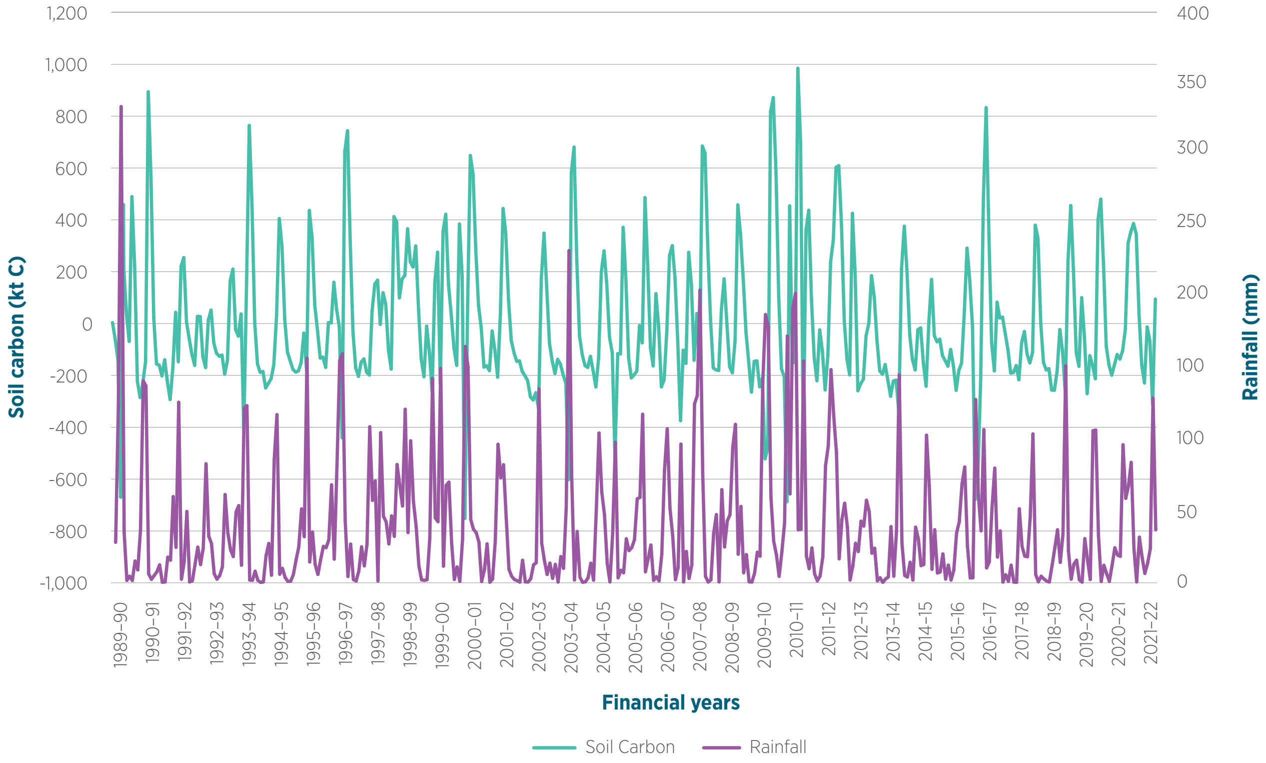
6.6.1.3 Uncertainty assessment and time-series consistency

Based on a qualitative assessment the uncertainties for *grassland remaining grassland* were estimated to be medium. Further details are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to methodology.

6.6.1.4 Category-specific QA/QC and verification

The impact of climate data on soil carbon change in pasture lands as simulated in FullCAM has been analysed to assure consistency with modelling expectations. The climate inputs (temperature, rainfall and open-pan evaporation) for selected regions and states have been verified against model outputs. An example of this is shown below in Figure 6.6.5 where soil carbon increases align with periods of increased rainfall.

Figure 6.6.5 Barcaldine SA2 region, soil carbon stock change charted against rainfall inputs in FullCAM



The QC of the activity data for detecting gains and losses of woody vegetation is described in Annex 5.6.1.4.

The savanna fire activity data is collated and quality assured by the Western Australian Land Authority (Landgate) before being used in emissions estimation.

6.6.1.5 Category-specific recalculations

Table 6.6.2 below provides the recalculation results, including reasons and quantified impacts.

A. Refinements to crop and grass sub-models in FullCAM

Changes to FullCAM this year include the revision of yield model. Yield response to rainfall has been revised through improvements to the water balance sub-model used in calculation of yields. Significant changes were made to the handling of grasses this year. Perennial grass handling has been modified so that yields are provided as a monthly growth increment, rather than a total standing dry matter mass. The die off component has been removed and FullCAM now handles removal of turnover at each time step. Annual grass growth was also modified to accept input yields as monthly growth increments rather than a single yearly value; this captured better the pasture growth and its response to climate. This aligns both perennial and annual grass growth, the major difference now being their growth periods: multiple years for perennial grasses and 9–12 months for annuals. Minor modifications were also made to the handling of turnover, which is included in growth increments.

B. FullCAM database and parameter updates including for croplands and grasslands

Updates and refinements were made to a range of parameters used in FullCAM, including updates to grazing pressure, crop and grass regimes and crop yield tables. Grazing pressure tables now reflect revised yields. Grazing is handled as a fraction of the crop mass. Annual grasses regimes were modified so the growth season is a minimum of 9 months to better reflect trends in annual pasture cultivations. Crop and grass yield tables were updated according to the revised yield.

Minor enhancements have also been made to the grass productivity parameters in the Savanna fire model.

C. Activity data updates

Activity data updates implemented in this submission include addition of:

- activity data and climate data covering 2021–22; and
- annual updates to spatial datasets (Woody Change, Plantation Type, Fire time series and Land Use spatial layers) based on recent satellite observations.

New activity data for the year 2021–22 affects the mean incremental value in earlier years for soil carbon stock change between steady states. La-Nina conditions in 2021-22 resulted in higher soil carbon accumulation.

D. N-leaching and N-mineralisation due to loss of soil carbon

Recalculations for soil carbon due to A-C lead to a recalculation of nitrogen leaching and N_2O emissions from N-mineralisation due to loss of soil carbon.

Table 6.6.2 Grassland remaining grassland: Recalculation of CO_2 emissions

	2023 submission	2024 submission	Change	Reasons for recalculation (kt CO_2-e)			
	(kt CO_2-e)	(kt CO_2-e)	(kt CO_2-e)	A	B	C	D
1989-90	5,758	-4,422	-10,180	-11,276	201	958	-62
1994-95	-6,203	1,956	8,159	8,719	-1,065	554	-49
1999-00	5,542	13,599	8,057	9,465	-1,780	380	-8
2004-05	14,749	16,804	2,055	1,524	458	218	-145
2005-06	21,811	30,907	9,097	9,515	-585	152	15
2006-07	20,301	22,778	2,477	5,762	-3,718	495	-62
2007-08	16,756	7,416	-9,340	-5,114	-4,589	602	-240
2008-09	22,991	12,088	-10,902	-10,205	-1,006	641	-333
2009-10	11,430	8,758	-2,672	-2,865	-268	676	-217
2010-11	7,289	4,794	-2,496	-3,904	876	740	-209
2011-12	11,116	-3,068	-14,185	-10,714	-3,866	819	-424
2012-13	6,544	-3,912	-10,457	-10,870	-335	966	-218
2013-14	8,463	963	-7,501	-10,371	1,920	1,027	-78
2014-15	6,927	866	-6,061	-7,913	851	1,081	-81
2015-16	-2,084	-2,533	-449	-1,793	135	1,259	-50
2016-17	-5,992	4,208	10,200	6,763	1,531	1,845	62
2017-18	-3,516	-2,373	1,143	-149	2,661	-1,372	3
2018-19	-6,854	-12,135	-5,281	-3,055	2,104	-4,229	-101
2019-20	-4,224	-14,880	-10,656	-7,582	1,703	-4,616	-161
2020-21	-1,230	-19,167	-17,937	-14,694	616	-3,560	-300

6.6.1.6 Category-specific planned improvements

Planned developments for the grasslands soil carbon model include how FullCAM handles grass growth and grazing, including spatialisation of grass yields. and improvements to the grazing pressure mechanism.

6.6.2 Land converted to grassland

6.6.2.1 Category description

Within the *land converted to grassland* subcategory, Australia reports emissions for *forest land converted to grassland* and *wetlands converted to grassland* subcategories. Net emissions from conversions between croplands and grasslands are included in *croplands remaining croplands* as it is common for cropping systems to include pasture/grazing rotations.

The activity data for forest conversions is drawn from the spatial monitoring program (Annex 5.6.1) and is dominated by the land clearing practices which occur in Australia. Where regrowth is identified, the land is transferred to the *land converted to forest land* category. Cyclical activity of regrowth and re-clearing is common in some parts of Australia, and so parcels of land can frequently move between these reporting categories. Over time, the clearing of primary forest with high carbon stocks has become less prevalent, reducing the emissions from this category. Around 88 per cent of clearing activity in 2021–22 was re-clearing of secondary forests on land that has been cleared previously, where graziers are maintaining pasture. Around three quarters of this is regrowth less than 10 years old, which stores far less carbon than primary forests, resulting in lower emissions when it is cleared.

The net emissions associated with fires or with harvesting of forest for timber are reported under *forest land remaining forest land* (as neither fire nor harvesting constitute a permanent land use change), unless a subsequent land use change or permanent loss of forest cover is identified.

The net emissions associated with the removal of orchards are reported under *cropland remaining cropland.* Orchards are not defined as forests in the Australian inventory. Net emissions from the clearing of sparse woody vegetation are reported under *grassland remaining grassland.*

Areas of *Wetlands converted to grassland* were estimated for each State and Territory using IPCC Approach 2 and based on land use data from the 1996 and 2010 Land use of Australia surveys (BRS, n.d., (ABARES 2016)). Conversions involved both mineral and organic hydrosols.

Emission estimates for the components of *land converted to grassland* are reported in Table 6.6.3.

Table 6.6.3 Net emissions and removals from land converted to grassland sub-categories, kt CO_2-e

Year	Forest land converted to grassland	Wetlands converted to grassland	All
1989-90	147,337	466	147,803
1994-95	64,391	466	64,857
1999-00	66,283	466	66,749
2004-05	82,676	466	83,142
2005-06	94,227	466	94,693
2006-07	76,144	466	76,610
2007-08	66,006	466	66,473
2008-09	46,093	466	46,559
2009-10	52,658	466	53,124
2010-11	35,281	466	35,747
2011-12	30,549	466	31,015
2012-13	44,927	466	45,393
2013-14	47,774	466	48,240
2014-15	36,929	466	37,395
2015-16	23,604	466	24,070
2016-17	45,434	466	45,901
2017-18	37,592	466	38,058
2018-19	23,163	466	23,629
2019-20	35,176	466	35,643
2020-21	17,820	466	18,286
2021-22	6,208	466	6,674

6.6.2.2 Methodological issues

Forest land converted to grassland

Emissions and removals from *forest land converted to grassland* (and *other land uses)* are estimated using the Approach 3, Tier 3 Full Carbon Accounting Model (FullCAM) as described in Annex 5.6.2. The reporting includes all carbon pools (living biomass, dead organic matter (DOM) and soil) other than the agricultural debris of perennial grasses. The model runs in a mixed configuration (i.e., both forest and agricultural systems) using the *CAMFor, CAMAg* and *Roth-C* sub-models. Table 6.6.4 below shows the FullCAM configuration for modelling emissions and removals for this sub-category.

N_2O emissions from disturbance associated with land-use conversion to cropland and grassland are estimated using the methods described in Chapter 6.13.

Table 6.6.4 FullCAM configuration used for the forest land converted to cropland and forest land converted to grassland sub-categories

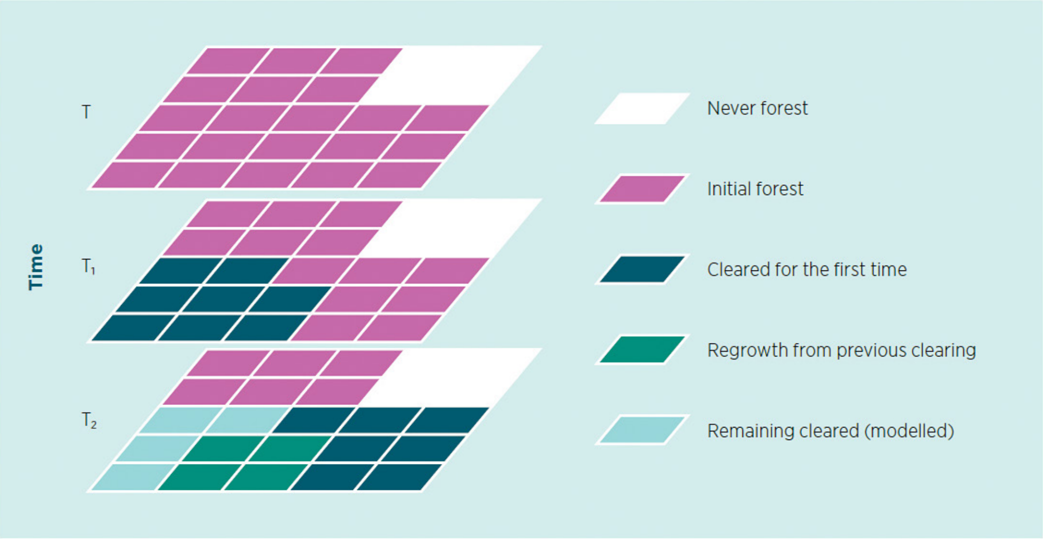
Component	Forest	Agriculture
Living biomass	CAMFor – Forest Productivity Index and Tree Yield Formula	CAMAg – Crop and pasture growth sub-models
Dead organic matter	CAMFor	CAMAg
Soil carbon	Roth-C	Roth-C
Offsite products	NA	NA

Entry of lands into forest land converted to grassland

The fundamental analytic unit of Tier 3, Approach 3 land sector reporting in Australia is the land cover change pixel (25 m x 25 m) derived from the satellite remote sensing programme. Beginning in 1971-72, forest clearing and regrowth events are detected through the remote sensing programme.

In interpreting pixels and events (Figure 6.6.6), the first class of forest pixel is 'initial forest' (pink). This means that the forest cover has not been subject to a forest clearing event since before 1971-72 and is categorised as *forest land remaining forest land.* The second class of forest pixel is 'cleared for the first time'. This means that the forest on that pixel has undergone a forest clearing event in the current year (T1, dark blue). These pixels become categorised as forest converted to grasslands, cropland, settlements or wetland (flooded land) depending on the land use at that location. FullCAM simulations are initiated to calculate the emissions and removals on that pixel from the moment that the pixel is observed to have a clearing event and the tracking continues each year into the future (T2, light blue and green). These active pixels may remain cleared (light blue) or may temporarily regrow some forest cover as part of a cyclic clearing/re-clearing management system (green). Where forest regrowth is identified, the pixel will be re-categorised as *land converted to forest* for as long as the forest continues to be observed on the pixel.

Figure 6.6.6 Diagram representing the spatially explicit approach for estimating forest land conversion sub-categories



Modelling emissions and removals

Once lands enter the conversion category through a forest clearing event, based on activity data, FullCAM:

- Randomly allocates a date of clearing between the two dates of satellite images;
- Obtains site, climate, management and initial assumed biomass data (see Annexes 5.6.2 to 5.6.5) for that pixel from a series of spatial grids and databases;
- Begins to model changes in living biomass, debris and soil carbon pools associated with the change in forest cover; and
- Sums the estimates for each pixel each year to estimate the emission/removals.

Where the forest has regrown after clearing as identified from the remote sensing, FullCAM begins to model forest regrowth using the same databases and systems as used for native vegetation in *land converted to forest.*

Where this regrowth is subsequently re-cleared, the biomass at re-clearing is based on what has been modelled to have accumulated at the individual pixel level based on that pixel's history, including site conditions and climate over the period of forest growth. The emissions associated with the re-clearing along with the subsequent emissions and removals on the converted land, including those associated with the decay of DOM and soil carbon, are reported under the *grassland* sub-category.

After 50 years, these forest conversion lands and their associated emissions/removals will be reallocated to the sub-categories for land remaining within its land use.

Estimating changes in carbon stocks

The ratios used to partition biomass to the different tree components are drawn from a synthesis of available data compiled by (Paul and Roxburgh 2017), with this partitioning varying as the stand matures, and being different for different forest types based on their typical productivity.

Table 6.6.5 Partitioning of biomass between the tree components under different rainfall zones. Estimates are for mature stands of assumed stand age 100 years

	Fraction of biomass allocated to:					
Rainfall zone	Stems	Branches	Bark	Leaves	Coarse Roots	Fine Roots
>500mm	0.49	0.11	0.09	0.04	0.24	0.03
<500mm	0.28	0.22	0.08	0.07	0.27	0.08

The carbon content of various tree components are drawn from an analysis of a range of species across a range of environments by Gifford (2000a) and (2000b).

Table 6.6.6 Carbon content of tree components – forest conversion categories

Tree Component	Carbon Content (fraction of dry matter)
Stems	0.50
Branches	0.47
Bark	0.49
Leaves and Twigs	0.52
Coarse Roots	0.50
Fine Roots	0.48

Turnover rates impact predictions of inputs to DOM under regenerating forests. But under simulations of both permanently cleared and regenerated forests, decomposition of DOM will be important. The rates of turnover and decomposition are based on a review by Paul et al. (2017).

Table 6.6.7 Tree component turnover rates

Tree component	Turnover % per month
Branches	0.74
Bark	0.41
Leaves (rainfall >500mm)	2.96
Leaves (rainfall <500mm)	1.28
Coarse Roots	0.87
Fine Roots	12.55

Table 6.6.8 Decomposition rates for standing dead pools used in the forests model

Standing Dead component	Breakdown % per month
Stems, branches and coarse roots	0.83
Bark	1.25
Leaves and fine roots	1.67

Table 6.6.9 Decomposition rates for debris pools used in the forests model

Debris component	Breakdown % per month
Deadwood	1.25
Bark litter	1.44
Leaf litter, decomposable*	81.20
Leaf litter, resistant*	2.70
Coarse dead roots	2.93
Fine dead roots	81.20

* The fraction of leaf litter that was resistant was 77 per cent.

For each major vegetation group (MVG), initial pools of debris just prior to clearing are based on equilibrium simulations of mature forests, with these simulations being undertaken in regions which typify their productivity. Post-clearing, the pools of live biomass are transferred to the DOM pools.

The principal methods of forest conversion involve the extraction of root material (e.g., tree pulling) to allow for subsequent cultivation for pasture and cropping. Tree pulling usually involves forming 'wind rows' for subsequent burning. Burning of wind rows follows a period of curing (drying), but combustion is still not always complete. FullCAM has been developed to accommodate these processes by implementing a delayed burning, with subsequent decomposition of residual material remaining post-burn. The residual decomposing pool is 'standing dead' of relatively slow decomposition rates (Paul and Roxburgh, 2018b). The standing dead residues burnt is set at 98 per cent, leaving 2 per cent to subsequently decompose on-site. The predictions of post-clearing residues draws upon work by (Murphy, et al. 2002); (Griffin, Verboom and Allen 2002); (Harms and Dalal 2003); (Harms, Dalal and Cramp 2005) and (Mackensen and Bauhus 1999). Of residues burnt post-clearing, combustion efficiencies were set at 90% for deadwood, 95 per cent for bark, 95 per cent for leaf litter, 80 per cent for coarse dead roots, and 70% for fine roots (Paul and Roxburgh 2018b).

A full description of the soil carbon model *(Roth-C)* and the parameterisation of the model are provided in Annex 5.6.2. Parameters governing the input of carbon to the soil following the decomposition of DOM are the fractions of decomposed DOM that is lost as CO_2 to the atmosphere (CO_2-C). The remaining decomposed DOM that is not lost as CO_2-C is predicted to enter the pools of soil C. Values for these parameters calibrated using forest soil carbon studies as described by Paul et al. (2017).

Fires

Carbon dioxide emissions from on-site burning associated with land conversion are estimated using FullCAM and are reported for *forest land converted to cropland, to grassland, to settlements* and *to wetlands (flooded land).* The mass of carbon burnt annually (FC_{jk}) is a FullCAM output and CO_2 emissions associated with biomass burning are therefore included in carbon stock changes, however this FullCAM output is also used to estimate the non-CO_2 gases reported for biomass burning (controlled burning).

There are no direct measurements of trace gas emissions from the burning of cleared vegetation in Australia. However, it is considered that these fires will have similar characteristics to hot prescribed fires and wildfires (Hurst and Cook 1996).

The algorithms for total annual emissions of CH_4, CO and NMVOCs are:

$$E_{ijk}\ FC_{jk}\ EF_{ijk}\ C_{i} \qquad (6.6.1)$$

and for total annual emissions for N_2O and NO_x are:

$$E_{ijk} = FC_{jk} * NC_{jk} * EF_{ijk} * C_{i} \qquad (6.6.2)$$

Where FC_{jk} = annual fuel carbon burnt in land conversion (kt),
EF_{ijk} = emission factor for gas i from vegetation (Tables A5.6.11.10-12),
NC_{jk} = nitrogen to carbon ratio in biomass (Annex 5.6.11.9)
C = factor to convert from elemental mass of gas species i to molecular mass (Annex 5.6.11.9).

Carbon dioxide emissions and removals associated with the burning and subsequent regrowth of savanna grasslands which occur on *land converted to grassland* are included in reporting and are estimated consistent with the methods described in Chapter 6.3.2.

Wetlands converted to grassland

The methodology for activity data collection and modelling of emissions and removals is similar to that underpinning estimates for *wetlands converted to croplands* as described in Chapter 6.5.2.2. This includes an equivalent analysis of activity data involving wetlands on organic and mineral soils and the use of EF values appropriate to the climate zones in which the conversions occurred.

Expert opinion provided by C. Meyer (personal communication, 2019) identified 4,000 ha of histosols associated with cropping or grazing in Queensland and Victoria, based on the CSIRO Australian Soil Classification System (Isbell 2002) . Wetland transitions recorded elsewhere were considered to involve mineral soils only.

Annual changes in carbon stocks for mineral soils were derived based on climate zone and applied to their respective states to estimate annual emissions:

- Queensland/Northern Territory: 2.12963 tonnes C / ha / year,
- Tasmania: 0.882 tonnes C / ha / year,
- All other States/Territories: 2.7375 tonnes C / ha / year.

Conversions involving organic soils are reported for Queensland and Victoria, which are in the tropical and temperate climate zones respectively. The annual emission factors for drained grassland organic soils in tropical and temperate climate zones are 9.6 and 6.1 tonnes of carbon per hectare per year ((IPCC 2013), Table 2.1). Emissions from each state and territory were calculated, based on area, and then aggregated to give the annual national totals for both.

Activity data

The activity data for the *forest land converted to grassland* classification is drawn from the remote sensing program (see Annex 5.6.1), and that for the *wetlands converted to grassland* classification comes from the 1996 and 2010 Land use of Australia surveys to which extrapolation and interpolation methods were applied to calculate an average annual rate of conversion. Table 6.6.10 shows cumulative areas for *land converted to grassland* over the period since remote sensing commenced in 1971-72.

Table 6.6.10 Cumulative area of land converted to grassland, kha

Year	Forest land converted to grassland	Wetlands converted to grassland	Total
1989-90	6,885	49	6,934
1994-95	8,720	49	8,769
1999-00	10,378	49	10,427
2004-05	12,580	49	12,629
2005-06	13,004	49	13,053
2006-07	13,370	49	13,418
2007-08	13,554	49	13,603
2008-09	13,567	49	13,615
2009-10	13,479	49	13,528
2010-11	13,405	49	13,454
2011-12	13,366	49	13,415
2012-13	13,360	49	13,409
2013-14	13,332	49	13,381
2014-15	13,231	49	13,280
2015-16	13,216	49	13,265
2016-17	13,231	49	13,279
2017-18	13,377	49	13,426
2018-19	13,492	49	13,541
2019-20	13,592	49	13,641
2020-21	13,660	49	13,709
2021-22	13,470	49	13,519

6.6.2.3 Uncertainty assessment and time-series consistency

Uncertainties for *forest land converted to grassland* at the national scale were estimated to be ±27.3 per cent for CO_2. Further details are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to the methodology.

The current Tier 1 method for *wetlands converted to grassland* relies on interpolation and extrapolation with respect to two observational years. ABARES does not report on uncertainty about the land use estimates. However, these are likely to fall in the medium to high range.

While there is a higher uncertainty in *wetlands converted to grassland* than in *forest land converted to grassland,* the former category makes only a small contribution to the overall uncertainty of *land converted to grassland* due to its lower emissions.

6.6.2.4 Category-specific QA/QC and verification

The QA/QC process includes an overview of the top-level trends in emissions, broken down by jurisdiction, examining their consistency with trends in previous submission reports and reasons for any deviations.

Verification of area of forest clearing estimates

In accordance with the recommendations of an independent review of forest clearing estimates (Federici 2016b), quality control processes were established to compare the remote sensing-based forest change data used in the inventory to similar information published by the Queensland Department of Environment and Science (DES) in order to verify the quality of the remote sensing programme. As reported in Annex 5.6.1, the annual monitoring data from Queensland and NSW Statewide Landcover and Trees Study is also used as an input into the identification and attribution of forests converted to other land uses.

Validation and updates to biomass estimates using empirical data

Following on from a verification study undertaken in 2016 (S. Roxburgh, K. Paul and R. Lucas, et al. 2016), CSIRO scientists have utilised a collation of approximately 6,000 new empirical biomass datapoints to update FullCAM's M layer to fine tune the accuracy of predicting biomass, particularly in tall temperate forests (Roxburgh, Karunaratne, et al. 2017). The simulation of above-ground forest biomass in FullCAM is based on an empirical relationship between model-predicted forest growth (the Forest Productivity Index or FPI) and observations of biomass collected from minimally disturbed stands. This relationship is used to predict M – the maximum attainable site above-ground biomass. In the update by Roxburgh et al. (2019), the original calibration database was augmented with forest biomass observations from the TERN/AusCover National Biomass Library (See Appendix 6.D for details the latest validation and fine-tuning of FullCAM). Further information on FullCAM, along with the associated quality assurance and quality control program, are in Annex 5.6.

Verification using Tier 2 model

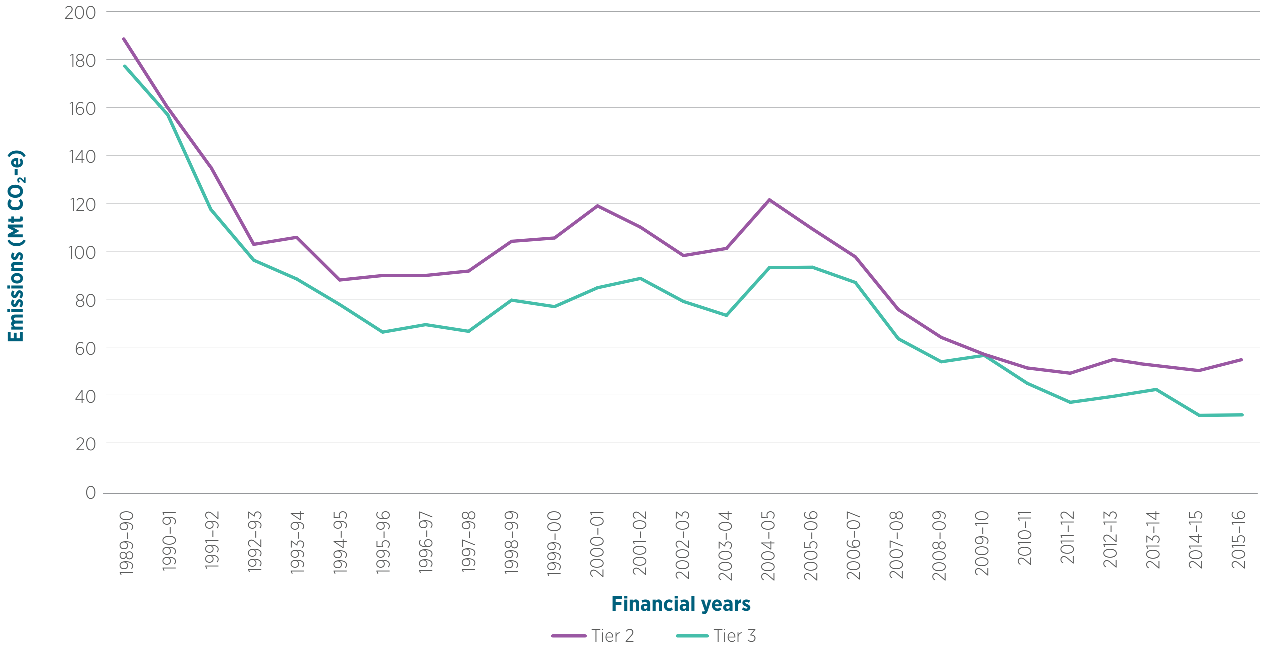
In past submissions, verification of the Tier 3 based emission estimates from this sub-category was performed through comparison with a Tier 2, Approach 2 method (described in Appendix 5.6.8). The Tier 2 method is a spreadsheet model based on country specific biomass data for three broad ecosystem types and uses the areas from the remote sensing analysis, applied using an Approach 2 method (i.e., not fully spatially explicit). The model includes all carbon pools (living biomass, DOM and soil) and emissions from fire.

The results from the two models have been largely consistent and followed a similar trend since 1989-90 (Figure 6.6.7). The emissions output has not varied substantially between the Tier 2 and Tier 3 models; however, the discrepancies between the two model approaches can be explained further.

The Tier 2 method uses country-specific coefficients for three regions differentiated by vegetation class to estimate emissions and removals from deforestation (land use change). It standardises the biophysical (soil, climate, etc.) environment, and hence forest productivity, across Australia. That is, the Tier 2 model does not encompass the finely disaggregated spatial variability relating to soil types (and their characteristics) and climate variability (particularly rainfall) which would have an effect on emission levels. As such, CO_2 emissions and removals could be overestimated or underestimated. The Tier 3, Approach 3 method is spatially explicit, operates at a fine scale (25 m) and incorporates the variability of the biophysical environment (climate and soil) across Australia.

This therefore includes the effects of climate, better represents regrowth and re-clearing cycles and varies emissions based on the site characteristics of the land subject to clearing.

Figure 6.6.7 Emissions from forest land converted to cropland and grassland output from Tier 2 and Tier 3 methodology from 1989–90 to 2015–16



Quality assurance/quality control measures for *wetlands converted to grassland* involve internal reviews of data entry and model outputs, including a check on the consistency of land use statistics across Australian jurisdictions.

6.6.2.5 Category-specific recalculations

Table 6.6.11 shows the overall size of the recalculations applicable to *land converted to grassland and* includes a break-down of the contributions by the main factors influencing these changes.

A. Refinements to crop and grass sub-models in FullCAM

Significant improvements have been made to the way the FullCAM model reflects climate impacts on crop and grass production and soil carbon. This is described in more detail in Chapters 6.5.1.5 and 6.6.1.5.

B. FullCAM database and parameter updates including for croplands and grasslands

Refinements have been made to a range of parameters used in FullCAM, including updates to grazing pressure, crop and grass regimes and crop yield tables, as well as minor enhancements including for implementation of savanna fire model parameters. These are outlined in further detail in Chapters 6.5.1.5 and 6.6.1.5.

C. Activity data updates

Activity data updates implemented in this submission include addition of:

- activity data and climate data covering 2021–22; and
- annual updates to spatial datasets (Woody Change, Plantation Type, Fire time series and Land Use spatial layers) based on recent satellite observations.

Table 6.6.11 Forest land converted to grassland: recalculation of total CO_2-e emissions

	2023 submission	2024 submission	Change	Reason for recalculations (Kt CO_2-e)		
Year	(kt CO_2-e)	(kt CO_2-e)	(kt CO_2-e)	A	B	C
1989-90	150,020	147,337	-2,682	745	-582	-2,845
1994-95	68,731	64,391	-4,340	-3,451	263	-1,152
1999-00	72,629	66,283	-6,347	-4,942	-410	-995
2004-05	90,140	82,676	-7,464	-4,240	-1,470	-1,754
2005-06	87,304	94,227	6,924	9,849	-341	-2,584
2006-07	89,157	76,144	-13,014	-11,997	1,092	-2,109
2007-08	68,387	66,006	-2,380	-1,270	418	-1,529
2008-09	55,909	46,093	-9,816	-5,524	-2,829	-1,463
2009-10	61,752	52,658	-9,094	-9,939	1,866	-1,021
2010-11	46,878	35,281	-11,597	-10,790	-1,570	762
2011-12	43,707	30,549	-13,158	-11,821	-552	-785
2012-13	45,395	44,927	-467	1,091	-298	-1,260
2013-14	48,388	47,774	-613	2,943	-2,018	-1,538
2014-15	39,399	36,929	-2,471	-4,060	2,958	-1,369
2015-16	39,369	23,604	-15,765	-12,831	-1,720	-1,214
2016-17	38,309	45,434	7,126	9,688	-1,664	-898
2017-18	43,607	37,592	-6,016	-4,820	-286	-910
2018-19	29,020	23,163	-5,858	-5,475	635	-1,018
2019-20	35,634	35,176	-458	853	-604	-706
2020-21	21,328	17,820	-3,508	-7,441	-2,233	6,166

6.6.2.6 Category-specific planned improvements

The remote sensing programme to detect forest cover change is being updated from the Landsat time series at 25m resolution to use Sentinel 2 satellite imagery at 10m resolution. It is expected that this significant improvement will be included in the next submission.

Systems for the estimation of areas of forest conversion and related assessments of the gains and losses of sparse woody vegetation will continue to be updated to enable consumption of information contained in datasets obtained from the NSW and Queensland Statewide Landcover and Trees Study programs and similar products as they develop. The new systems will continue to build on experience gained in the use of these datasets during the finalisation of the area estimates for this inventory.

Specifically, the remote sensing programme is further advancing the methods to enable:

- ongoing improvements and development of rule-based methods for change detection and attribution;
- processing of remaining areas of vegetation monitoring for parts of central Australia to complete the national coverage; and
- estimation of above-ground biomass from remote-sensed canopy cover.

Improved calibrations for forest growth and disturbance

Work is in progress to compile additional field measurements for growth and disturbance in forests and rangelands. This will result in revision of parameters including those relating to tree growth, standing dead, turnover and decay, loss of biomass due to fire and timber harvesting, and the rate at which biomass recovers from disturbances. A revised vegetation classification in development will refine the association of these parameters to vegetation types.

Improved parameters for soil carbon will also be applied, with a run-in process to begin models with soil at equilibrium for the prevailing conditions.

6.7 **Wetlands** (CRT category 4.D)

6.7.1 Wetlands Remaining Wetlands

6.7.1.1 Category description

The estimates in this category are guided by the 2013 Wetlands Supplement and the 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2006). In this category, the Australian inventory includes estimates for.

- Gains and losses of sparse woody vegetation on wetlands;
- Biomass burning on tropical savannas that are categorised as wetlands;
- Emissions from coastal aquaculture production in Australia;
- Emissions from seagrass removal due to capital dredging projects; and
- Methane emissions from *reservoirs* (over 20 years old) and *other constructed waterbodies* under *Flooded land remaining flooded land,* including an estimate for ponded pastures.

Methane emissions from reservoirs up to 20 years in age are reported under *Land converted to flooded land.* Continuing CO_2 flux from these younger reservoirs, due to decaying inundated biomass, is also accounted for in this category.

Due to the structure of the Common Reporting Tables for submission to the UNFCCC, which are designed around the premise of LULUCF emissions being associated with activity data on land areas rather than other forms of activity data, emissions for aquaculture activity and seagrass removal as off-shore activities are reported in category 4.H (Other), but are included in this document and in the Australian National Greenhouse Accounts online reporting within *wetlands remaining wetlands* for the purposes of transparency and completeness.

The key input data and estimated net emissions from changes in sparse woody vegetation and biomass burning on wetlands are presented in Table 6.7.1 below:

Table 6.7.1 Area and net emissions of sparse woody vegetation transitions and biomass burning, Wetlands remaining wetlands

Year	Sparse woody vegetation			Biomass burning	
	Area gains kha	Area losses kha	Net emissions kt CO_2-e	Area losses kha	Net emissions kt CO_2-e
1989-90	50	71	370	455	685
1994-95	18	26	419	460	65
1999-00	40	26	287	606	1,415
2004-05	76	41	155	726	1,155
2005-06	34	129	241	174	1,588
2006-07	30	78	264	898	1,340
2007-08	29	58	283	985	1,672
2008-09	26	53	244	768	1,860
2009-10	40	67	250	854	1,117
2010-11	35	43	234	606	1,149
2011-12	73	31	89	871	893
2012-13	58	57	69	1,066	944
2013-14	31	76	90	608	902
2014-15	32	70	117	1,076	965
2015-16	60	57	120	487	197
2016-17	28	93	186	817	57
2017-18	29	73	240	715	-418
2018-19	34	37	268	673	-230
2019-20	45	30	278	723	-823
2020-21	36	29	294	624	-545
2021-22	36	29	324	524	-468

The key input data and estimated net emissions from aquaculture and seagrass removal are shown in Table 6.7.2 below.

Table 6.7.2 Annual activity and emissions for coastal aquaculture production and seagrass removal

Year	Annual coastal aquaculture Production – finfish and crustaceans (kt)	N_2O emissions (kt CO_2-e)	Seagrass area removed (ha)	CO_2 Emissions (kt CO_2-e)
1989-90	5	3	0	0
1994-95	13	9	0	0
1999-00	24	17	1	1
2004-05	30	21	26	11
2005-06	36	25	22	10
2006-07	39	27	3	1
2007-08	42	29	235	54
2008-09	46	32	1	0
2009-10	48	34	1	0
2010-11	51	36	0	0

Year	Annual coastal aquaculture Production – finfish and crustaceans (kt)	N_2O emissions (kt CO_2-e)	Seagrass area removed (ha)	CO_2 Emissions (kt CO_2-e)
2011-12	60	42	6	1
2012-13	58	41	7	2
2013-14	57	40	76	34
2014-15	66	47	3	1
2015-16	73	52	0	0
2016-17	70	49	0	0
2017-18	79	56	0	0
2018-19	74	52	0	0
2019-20	86	60	0	0
2020-21	108	76	0	0
2021-22	108	76	0	0

The key input data and estimated net emissions from Reservoirs and Other constructed waterbodies, including ponded pasture, are shown in Table 6.7.3 below.

Table 6.7.3 Annual area and CH_4 emissions from Reservoirs and Other constructed waterbodies under Flooded Land remaining Flooded Land

Year	Reservoir methane emissions (kt CO_2-e)	Reservoir area (kha)	Other constructed waterbody methane emissions (kt CO_2-e)	Other constructed waterbody area (kha)
1989-90	536	170	358	166
1994-95	985	305	327	154
1999-00	1,192	350	463	205
2004-05	1,047	318	430	188
2005-06	1,055	322	450	194
2006-07	947	290	365	164
2007-08	1,141	333	405	179
2008-09	1,194	344	449	194
2009-10	1,248	361	454	194
2010-11	1,443	416	514	223
2011-12	1,519	441	525	227
2012-13	1,477	431	467	203
2013-14	1,398	411	463	198
2014-15	1,351	398	477	204
2015-16	1,231	362	496	206
2016-17	1,378	406	519	219
2017-18	1,373	407	416	179
2018-19	1,199	363	395	171
2019-20	1,084	335	367	166
2020-21	1,150	352	467	203
2021-22	1,313	394	525	224

6.7.1.2 Methodological issues

Sparse woody vegetation gains/losses

Carbon stock-changes from gains and losses in sub-forest sparse woody vegetation on wetlands have been identified using the same monitoring systems used to identify areas of sparse woody vegetation for grassland systems as described in Chapter 6.6.1.2.

Biomass burning

Emissions and removals due to *biomass burning* on savannas that are wetlands are modelled using the same methods, factors and data as described in Chapter 6.3.2.

Aquaculture production

This sub-category accounts for N_2O emissions from the production of finfish and crustaceans in aquaculture systems located in coastal wetland habitats using methods informed by the 2013 Wetlands Supplement.

Australian aquaculture production figures, of the previous financial year, are published annually by the Australian Bureau of Agriculture and Resource Economics (ABARES) in the Australian Fisheries and Aquaculture Statistics report (A. D. Steven 2021). These statistics are available at the state and territory jurisdiction level. Production data are reported for various broad groups of animals, and the subgroups within those. The two groups of interest are “Fish” and “Crustaceans”, both of which contain sub-groups that represent marine and/or freshwater species. Only production figures involving sub-groups that are mostly cultured in coastal wetland-based facilities are included in this analysis. Therefore, fish production data for salmonids, tuna and barramundi are included from “Fish”, while prawns is the only sub-group reported from the “Crustacean” group. There are no other groups from the ABARES dataset reported here.

The 2022 update of 2020–21 production data was not available at the time of publication so that the 2020–21 data was carried through to 2021–22 as an interim result.

Direct N_2O emissions were estimated using Equation 4.10 in the 2013 Wetlands Supplement. Note that quantities are expressed here in tonnes rather than kg, so that:

$$N_2O\text{-}N_{AQ} = F_F \bullet EF_F \qquad (6.7.1)$$

Where $N_2O\text{-}N_{AQ}$ = annual direct N_2O-N emissions from aquaculture use; tonnes N_2O-N per year

F_F = annual fish production; tonnes of fish per year

EF_F = emission factor for N_2O emissions from fish produced; 0.00169 tonne N_2O-N per tonne of fish produced

Seagrass removal due to capital dredging

Seagrasses are a diverse group of marine flowering plants adapted to a submerged life. Seagrasses are found along both tropical and temperate Australian coasts, where they may occupy intertidal flats, as well as the sub-tidal near-shore and deeper offshore locations. They cover an estimated area of 5 to 9 million hectares in Australia. Species diversity is greatest in tropical waters, but biomass per unit area increases with increasing latitude in Australia (Butler and Jernakoff 1999).

A report (Kettle 2017) was commissioned to capture the timing and extent of current and historical capital dredging activity in Australia that informs the seagrass excavation model. The seagrass excavation model has a Tier 2 model structure using country-specific parameter values estimated from pooled data collected from the scientific literature and stratified by coastal region.

The timing and extent of capital dredging activity in Australian waters was reported for the period 1988–89 to 2015–16 (Kettle 2017), noting there was no recorded capital dredging activity for 1989–90 to 1994–95, 2010–11 and 2015–16. A review of the Australian Notices to Mariners (Australian Hydrographic Office, 2017–2022) did not identify any stated capital dredging activity after 2015-16. An industry report, Dredging Services in Australia (Allday 2021), stated that the dredging industry peaked in 2013-14, but then declined as port expansion programs slowed under reduced natural resource exports and covid-related impacts in the five years to 2020–21. While capital dredging projects declined, maintenance dredging continues to be in demand but is not included this account.

It is reported in the literature that seagrass habitat takes time to recover after removal or burial, depending on the species involved ((Preen, Lee Long and Coles 1995); (Campbell and McKenzie 2004); (Smith, et al. 2016); (Vanderklift, et al. 2017)). Some seagrass habitat, including that dominated by temperate, high biomass species, may not re-establish when disturbance is regular, periodic, or catastrophic ((Meehan and West 2002); (Erftemeijer and Robin Lewis 2006); (Wu, et al. 2015)). As navigational channels also undergo scheduled periodic maintenance dredging it is assumed that seagrass habitat is removed permanently when establishing a channel. In keeping with Tier 1 assumptions, all excavated plant and soil based organic carbon is mineralised in the year of removal. An estimation of the soil organic carbon removed by dredging is based on an excavated depth of one meter.

The model is populated with area estimates for excavated seagrass meadow obtained by spatial modelling. Kettle (2017) provided dredge-related shapefiles that are overlaid on seagrass habitat shapefiles to determine the areas of seagrass and underlying sediment removed by dredging activity. Seagrass habitat shapefiles are sourced from State and Territory jurisdictions and the University of Tasmania.

Further information is provided in Annex 5.6.10.

Reservoirs and Other constructed waterbodies

Drawing upon guidance on *Flooded lands* from the 2019 Refinement to the IPCC Guidelines (pp 7.1–7.29) (IPCC 2019), Australia reports methane emissions from *Reservoirs* older than 20 years and *Other constructed waterbodies* as part of *flooded land remaining flooded land.* Carbon dioxide and methane emissions from inundated land associated with newly established reservoirs are reported under *land converted to flooded land* for a period of 20 years from the date the reservoir was completed. After 20 years the reservoir is established and is included *in Flooded land remaining flooded land.*

The age of each reservoir included in this account is based on available public records that report the date of completion of dam construction. Activity data, reported as an annual average surface area, is provided by gauge depth to surface area lookup tables established for each reservoir.

For ease of reporting, all *Reservoirs* and *Other constructed water bodies* methane emissions are reported in *Common Reporting* table 4(II): 4.D.2 *Flooded Lands* (on mineral soils). CO_2 emissions are included in the carbon stock changes of *forest land converted to flooded land.*

The Tier 1 and Tier 2 estimation methods for reservoirs and farm dams respectively are described here, with further information provided in Annex 5.6.10.

For *Reservoirs* within a specific climate zone:

$$FCH_4 = EFCH_4 \times A \qquad (6.7.2)$$

Where FCH_4 = Annual emission of CH_4 from all Reservoirs

A = Area of water body water surface

$EFCH_4$ = Emission factor for CH_4 emitted from the water body surface, which is specific for the type of water body and climate zone in which that waterbody is located and, additionally for Reservoirs, its age.

The 2019 Refinement provides default values for methane emission factors ($EFCH_4$) for *Reservoirs* that are specific to waterbody age and climate zone (Tables 7.9 and 7.15 in the 2019 Refinement) (IPCC 2019), and which are reproduced in Table 6.7.4. Methane is also emitted from water released downstream of the reservoir, FCH_4 downstream Emissions from this source, which under Tier 1 are calculated as 9% of the total reservoir related emissions, are estimated in this account. In higher Tier models, an emission factor adjustment may be applied to account for the influence of eutrophication of reservoir waters. This has a default value of one for Tier 1 models, which is applied here and therefore does not influence the emission estimate.

Activity data for methane emissions from *Reservoirs* and *Other Constructed Waterbodies* are reported as the aggregated surface areas (by state and nationally) for each of these categories of water bodies.

Average monthly reservoir surface area is estimated based on the development of water gauge depth to surface area look-up tables for each reservoir included in the account and is described in Annex 5.6.10. Where reservoirs did not have a complete time series of gauge data (1990 to present), or for which gauge data was not available, then a hybrid model was produced that included annual data to fill the data gaps. Gap-fill data was extracted by intersecting data from the Bureau of Meteorology (BOM) geofabric data and the Geoscience Australia/Digital Earth Australia (DEA) Waterbodies data to provide the annual average surface area for reservoirs with missing gauge-based activity data.

The Australian National Committee on Large Dams (ANCOLD) list of dams (2010) names more than 600 dams and their associated reservoirs, a subset of which are included in this account. This subset, which totals 200 reservoirs (Table A5.6.10.12), collectively represents more than 95% of the maximum aggregated surface area of all reservoirs on the ANCOLD list.

Table 6.7.4 $EFCH_4$ and $EFCO_2$ values for Reservoirs

	Reservoirs		
Australian Climate Zone	**AGE (Old > 20 years)**	**$EFCH_4$ (kg CH_4/ha/year)**	**$EFCO_2$ (Tonnes CO_2/ ha/yr)**
Tropical – wet	Young	252	2.77
Tropical – dry	Young	392	2.95
Tropical – moist	Young	196	1.7
Temperate – warm	Young	128	1.46
Temperate – cool	Young	85	1.02
Tropical – wet	Old	141	–
Tropical – dry	Old	284	–
Tropical – moist	Old	151	–
Temperate – warm	Old	151	–
Temperate – cool	Old	54	–

Other constructed waterbodies include freshwater ponds such as stock dams, crop dams and farm tanks that are small to large, shallow impoundments used for crop irrigation and stock watering. These small to medium water bodies (up to 8 ha) comprise a common water source for Australian agriculture and are distributed extensively throughout Australia's rural landscape. They are difficult to identify by satellite, except through high-resolution satellite imagery, so that a remote sensing approach to estimating their annual average surface area at state and national levels is impractical. The prior approach was to use agricultural survey data on water use as a basis for modelling surface area estimates. However recent applications of machine learning to the problems of estimating the distribution, water surface area, and methane emissions of Australia's farm dam population have been applied in developing a new method for estimating Australian annual methane emissions from *Other constructed waterbodies*.

The methods employed in constructing this farm dam account were developed by scientists at Deakin University's Blue Carbon Lab (Melbourne, Australia) and the West Australia Department of Primary Industries and Regional Development and published in a series of peer-reviewed papers. A brief overview of the methods is provided here, with a comprehensive summary presented in Annex 5.6.10.

The size and historical and current distribution of Australian farm dams was reported in Malerba et al. (2021). A deep learning convolutional neural network (CNN) was employed to detect farm dams from satellite images. Training of the CNN was based on high-resolution satellite images (~ 0.5 m resolution) of Australian agricultural landscapes containing farm dams.

Malerba et al. (2021) compiled State and National datasets on Australian dams. These datasets are generally incomplete (analysis of lower-res satellite images missed smaller dams) and may be temporally static by providing only a "snapshot" at one time point. The authors employed the trained CNN to verify the existence of each dam from the combined data sources. In addition, the CNN model was given imagery from locations where no dam had previously been recorded. The combination of these enabled the authors to develop better estimates of dam densities and dam water capacity across Australia than could be provided by the original national and state data sets. In addition, they were also able to quantify the rate of new farm dam development for each Australian State and Territory.

A second paper (Malerba, Wright and Macreadie 2022a) describes the use of satellite images and deep-learning convolutional neural networks to analyse the impacts of local conditions of rain and temperature on the water levels of Australian farm dams over time. This work allowed the authors to develop a predictive model of regional dam level (water surface area and volume), based on climate data. To account for the effects of climate both spatially and temporally over the modelled period, 1989–90 to 2021–22, monthly averages of rainfall and temperature were obtained from weather stations of the Bureau of Meteorology across Australia. Monthly climate surfaces at 1 km resolution for each variable were then derived using ANUSPLIN (Hutchinson and Xu 2013) surface interpolation techniques (Annex 5.6.1). Overall, using climate data to estimate regional farm dam capacity reduced the necessity of expensive and time-consuming satellite image analysis to measure water surface in farm dams.

The emission rate of total methane (diffusive and ebullitive) from agricultural ponds, estimated for different climate zones, is employed in this model. The climate zone-adjusted rates are based on a meta-analysis of data compiled from the scientific literature on methane fluxes from 286 agricultural ponds in subtropical, temperate, semi-arid, and tropical climates (Malerba, et al. 2022b). The reported methane fluxes were compared across sites and climate zones by standardising daily emissions to 15°C using the Boltzmann-Arrhenius relationship. A second meta-analysis estimated the ratio of methane diffusion to methane ebullition (bubbling) in freshwater systems were, so that total methane emission rates could be estimated from the published data in which only methane diffusion was reported. The two meta-analyses developed by (Malerba, et al. 2022b) were based on the dataset published by Rosentreter et al. (Rosentreter, et al. 2021).

Annual total methane emissions from agricultural ponds were then estimated by converting the density of pond surface area (pond ha ha^{-1}) into cumulative methane emissions (kg CH_4 year-1 ha^{-1}) by re-organising the Boltzmann-Arrhenius relationship and adjusting for local temperature (see Annex 5.6.10). Methane emissions from farm dams are then estimated by multiplying the cumulative methane emissions by the estimated surface area of agricultural ponds (described above) in that climate zone and reporting the results by state and territory.

A preliminary review of Australian studies (Grinham, et al. 2018); (Q. R. Ollivier, et al. 2018) demonstrated that emissions from farm dams not located on grazing land generally have lower methane emissions. This is presumably because these dams are not contaminated with manure, either through direct deposit, or as a component of rain runoff into the dam. (Grinham, et al. 2018) reported on emissions from freshwater ponds, with primary uses including irrigation, stock watering or urban use. They also recorded the primary land use against each individual pond. A comparison of emission rates between ponds used for stock watering on grazing land (assumed high organic input) against ponds used for irrigation or "urban use" on cropland or settlement land (assumed lower organic inputs) resulted in a mean ratio of 0.4 for crop dams and farm tanks relative to stock dams, upon which the total emissions estimate is based. This ratio is used as a multiplier to estimate the baseline methane emissions for all agricultural ponds reported under *Other constructed waterbodies* (0.4 X total CH_4 emissions). The "manure component" of the estimated methane emissions is then (1 – 0.4) X total CH_4 emissions. The manure-related methane emissions are reported elsewhere, in manure management in Agriculture.

Ponded pasture

Ponded pastures are ponds constructed in grazing lands in tropical and subtropical regions that experience distinct wet and dry seasons. The ponds are designed to flood seasonally (during the wet) and are sown with water tolerant grasses. The grasses grow during the wet season and become pasture in the dry season, providing highly nutritious fodder for cattle as the ponds dry out.

Australia has an area of 52,500 ha of certain ponded pastures in Australia's dry tropics and subtropics. An estimate of methane emissions from this source is provided in this submission under *Other constructed waterbodies.*

There is no information on the emission rates from these water bodies. However, as they are vegetated, it is likely that methane emissions are high. The full EF values reported in Table 6.7.4 are therefore used in this instance.

The Tier 1 method is briefly described here:

$$FCH_4 = EFCH_4 \times A \times B \qquad (6.7.3)$$

Where A = Area of water body water surface (ha)

$EFCH_4$ = Emission factor for CH_4 emitted from the water body surface, which is based on the dry tropical and subtropical climate zone values reported in Table 6.7.4.

B is the proportion of the year that are emissive days (when water is present in the pond)

A total area of 52,500 ha is divided between the dry tropics (35,000ha) and the moist tropics (17,500ha)

The number of emissive days is assumed to be 240 days annually, so that B = 0.66

6.7.1.3 Uncertainty assessment and time-series consistency

Based on a qualitative assessment, the uncertainties for sparse woody vegetation transitions on *wetlands remaining wetlands* is estimated to be medium. Further information is provided in Annex 2. Time series consistency is ensured using a stable method across the time series.

For the subdivision, N_2O from Aquaculture Use, ABARES aquaculture production data is available for the period since 1991 (ABARES: *Australian fisheries and aquaculture production publications).* These data are reported nationally and by state/territory and represent live-weight quantity of aquaculture product that is produced and marketed. The data generally excludes hatchery production. ABARES does not specify a level of uncertainty with its aquaculture and fisheries production figures. Uncertainty regarding annual finfish and crustacean production in coastal facilities is likely to be within the low to medium range.

The confidence intervals associated with 2013 IPCC Wetlands Supplement guidance (IPCC 2013) for parameters associated with coastal wetlands range from 24 per cent to over 200 per cent. For seagrass removal this inventory applies available country-specific values, sourced from the scientific literature, to reduce that level of uncertainty. Although a formal uncertainty analysis is not yet available, the level of uncertainty is anticipated to be towards the lower end of the guidance values and is within the medium range.

Estimates of CH_4 and CO_2 emissions from reservoirs are based on the Tier 1 methodology provided in the 2019 Refinement to the 2006 IPCC Guidelines, combined with refinement in spatial analysis of activity data. Based on the summary of emission factor values published in the 2019 Refinement (IPCC 2019), the 95% confidence interval around the default emission factor values is large. It is anticipated that the level of uncertainty will reduce as research on methane emissions from Reservoirs continues to be published and the results incorporated into Australia's future modelling efforts.

The overall estimate of uncertainty around quantifying CH_4 emissions from agricultural ponds was produced by applying non-parametric bootstrapping to compound all sources of error. The upper and lower 95% confidence intervals are reported across the time series and for each state in Annex 5.6.10.

Additionally, the coefficient of variation of the mean, a standardised measure of dispersion of a data set, was used to compare the magnitude of each source of uncertainty. The following estimates of CVs are, for pond area (10%), temperature sensitivity (21%), methane flux (22%) and ebullition (27%).

Time series consistency is ensured by using stable, well-defined methods across the time series.

6.7.1.4 Category-specific QA/QC and verification

Quality control measures for *aquaculture and seagrass removal* involve internal reviews of data entry and model outputs, including a check on the consistency of aquaculture production statistics across Australian jurisdictions.

The quality control measures employed in estimating activity data from *reservoirs* include comparing the model derived gauge data to surface area tables used in the model against several official gauge tables supplied by reservoir operators. The model applies IPCC default values for reservoir methane EF values.

Activity data for reservoirs is derived from satellite image analysis to obtain the annual change in their individual surface areas. A subset of these estimates is checked against corresponding water storage levels for major reservoirs as reported annually by each state and territory.

The methods used to develop estimates of methane emissions from Australian agricultural ponds are derived directly from a series of methodologies now published in the scientific literature. Each of the published methods was subject to rigorous peer review prior to publication. The current CH_4 emission estimates for Australian agricultural ponds are the most recent iteration of the published data and modified to distribute those emissions between the base-level methane emissions reported here and the manure-based methane emissions reported in the Agriculture sector.

6.7.1.5 Category-specific recalculations

Recalculations for *wetlands remaining wetlands* are shown in Table 6.7.5 below. Recalculations are due to:

A. FullCAM database and parameter updates including for croplands and grasslands

Significant improvements have been made to the way the FullCAM model reflects climate impacts on crop and grass production and soil carbon. This is described in more detail in Chapters 6.5.1.5 and 6.6.1.5.

B. Refinements to the model used to estimate farm dam emissions

The Malerba, et al. 2023 model introduces a local weather and satellite-based method to model methane emissions from agricultural ponds accounting for fluctuations in water surface area and temperature-dependent methane flux.

C. Activity data updates

Activity data updates implemented in this submission include addition of:

- activity data and climate data covering 2021-22; and
- annual updates to spatial datasets (Woody Change, Plantation Type, Fire time series and Land Use spatial layers) based on recent satellite observations.

Table 6.7.5 Wetlands remaining wetlands: recalculation of total CO_2-e emissions

	2023 submission	2024 submission	Change	Reasons for recalculation (Kt CO_2-e)		
Year	(kt CO_2-e)	(kt CO_2-e)	(kt CO_2-e)	A	B	C
1989-90	2,122	1,952	-170	-35	-135	0
1994-95	2,000	1,805	-195	-23	-172	0
1999-00	3,520	3,375	-145	-18	-126	0
2004-05	3,003	2,819	-183	-3	-180	0
2005-06	3,556	3,370	-186	-4	-182	0
2006-07	3,141	2,945	-196	-16	-180	0
2007-08	3,801	3,585	-216	-5	-211	0
2008-09	3,959	3,780	-179	-7	-173	0
2009-10	3,285	3,104	-182	-6	-175	0
2010-11	3,553	3,376	-177	-5	-172	0
2011-12	3,245	3,070	-176	-5	-170	0
2012-13	3,156	2,999	-156	-6	-151	0
2013-14	3,067	2,927	-140	-5	-135	0
2014-15	3,097	2,958	-139	-6	-133	0
2015-16	2,239	2,095	-145	-8	-136	0
2016-17	2,425	2,189	-236	-1	-235	0
2017-18	1,954	1,667	-287	3	-290	0
2018-19	1,932	1,685	-247	13	-259	0
2019-20	1,180	967	-213	6	-219	0
2020-21	1,499	1,442	-57	128	-202	16

Note: Recalculations include estimates reported in CRT 4.H (Other)

6.7.1.6 Category-specific planned improvements

In terms of seagrass removal activity data, the capital dredging report (Kettle 2017) has catalogued the capital dredging activity associated with port and related infrastructure projects for the current reporting period 1989–90 to 2017–18. A review of government and industry sources continues with a focus to update data on new and on-going capital dredging activity from 2018-19 onwards.

Modelling of methane emissions associated with *Reservoirs* will continue to undergo improvement in step with the developing scientific literature in this area, which will also improve the confidence limits of future submissions.

A process of continuous improvement regarding regionally based seagrass removal parameter values to underpin the emissions model has been established to incorporate updated values acquired in regular surveys of the scientific literature.

6.7.2 Land converted to wetlands

This category comprises the subcategory *forest land converted to wetlands* (flooded land). Forest conversion occurs where forests are cleared as part of the construction of reservoirs and other land categorized in the IPCC 2006 Guidelines (IPCC 2006) as 'flooded lands' under *forest land converted to wetlands,* within the broader *land converted to wetlands source category.* Emissions are reported for land clearing associated with the flooding of the land, and for methane from young reservoirs.

Where mangrove forests are cleared for commercial developments such as marinas, these conversions are categorised as *forest land converted to settlements* within the broader *land converted to settlements* source category (see Chapter 6.8.2).

The annual area identified, and associated net emissions are in Table 6.7.6 below.

Table 6.7.6 Areas of forest land converted to wetlands (flooded land) and Reservoirs (up to 20 years old), and associated net annual emissions

Year	Forest Converted to Flooded land: Cumulative National Area (kha)	Forest Converted to Flooded land: Net Annual Emissions (kt CO_2-e)	Young Reservoirs (up to 20 years): Annual area (kha)	Young Reservoirs (up to 20 years): Annual CH_4 emissions (kt CO_2-e)	Young Reservoirs (up to 20 years): Annual CO_2 emissions (kt CO_2)
1989-90	25	721	203	1,121	422
1994-95	32	232	69	354	137
1999-00	35	57	70	374	144
2004-05	37	45	46	266	103
2005-06	38	80	36	211	84
2006-07	38	48	37	228	91
2007-08	38	36	11	47	20
2008-09	39	1	12	56	23
2009-10	41	826	12	62	25
2010-11	45	1,458	4	29	11
2011-12	45	13	5	30	11
2012-13	45	-	5	30	11

Year	Forest Converted to Flooded land: Cumulative National Area (kha)	Forest Converted to Flooded land: Net Annual Emissions (kt CO_2-e)	Young Reservoirs (up to 20 years): Annual area (kha)	Young Reservoirs (up to 20 years): Annual CH_4 emissions (kt CO_2-e)	Young Reservoirs (up to 20 years): Annual CO_2 emissions (kt CO_2)
2013-14	45	-	3	17	6
2014-15	45	-	4	23	9
2015-16	45	-	4	28	10
2016-17	45	-	3	21	8
2017-18	45	-	3	22	8
2018-19	45	-	3	18	7
2019-20	45	-	2	15	5
2020-21	45	-	2	12	4
2021-22	45	-	2	14	5

6.7.2.1 Methodological issues

Like for areas of forest conversions for cropping and grazing, areas of forest converted to wetland are identified at fine spatial resolution via Australia's Approach 3 remote sensing programme. In this case, the satellite imagery is analysed to identify where forest is cleared for construction of perennial water bodies such as reservoirs.

The method for estimating net emissions is taken from the 2006 IPCC Guidelines (IPCC 2006) as a conversion of land to flooded land. This model is implemented in FullCAM in fully spatial Tier 3 mode considering only fluxes in living biomass, considered using the same methods as for the loss of native vegetation in forest land converted to grassland (Chapter 6.6.2.2). The soil and dead organic matter emissions from conversion of land to flooded land are handled by the reservoir methane method described in Chapter 6.7.1.2 and Annex 5.6.10. Due to the application of Tier 1 emission factors, a transition period of 20 years is applied to this land conversion category rather than the 50-year period used in other categories.

Emissions at the time of land use conversion are reported in CRT 4.D.2. Lagged carbon dioxide and methane emissions are reported in *CRT*4(II) under *Flooded Land.*

6.7.2.2 Uncertainty assessment and time-series consistency

Uncertainties for *land converted to wetland* at the national scale were estimated to be ±27.3 per cent for CO_2. Further details are provided in Annex 2. Time series consistency is ensured using consistent methods and full recalculations in the event of any refinement to the methodology.

6.7.2.3 Category-specific QA/QC and verification

The category specific QA/QC for the subcategory *forest land converted to wetland* is covered in detail under *forest land converted to grassland* (Chapter 6.6.2.4).

6.7.2.4 Category-specific recalculations

Recalculations for *land converted to wetlands* are shown in Table 6.7.7 below.

The recalculations are due to:

A. Activity data updates

Activity data updates implemented in this submission include addition of:

- activity data and climate data covering 2021–22; and
- annual updates to spatial datasets (Woody Change, Plantation Type, Fire time series and Land Use spatial layers) based on recent satellite observations.

B. Reservoirs (up to 20 years in age)

Corrections to data entry has led to a recalculation in the CO_2 emissions of New Reservoirs (Up to 20 years in age)

Table 6.7.7 Land converted to Wetlands: Recalculation of total CO_2-e emissions

	2023 submission	2024 submission	Change	Reasons for recalculation (kt CO_2-e)	
	(kt CO_2 -e)	(kt CO_2 -e)	(kt CO_2 -e)	A	B
1989-90	1,839	2,263	424	7	417
1994-95	580	722	143	10	132
1999-00	412	575	162	18	144
2004-05	310	415	105	2	103
2005-06	287	375	88	3	84
2006-07	268	367	99	8	91
2007-08	74	103	29	9	20
2008-09	62	80	18	-5	23
2009-10	414	912	499	474	25
2010-11	806	1,497	691	680	11
2011-12	44	55	11	-0	11
2012-13	30	41	11	0	11
2013-14	18	23	6	0	6
2014-15	25	32	7	0	7
2015-16	29	38	9	0	9
2016-17	23	29	6	0	6
2017-18	23	30	6	0	6
2018-19	19	24	5	0	5
2019-20	16	20	4	0	4
2020-21	13	16	2	0	2

6.7.2.5 Category-specific planned improvements

The category specific planned improvements for the subcategory *forest land converted to wetland* are covered in detail under *forest land converted to grassland* (Chapter 6.6.2.6).

Improvements for the Reservoir subcategory are covered in detail under *Wetlands remaining wetlands* (Chapter 6.7.1.6).

6.8 **Settlements** (CRT category 4.E)

6.8.1 Settlements Remaining Settlements

6.8.1.1 Category Description

The *settlements remaining settlements* subcategory includes urban environments and infrastructure that have not observed a land use conversion. It does not include areas of woody vegetation that constitute a forest to avoid double-counting of lands classified as *forest land.* This subcategory includes only estimates of net emissions from changes in sparse woody vegetation, such as due to changes in urban parks and gardens.

The key input data and estimated net emissions are presented in Table 6.8.1.

Table 6.8.1 Area and net emissions of sparse woody vegetation, settlements remaining settlements

	Area gains	Area losses	Net emissions
Year	kha	kha	kt CO_2-e
1989-90	5.4	-9.8	-25.4
1994-95	3.4	-4.7	9.6
1999-00	3.8	-4.1	27.3
2004-05	6.4	-9.0	31.6
2005-06	7.5	-7.9	32.3
2006-07	7.5	-8.2	33.1
2007-08	7.0	-9.0	35.0
2008-09	10.0	-9.2	26.1
2009-10	10.2	-8.4	20.4
2010-11	16.8	-5.9	6.9
2011-12	19.4	-5.4	-10.1
2012-13	14.0	-8.5	-16.0
2013-14	15.4	-9.0	-21.5
2014-15	11.9	-8.5	-25.8
2015-16	13.4	-9.1	-32.2
2016-17	19.7	-7.2	-46.2
2017-18	24.3	-5.5	-65.0
2018-19	16.2	-6.0	-75.3
2019-20	10.2	-7.5	-78.1
2020-21	8.6	-9.3	-76.7
2021-22	5.5	-6.6	-75.3

6.8.1.2 Methodological issues

Carbon stock-changes from gains and losses in sub-forest sparse woody vegetation on settlements have been identified using the same monitoring and modelling systems used to identify areas of sparse woody vegetation for *grassland remaining grassland* and estimate the associated emissions and removals (see Chapter 6.6.1.2).

6.8.1.3 Uncertainty assessment and time-series consistency

Based on a qualitative assessment, the uncertainty for *settlements remaining settlements* is estimated to be medium. Further information is provided in Annex 2. Time series consistency is ensured by the use of consistent methods across the time series.

6.8.1.4 Category-specific QA/QC and verification

The QA/QC of the activity data for detecting gains and losses of woody vegetation is described in Annex 5.6.1.

6.8.1.5 Category-specific recalculations

Recalculations for *settlements remaining settlements* are shown in Table 6.8.2. Like for *grassland remaining grassland*, activity data for grass and shrub transitions has been revised due to annual updates in image analysis.

Table 6.8.2 Settlements remaining settlements: recalculation of total CO_2-e emissions

	2023 submission	2024 submission	Change
	(kt CO_2-e)	(kt CO_2-e)	(kt CO_2-e)
1989-90	-38	-25	13
1994-95	-4	10	14
1999-00	17	27	10
2004-05	28	32	3
2005-06	29	32	3
2006-07	31	33	2
2007-08	35	35	0
2008-09	26	26	0
2009-10	21	20	0
2010-11	7	7	0
2011-12	-10	-10	0
2012-13	-16	-16	0
2013-14	-22	-21	0
2014-15	-26	-26	0
2015-16	-33	-32	0
2016-17	-47	-46	0
2017-18	-66	-65	1
2018-19	-77	-75	1
2019-20	-80	-78	2
2020-21	-80	-77	3

6.8.1.6 Category-specific planned improvements

All data and methodologies are kept under review and development.

6.8.2 Land Converted to Settlements

6.8.2.1 Category Description

The land converted to settlements category includes *forest land converted to settlements.*

In reporting net emissions from conversion of forest land to settlements, the emissions and removals from the clearance of terrestrial forests is estimated separately from mangrove forests using FullCAM (see Annex 5.6.10).

Identified land category transitions and associated annual emissions are in Table 6.8.3 below.

Table 6.8.3 Net emissions from land converted to settlements, kt CO_2-e

	Land converted to settlements		
Year	Mangrove forest	Terrestrial forest	All
1989-90	2,938	4,649	7,587
1994-95	2,716	2,593	5,309
1999-00	2,312	2,893	5,205
2004-05	2,148	3,101	5,249
2005-06	2,770	3,969	6,739
2006-07	2,657	2,143	4,799
2007-08	2,280	2,644	4,925
2008-09	2,278	2,070	4,348
2009-10	2,139	2,753	4,892
2010-11	2,971	978	3,949
2011-12	2,830	1,678	4,508
2012-13	2,459	2,598	5,057
2013-14	2,642	1,953	4,596
2014-15	2,530	1,231	3,760
2015-16	3,180	290	3,470
2016-17	3,346	1,189	4,535
2017-18	2,695	875	3,570
2018-19	2,705	537	3,242
2019-20	2,665	905	3,570
2020-21	2,668	-264	2,403
2021-22	2,579	-726	1,854

6.8.2.2 Methodological issues

While activity data is collected via satellite imagery for both types of clearance, the modelling methods differ, reflecting the significant differences between mangrove and terrestrial forests in terms of their allometrics and carbon fluxes.

Clearance of terrestrial forests for settlement development is modelled using FullCAM, considering fluxes between all five carbon pools using the same methods and approaches as applied for conversions from forest land to grassland (see Chapter 6.6.2). Mangrove forest conversion to settlements is also modelled using FullCAM, calibrated for mangrove species as described in Annex 5.6.10 and Chapter 6.4.2.2 (wetlands converted to forest lands).

Table 6.8.4 Cumulative area of land converted to settlements, kha

Year	Terrestrial forest converted to settlements	Mangrove forest converted to settlements	Total
1989-90	149.8	43.3	193.1
1994-95	217.9	62.5	280.4
1999-00	280.1	70.0	350.0
2004-05	350.6	79.1	429.7
2005-06	369.3	81.3	450.7
2006-07	383.0	82.2	465.3
2007-08	395.2	82.7	477.8
2008-09	403.9	83.2	487.1
2009-10	409.5	84.3	493.9
2010-11	414.1	87.5	501.5
2011-12	417.1	87.3	504.4
2012-13	419.4	87.9	507.4
2013-14	419.4	90.3	509.7
2014-15	416.5	92.4	508.8
2015-16	416.7	96.4	513.2
2016-17	415.8	97.4	513.2
2017-18	417.1	97.9	514.9
2018-19	415.0	98.9	513.8
2019-20	413.8	100.9	514.7
2020-21	413.8	103.5	517.3
2021-22	411.0	104.1	515.2

6.8.2.3 Uncertainty assessment and time-series consistency

Uncertainties for *terrestrial forest land converted to settlements* at the national scale were estimated to be ±28.4 per cent for CO_2. Further details are provided in Annex 2. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to the methodology.

Under *mangrove forest land converted to settlements* the confidence intervals associated with 2013 Wetlands Supplement guidance for parameters associated with coastal wetlands are moderate. This inventory applies spatially explicit FullCAM modelling calibrated to available, representative field data, sourced from scientific literature, to reduce uncertainty. Although a formal uncertainty analysis is not yet available, the level of uncertainty is anticipated to be 30-50% or towards the lower-mid end of the IPCC guidance values and is considered to be within the medium range. Other uncertainties and time series inconsistencies relevant to FullCAM simulations (Annexes 5.6.1-2) in general also apply here.

6.8.2.4 Category-specific QA/QC and verification

The category specific QA/QC for the subcategory *terrestrial forest land converted to settlements* is covered in detail under *forest land converted to grassland* (Chapter 6.6.2.4).

For *mangrove forest land converted to settlements,* category specific QA/QC was included in general in the approach to designing and calibrating the coastal wetlands sub-model in FullCAM. The mangrove extent has been manually inspected against Google Earth satellite imagery and also overlaid with Digital Earth Australia product (DEA Mangrove; Landsat, mangrove_cover_v2_0_2, Lymburner et al. 2020) and manually compared in numerous regions of Australia that have significant mangrove and tidal marsh vegetation cover. Parameter value estimations governing growth and recovery after clearing included screening field data to obtain a subset of available data representative of different mangrove sites around Australia, prior to model calibration (Annex 5.6.10).

6.8.2.5 Category-specific recalculations

Recalculations for *land converted to settlements* are reported in Table 6.8.5 below.

These include:

A. Refinements to crop and grass sub-models in FullCAM

Significant improvements have been made to the way the FullCAM model reflects climate impacts on crop and grass production and soil carbon. This is described in more detail in Chapters 6.5.1.5 and 6.6.1.5.

B. FullCAM database and parameter updates including for croplands and grasslands

Refinements have been made to a range of parameters used in FullCAM, including updates to grazing pressure, crop and grass regimes and crop yield tables. These are outlined in further detail in Chapters 6.5.1.5 and 6.6.1.5.

C. Activity data updates

Activity data updates implemented in this submission include addition of:

- activity data and climate data covering 2021-22; and
- annual updates to spatial datasets (Woody Change, Plantation Type, Fire time series and Land Use spatial layers) based on recent satellite observations.

Table 6.8.5 Land converted to settlements: recalculation of total CO_2-e emissions

	2023 submission	2024 submission	Change	Reasons for recalculation (Kt CO_2-e)		
	(kt CO_2-e)	(kt CO_2-e)	(kt CO_2-e)	A	B	C
1989-90	7,528	7,587	60	81	-7	-14
1994-95	5,393	5,309	-83	-90	19	-11
1999-00	5,211	5,205	-7	-2	-1	-4
2004-05	5,657	5,249	-408	-454	34	12
2005-06	6,063	6,739	676	746	-72	3
2006-07	5,863	4,799	-1,063	-1,141	86	-8
2007-08	5,164	4,925	-240	-236	-7	3
2008-09	4,874	4,348	-526	-503	-17	-5
2009-10	4,658	4,892	235	180	42	12
2010-11	5,238	3,949	-1,289	-1,258	-32	1
2011-12	4,976	4,508	-468	-495	-30	58
2012-13	4,145	5,057	912	612	33	266
2013-14	4,201	4,596	395	530	-99	-36
2014-15	3,879	3,760	-118	-163	92	-47
2015-16	4,498	3,470	-1,028	-946	-8	-74

	2023 submission	2024 submission	Change	Reasons for recalculation (Kt CO_2-e)		
	(kt CO_2-e)	(kt CO_2-e)	(kt CO_2-e)	A	B	C
2016-17	4,496	4,535	39	-56	102	-8
2017-18	3,730	3,570	-160	-136	14	-38
2018-19	3,513	3,242	-271	-241	37	-67
2019-20	3,433	3,570	137	119	52	-33
2020-21	3,178	2,403	-775	-921	-8	155

6.8.2.6 Category-specific planned improvements

Grassland and *cropland converted to settlements* are included within *settlements remaining settlements,* based on land representation Approach 1 (IPCC 2006 Guidelines, Volume 4, page 3.10) (IPCC 2006). Work is planned to accommodate the reporting of all conversions to settlements using land representation Approach 3 (spatially explicit land-use conversion data) in future inventory submissions.

The category specific planned improvements for the subcategory of terrestrial *forest land converted to settlements* is described under *forest land converted to grassland* (Chapter 6.6.2.5).

6.9 **Other Land** (CRT category 4.F)

Australia does not report emissions and removals from the reporting category of *other lands remaining other lands*. *Other lands* typically occur in regions of central Australia, e.g., deserts, with minimal anthropogenic impacts on biomass, dead organic matter, and soil carbon.

Other lands, by definition, cannot include any land on which a forest has been observed in the Landsat time series since 1972. As a consequence of this definition *land converted to other land* is not observed.

6.10 **Harvested Wood Products** (CRT category 4.G)

6.10.1 Category Description

Australia applies the stock-change approach for *harvested wood products* (HWP) in use and in solid waste disposal sites (SWDS). The carbon pool is therefore defined as the wood products in service life within Australia —that is, products consumed in Australia, including those imported and excluding those exported. In accordance with the *IPCC 2006 Guidelines*, HWP in SWDS are also reported, as the pool exceeds the significance threshold.

To meet transparency requirements of the Paris Agreement, estimates are also provided for HWP in-use using the production approach, which considers the service life of HWP sourced from Australian forests, including where exported and excluding imports.

Table 6.10.1 Net emissions from harvested wood products, kt CO_2-e

Year	HWP in-use (stock-change approach)	HWP in SWDS	Total HWP Emissions	HWP in-use (production approach)
1989-90	-4,012	-3,125	-7,137	*-2,577*
1994-95	-4,245	-3,250	-7,495	*-3,478*
1999-00	-4,471	-3,256	-7,728	*-5,092*
2004-05	-4,368	-3,567	-7,935	*-4,692*
2005-06	-4,184	-3,322	-7,505	*-4,599*
2006-07	-3,629	-2,843	-6,472	*-4,877*
2007-08	-3,884	-2,478	-6,362	*-4,697*
2008-09	-2,365	-2,252	-4,616	*-3,466*
2009-10	-2,606	-1,531	-4,137	*-3,755*
2010-11	-2,733	-1,842	-4,575	*-4,101*
2011-12	-2,612	-1,322	-3,935	*-3,535*
2012-13	-2,738	-1,249	-3,987	*-3,144*
2013-14	-2,687	-1,176	-3,863	*-4,363*
2014-15	-3,021	-1,103	-4,124	*-4,786*
2015-16	-3,287	-1,109	-4,396	*-5,269*
2016-17	-3,473	-905	-4,378	*-5,747*
2017-18	-3,865	-1,224	-5,089	*-5,706*
2018-19	-3,569	-1,383	-4,952	*-5,109*
2019-20	-3,187	-1,233	-4,420	*-4,299*
2020-21	-3,756	-1,175	-4,931	*-4,077*
2021-22	-4,401	-1,210	-5,611	*-3,368*

6.10.2 Methodological issues

The stock of HWP in-use is estimated as the national production plus the imported material, minus exported material and product disposed to the waste system. Transfer of carbon from HWP in-use to landfill is recorded as a loss of carbon stock from the in-use HWP pools and as a gain in the HWP in SWDS pool. HWP in SWDS is tracked using methods consistent with those of the *Waste* sector, which are compatible with the stock-change approach.

A national database of domestic wood production, including import and export quantities, has been maintained in Australia since the 1940s. It is currently maintained as the Australian Forest and Wood Products Statistics (AFWPS) by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES 2023). This consistent and detailed collection of time-series data provides a sound basis for the development of a national wood products model.

Model components

Information has been obtained and examined under the following components of the model:

- log flow from the forest: current annual production data were obtained by species groupings, and product classes, e.g., sawlogs, veneer logs, pulp logs, roundwood and other, e.g., sleepers;
- fibre flow from processing: data on the intake of raw materials to the various processing options and the output of products and by-products have been used in the model to estimate the total tonnes of carbon produced each year under various end product classes;
- import and export quantities of wood products;

- recycling;
- entry and decomposition in landfill;
- use for bioenergy; and
- other losses to atmosphere.

Wood flow

The model develops wood flows separately for each pool of wood products within the overall HWP pool and these are integrated to account for cross-linkages. This is particularly important in the accounting for waste or by-products, which are themselves used as resources in production for other wood product pools. In conjunction with the opening carbon stock and life cycle of timber products, this model enables the total and projected carbon stocks in HWP to be estimated.

In broad terms, the components of the models developed for each pool of HWP are similar, using:

- an estimate of raw materials input, whether of sawlogs, woodchips ex-sawmill, or pulp logs;
- an estimate of the products of processing, e.g., “x” percentage sawdust, shavings or sander dust for on-site energy generation or compost, “y” percentage woodchips for other manufacturing processes, “z” percentage of sawn timber products, panel products and paper;
- an estimate of the proportion of products by product categories, depending on whether their expected end use is long-term or short-term; e.g., framing timber, dry dressed boards, cases and pallet stock, panel products for use in house construction, panel boards for use in furniture and cabinets, newsprint paper, and writing and printing paper;
- a final figure for total Australian consumption by end use categories, converted to wood fibre content (oven-dry weight) and to tonnes of carbon; and
- import and export data obtained via the AFWPS source data by end use categories. Details of the flows are shown in Annex 5.6.9.

Treatment of bark

There has been no accounting for bark. All bark is regarded as being a component of logging slash (harvesting residue) and accounted for as a part of in-forest logging operations.

Basic density and carbon content

Basic wood density and carbon content estimates (Table 6.10.2) are relevant to all processing options, and the choice of values adopted has a significant bearing on the final outcome. In the case of all sawn timber, and treated softwood and hardwood poles, weighted basic densities for the species involved have been applied across each category and the values adopted based on (Ilic, et al. 2000). For board products and paper, which have been subjected to varying amounts of compression during manufacture, their basic densities have been adjusted to that of the finished products.

Carbon content is defined variably throughout the literature, with values ranging from 0.4 to 0.53 of the oven dry (bone dry) weight. A figure of 0.5 has been adopted for use in the model as a median value extracted from (R. Gifford 2000a).

Apart from the assumptions concerning basic density and carbon content, the other manufacturing assumptions were developed from interviews with representatives from the various industry associations and individual sawmilling companies.

Table 6.10.2 Basic densities, moisture and carbon contents

Carbon Fractions	
Description	**Value**
Fraction of softwood sawmilling dry matter that is carbon, by weight	0.50
Fraction of particleboard dry matter that is carbon, by weight	0.40
Fraction of MDF dry matter that is carbon, by weight	0.40
Basic Densities [(a)]	
Description	**Value kg m^{-3}**
Density of softwood sawmilling	460
Density of hardwood sawmilling	630
Density of cypress sawmilling	600
Density of plywood (softwood and hardwood) and veneer	540
Density of particleboard	520
Density of MDF	600
Density of hardboard	930
Density of softboard	230
Density of pulp and paper: Paper	1,000
Density of pulp and paper: Softwood	430
Density of pulp and paper: Hardwood	500
Density of pulp and paper: Waste paper	1,000
Density of pulp and paper: Pulp	1,000
Density of paper and paperboard imports and exports, on average	1,000
Density of chips and logs for export: Softwood logs	415
Density of chips and logs for export: Hardwood logs	630
Density of hardwood poles, sleepers and miscellaneous	790
Moisture Content of Green Wood	
Description	**Value**
Ratio of weight of water to weight of wood substance in softwood chips	1.10
Ratio of weight of water to weight of wood substance in hardwood chips	0.90

(a) Basic density = (mass of oven dry wood in kg) / (volume of green wood in m^3)

Wood flows from processing

Wood flows in the various wood products produced in Australia have been developed under the following species/industry headings:

- Softwood sawmilling;
- Hardwood sawmilling;
- Cypress sawmilling;
- Plywood;
- Particleboard and medium density fibreboard (MDF);
- Pulp and paper;
- Preservative treated softwood;
- Hardboard and Softboard;
- Hardwood poles, sleepers and miscellaneous; and
- Export of woodchips and logs.

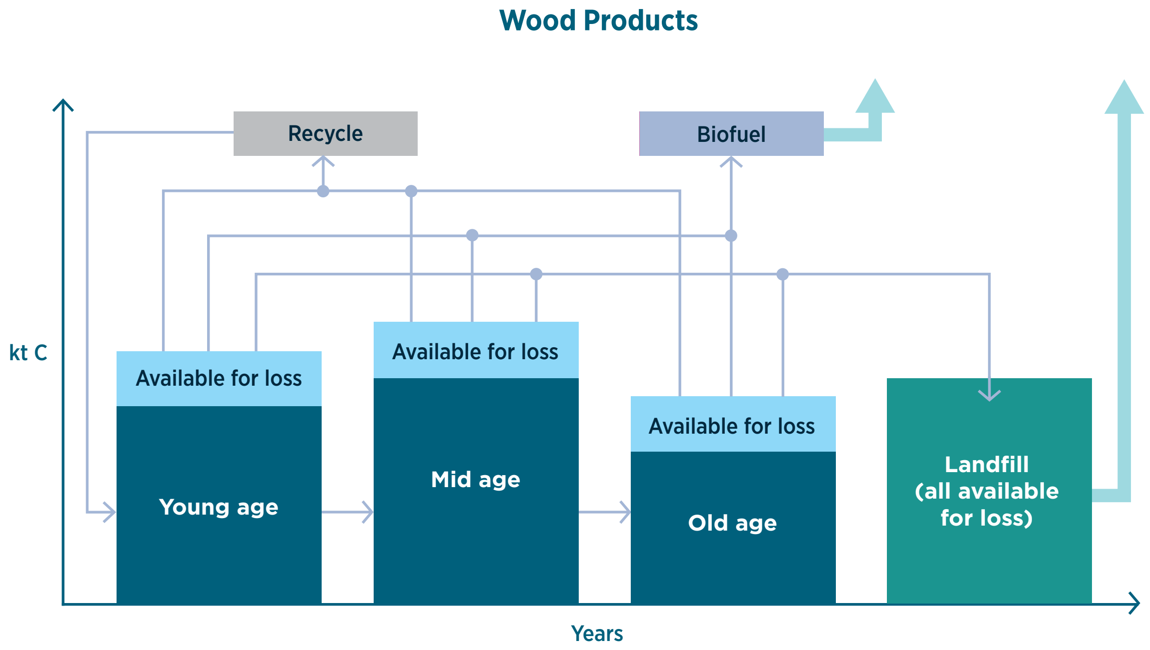
Life span of timber products (recycling and landfill)

The life span of wood products must be taken into account when ascertaining the quantity of carbon stored in timber products. Considerable attention has been given to subdividing the various timber products pools into different classes based on product and decay rates. The decay rates used assume that losses of material from service life will increase with product age. Therefore, the entry and exit of material from production to loss from each product pool is tracked and aged according to three age classes; young, medium and old. The proportion of material lost from each pool may vary (e.g., there may be little loss from young pools (excluding those to the medium age class)). Material is lost at a constant rate and may be placed in landfill, recycled, used for bioenergy or lost to the atmosphere (e.g., burnt with no energy capture) (Figure 6.10.1). The destination of material lost from service life is shown in Table 6.10.3.

Table 6.10.3 Destination of material lost from service life (kt C)

Year	Disposed to Landfill	Recycling and recovery of residues	Fuelwood consumed	Emissions other than biofuel (e.g. Aerobic decay)
1989-90	1,278	1,633	461	527
1994-95	1,363	2,022	531	321
1999-00	1,401	2,323	550	284
2004-05	1,518	2,477	544	423
2005-06	1,459	2,529	536	535
2006-07	1,335	2,530	546	698
2007-08	1,236	2,555	570	836
2008-09	1,170	2,512	444	908
2009-10	969	2,553	420	1,120
2010-11	1,041	2,464	401	1,117
2011-12	890	2,490	427	1,045
2012-13	859	2,426	318	1,177
2013-14	825	2,460	352	1,107
2014-15	805	2,535	360	1,037
2015-16	803	2,555	356	1,059
2016-17	722	2,716	317	1,166
2017-18	792	2,668	293	1,176
2018-19	821	2,707	271	1,108
2019-20	779	2,712	263	1,115
2020-21	742	2,752	300	1,031
2021-22	743	2,777	314	1,051

Figure 6.10.1 Structure of the Wood Products Model



For shorter-term products, the impact of the size of previous stocks is fairly slight, as the recent additions to the pools have the major impact. For long-term products, an estimate of the size of the initial pool is essential, but difficult. The size of the longest-lived pool representing housing products uses housing starts data.

Life span pools assumed for the Carbon Model

Very short-term products – Pool 1

- Paper and paper products.
- Woodchips and pulp logs for export.
- Age: young = 1; medium = 2; old = 3

Short-term products – Pool 2

- Hardwood – pallets and palings.
- Particleboard and MDF – shop fitting, DIY, miscellaneous.
- Plywood – form board.
- Hardboard – packaging.
- Age: young = 2; medium = 6; old = 10

Medium-term products – Pool 3

- Softwood – pallets and cases
- Plywood – other (noise barriers).
- Particleboard and MDF – kitchen and bathroom cabinets, furniture.
- Preservative treated softwood – decking and palings.
- Age: young = 10; medium = 20; old = 30

Long-term products – Pool 4

- Preservative treated softwood – poles and roundwood.
- Softwood – furniture.
- Roundwood logs for export.
- Age: young = 20; medium = 30; old = 50

Very long-term products – Pool 5

- Softwood – framing, dressed products (flooring, lining, mouldings).
- Cypress – green framing, dressed products (flooring, lining).
- Hardwood – green framing, dried framing, flooring and boards, furniture timber, poles, piles, girders, sleepers and other miscellaneous products.
- Plywood – structural, LVL, flooring, bracing, lining.
- Particleboard and MDF – flooring and lining.
- Softboard and Hardboard – weathertex, lining, bracing, underlay.
- Preservative treated softwood – sawn structural timber.
- Age: young = 30; medium = 50; old =90

A specified proportion of material is lost annually (an exponential loss) from each age class of each in-use product pool. The amount lost from each age class for each product pool can be capped and different proportions can be lost according to age. This feature of the model provides for 'steps' in product loss rather than functioning on either a simple linear or exponential loss applied to a whole product pool, irrespective of the average age of the pool. If inputs vary over time, the average age of products will vary, and this is represented by the amounts of material in each age class of each product pool.

Initial stock assumptions

Input data is available for the model since 1940. This has the benefit of allowing the model to establish equilibrium pools, as the input material may be 'turned-over' several times prior to an equilibrium stock being reached for recent years. Initial stock estimation (for 1940) is more important for Pool 5 as this material may remain in use in housing assets.

Model calibration

Once the data on production inputs, processing flows and initial stocks is determined, other model calibration requirements include:

- the age at which material moves from young to medium and medium to old pools;
- the amount of each age class for each product pool exposed to loss;
- the rate of loss from each age class in each product pool; and
- the fraction of losses from each age class in each product pool to each of landfill, recycling, bioenergy and otherwise to the atmosphere.

The model estimates used are presented in Table 6.10.4 and Table 7.6 (in Chapter 7).

Table 6.10.4 Decomposition rates and maximum possible loss

	YOUNG		MEDIUM		OLD	
Pool	Loss Yr^{-1}	Proportion of in use Pool exposed to decay	Loss Yr^{-1}	Proportion of in use Pool exposed to decay	Loss Yr^{-1}	Proportion of in use Pool exposed to decay
1	1.0	0.60	1.0	0.65	1.0	0.90
2	0.50	0.30	0.25	0.50	0.25	0.90
3	0.10	0.15	0.10	0.65	0.10	0.45
4	0.05	0.25	0.10	0.65	0.05	0.80
5	0.033	0.20	0.05	0.55	0.025	0.95

Model results

By integrating the carbon pools and life cycles of wood products, the model enables the total carbon pools and emissions to be estimated (Table 6.10.5).

Table 6.10.5 Carbon stock and emissions outcomes (kt C)

	Domestic Production of Wood Products	Imports of Wood Products	Exports of Wood Products	Increase Due to Wood Products	Carbon Pool (excl. landfill)
Year	kt C	kt C	kt C	kt C	kt C
1989-90	2,905	854	855	2,903	58,195
1994-95	3,503	989	1,190	3,302	63,612
1999-00	4,401	1,063	1,782	3,683	68,784
2004-05	4,931	1,226	2,193	3,964	74,437
2005-06	4,882	1,316	2,170	4,028	75,579
2006-07	5,045	1,198	2,389	3,855	76,569
2007-08	5,128	1,220	2,390	3,959	77,629
2008-09	4,700	1,075	2,259	3,516	78,276
2009-10	4,608	1,144	2,314	3,437	78,987
2010-11	4,694	1,252	2,467	3,480	79,733
2011-12	4,413	1,177	2,183	3,408	80,446
2012-13	4,145	1,186	1,994	3,336	81,193
2013-14	4,605	1,176	2,508	3,272	81,932
2014-15	4,989	1,188	2,811	3,366	82,759
2015-16	5,404	1,144	3,115	3,433	83,656
2016-17	5,798	1,116	3,472	3,443	84,603
2017-18	5,917	1,178	3,585	3,510	85,658
2018-19	5,837	1,121	3,506	3,452	86,631
2019-20	5,221	981	2,940	3,262	87,500
2020-21	4,887	939	2,509	3,318	88,525
2021-22	4,691	1,102	2,295	3,497	89,725

6.10.3 Uncertainty assessment and time-series consistency

A qualitative assessment of uncertainty was undertaken and uncertainties for *harvested wood products* were estimated to be medium. Time series consistency is ensured by the use of consistent methods and full recalculations in the event of any refinement to methodology.

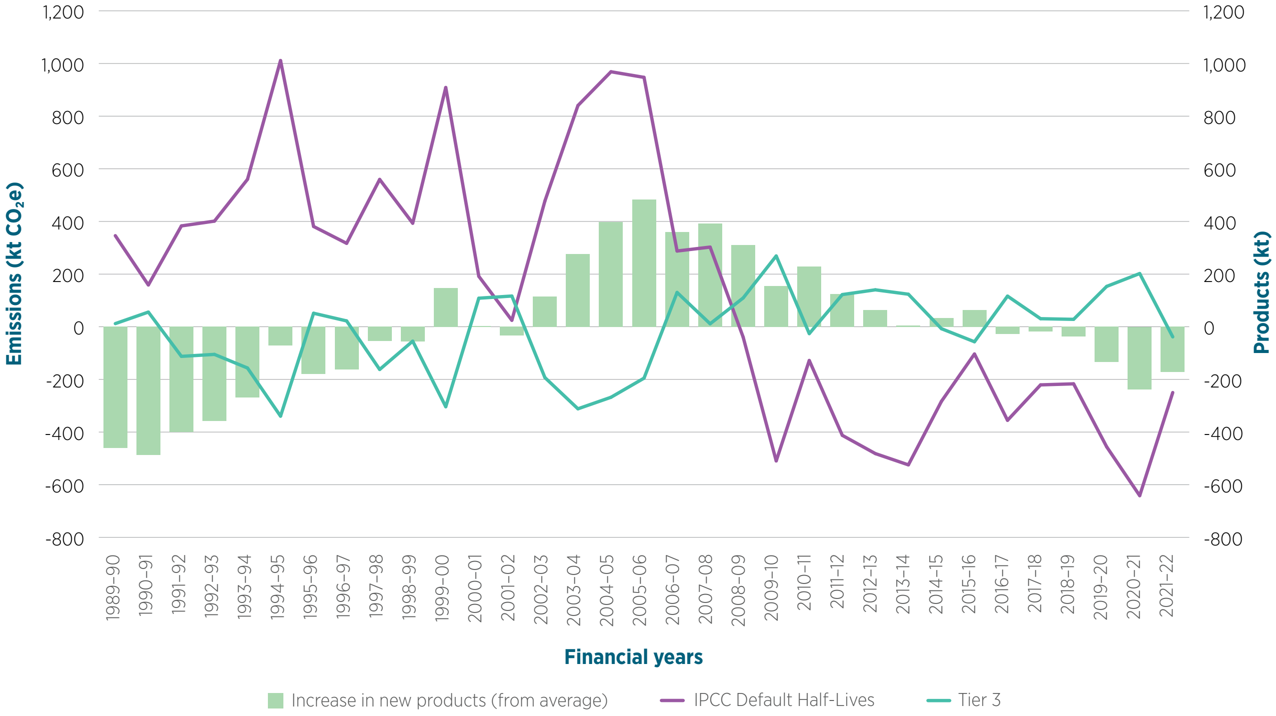
6.10.4 Category-specific QA/QC and verification

Principal quality control on the Australian Forests Products Statistics is undertaken by the ABARES. Economic data from the Australian Bureau of Statistics on the wood and paper products manufacturing industry is also used as a confrontational data source.

A Tier 2 model using IPCC default half-lives is used to compare Australia's tier 3 method with a tier 2 equivalent. Figure 6.10.2 shows that overall, both approaches yield similar results, with the difference predominantly reflecting how the two models account for declining production in short-lived paper products (see Table 6.10.6). Australia's Tier 3 model relies on country-specific factors and modelling that show young products turn over quicker than products that have been in service for longer periods, and so the emissions results are less influenced by short term variability of fresh inputs than the Tier 2 equivalent (Figure 6.10.3).

Figure 6.10.2 Verification of Tier 3 model for HWP by comparison to IPCC Tier 2 First Order Decay model

Figure 6.10.3 Comparison of the variability in the treatment of paper products by the Tier 3 model and IPCC Tier 2 First Order Decay Model



Decay of other short-term products (Pool 2 in Table 6.10.6) is faster than the default half-lives provided by the IPCC, while the effective loss rate of very long-lived products (Pool 5) is slower, as only a proportion of the pool is considered available for loss in each year in the T3 model. These counteracting differences have little impact on reported net emissions.

Table 6.10.6 Comparison of product pools (note exclusions in IPCC are to avoid double counting)

Pool	Australian Definition	IPCC Definition/equivalent (from 2019 refinement definitions, 12.12)
1 (very short-term products)	Paper and paper products. Woodchips and pulp logs for export. Composite half-life: 0.69	**Paper and paperboard** Aggregate category. The sum of: graphic papers; sanitary and household papers; packaging materials and other paper and paperboard. Excludes manufactured paper products such as boxes, cartons, books and magazines, etc. Default half-life: 2
2 (short-term products)	Hardwood – pallets and palings. Particleboard and MDF – shop fitting, DIY, miscellaneous. Plywood – form board. Hardboard – packaging. Composite half-life: 2.63	Wood-based panels An aggregate comprising: veneer sheets, plywood, particle board, and fibreboard Default half-life: 25
3 (medium-term products)	Softwood – pallets and cases Plywood – other (noise barriers). Particleboard and MDF – kitchen and bathroom cabinets, furniture. Preservative treated softwood – decking and palings. Composite half-life: 6.93	

Pool	Australian Definition	IPCC Definition/equivalent (from 2019 refinement definitions, 12.12)
4 (long-term products)	Preservative treated softwood – poles and roundwood. Softwood – furniture. Roundwood logs for export. Composite half-life: 11.07	**Sawnwood** Wood that has been produced from both domestic and imported roundwood, either by sawing lengthways or by a profile-chipping process and that exceeds 6 mm in thickness. It includes: planks, beams, joists, boards, rafters, scantlings, laths, boxboards and "lumber", etc., in the following forms: unplaned, planed, end jointed, etc. It excludes: sleepers, wooden flooring, mouldings (sawnwood continuously shaped along any of edges or faces, like tongued, grooved, rebated, V-jointed, beaded, moulded, rounded or the like) and sawnwood produced by re-sawing previously sawn pieces. Default half-life: 35
5 (very long-term products)	Softwood – framing, dressed products (flooring, lining, mouldings). Cypress – green framing, dressed products (flooring, lining). Hardwood – green framing, dried framing, flooring and boards, furniture timber, poles, piles, girders, sleepers and other miscellaneous products. Plywood – structural, LVL, flooring, bracing, lining. Particleboard and MDF – flooring and lining. Softboard and Hardboard – weathertex, lining, bracing, underlay. Preservative treated softwood – sawn structural timber. Composite half-life: 19.38	

6.10.5 Category-specific recalculations

Recalculations as shown in Table 6.10.7 are due to time-series revisions to the underlying source data on forestry and wood products produced by ABARES, and revisions in the Waste sector, which impact HWP in SWDS.

Table 6.10.7 Recalculations of the HWP inventory

Year	2022 submission (kt CO_2-e)	2023 submission (kt CO_2-e)	Change (kt CO_2-e)
1989-90	-7,384	-7,137	247
1994-95	-7,511	-7,495	16
1999-00	-7,754	-7,728	27
2004-05	-7,840	-7,935	-95
2005-06	-7,497	-7,505	-9
2006-07	-6,377	-6,472	-96
2007-08	-6,387	-6,362	25
2008-09	-4,763	-4,616	147
2009-10	-4,228	-4,137	91
2010-11	-4,734	-4,575	159
2011-12	-4,014	-3,935	79
2012-13	-4,045	-3,987	58
2013-14	-3,969	-3,863	107
2014-15	-4,199	-4,124	75
2015-16	-4,414	-4,396	18
2016-17	-4,538	-4,378	160
2017-18	-5,162	-5,089	73
2018-19	-4,929	-4,952	-23
2019-20	-4,400	-4,420	-20
2020-21	-4,913	-4,931	-19

6.10.6 Category-specific planned improvements

All data and methodologies are kept under review and development.

6.11 N_2O emissions from N fertilisation – 4(I)

Nitrous oxide emissions, associated with nitrogen fertilisers, are reported under the *Agriculture* sector (3D). N_2O released from the application of N fertiliser on forests is reported as Included Elsewhere (IE) in *Agriculture.* The amount of N applied to lands in Australia is obtained from national statistics of the amount of N purchased. It is not possible to disaggregate the use of N fertiliser between agriculture and forestry uses.

N fertilisation of native forests is very rare, if occurring at all. There is a limited amount of N fertiliser applied to forest plantations in Australia. Fertiliser application in plantations is typically done to correct for nutrient deficiencies and trace element correction at establishment. N may be applied on sites where it is shown that it is a significant limiting nutrient, but as most establishments are on pasture systems, background nutrient levels are typically sufficient.

6.12 Emissions and removals from drainage and rewetting and other management of organic and mineral soils – 4(II)

Drawing upon guidance on *Flooded lands* from the 2019 Refinement to the IPCC Guidelines (pp 7.1-7.29) (IPCC 2019), Australia is able to report methane emissions from *Reservoirs* and *Other constructed waterbodies* as part of *flooded land remaining flooded land.* Carbon dioxide emissions from inundated land associated with newly established reservoirs are also reported under *land converted to flooded land* for a period of 20 years from the date the reservoir was completed.

For ease of reporting, all *Reservoirs* and *Other constructed water bodies* emissions (CO_2 and CH_4) are reported in Common Reporting Table 4(11): 4.D.2 *Flooded Lands* (on mineral soils).More information is provided in Chapter 6.7 (Wetlands).

6.13 Direct and Indirect N_2O emissions from managed soils – 4(III) and 4(IV)

N_2O emissions from N mineralisation associated with loss of soil organic matter

An increase in N_2O emissions can be expected following a decline in soil organic carbon stocks. This is a consequence of enhanced mineralisation of soil organic matter that takes place as a result of soil disturbance. The conversion not only results in the net loss of soil organic carbon, but the corresponding effects on mineralised nitrogen can result in N_2O emissions from the process of nitrification and denitrification.

The (IPCC 2006) methods are used to calculate N_2O emissions from this source. The amount of nitrogen mineralised is calculated from the C:N ratio of soil. The C:N values used are 18 for *forest land* and forest conversion categories and 10 for *grassland remaining grassland,* reflecting the approximate median value extracted from a survey of national estimates (Snowdon, Ryan and Raison 2005). The country specific emission factor for fertiliser additions to non-irrigated crops and pastures (0.0021 (kt N_2O-N/kt N)) is then applied.

Emissions associated with N mineralisation in *cropland remaining cropland* soils are reported in the Agriculture sector (3.D).

Leaching and run-off

Estimates are made of emissions associated with leaching and run-off of the N mineralised through loss of soil carbon, using country-specific emission factors.

Annual nitrous oxide production from leaching and runoff is calculated as:

$$E_{ij} = M_{ij} \times FracWET_{ij} \times FracLEACH \times EF \times C_g \qquad (6.13.1)$$

Where M_{ij} = mass of N mineralised due to a loss of soil carbon (kt N)

$FracWET_{ij}$ = fraction of N available for leaching and runoff (Annex 5.5.10)

FracLEACH = 0.24 (kt N/kt applied) (IPCC 2019) default fraction of N lost through leaching and runoff

EF = 0.011 (kt N_2O-N/kt N) IPCC (2019) default EF

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

6.14 Biomass Burning – 4(V)

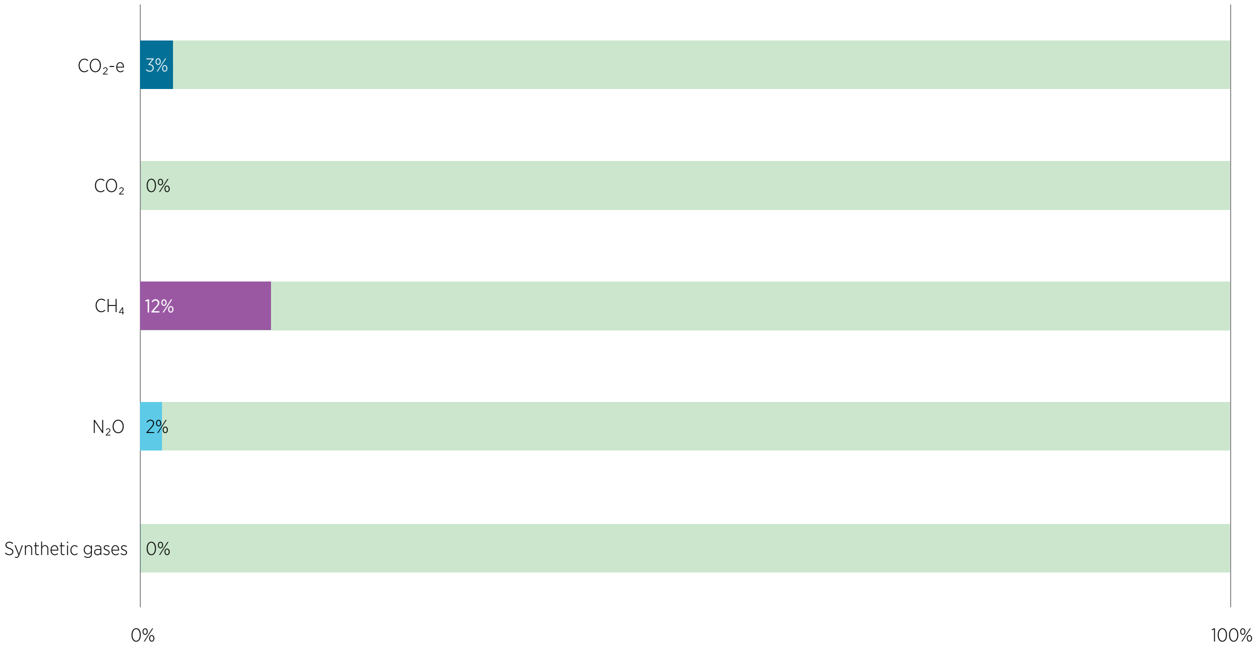
The methods applied to estimate emissions and removals associated with biomass burning are described in Chapter 6.3.2.

7. Waste

7.1 Overview of the sector and background information

The waste category covers greenhouse gas emissions from waste disposal and treatment systems. The waste sector as a portion of total emissions (excluding LULUCF) is presented in Figure 7.1.

Figure 7.1 Share of national emissions (excluding LULUCF) for the waste sector by gas, 2021–22



The majority of emissions within the waste sector are from *solid waste disposal,* followed by *wastewater treatment and discharge.* Emissions from waste *incineration* and *biological treatment of solid waste* contribute only a small amount. Waste emissions are predominantly methane, generated from anaerobic decomposition of organic matter. Small amounts of carbon dioxide are generated through the incineration of solvents and clinical waste and nitrous oxide through the decomposition of human wastes. Changes in emissions by subsector since 1989–90, 2004–05 and 2020–21 are shown in Figure 7.2.

Figure 7.2 Comparison of 2021–22 emissions with past emissions levels from key waste subsectors, million tonnes of carbon dioxide equivalent (Mt CO_2–e) and percentage change (%)

		Change in 2021–22 emissions since:		
Waste Subsectors	**2021–22 emissions**	**1989–90**	**2004–05**	**2020–21**
5.A Solid Waste Disposal	**11 Mt**	-7 Mt CO_2-e ▼ -38%	-2 Mt CO_2-e ▼ -14%	▲ +5% +0.5 Mt CO_2-e
5.B Biological Treatment of Solid Waste	**0.3 Mt**	▲ +1,215% +0.3 Mt CO_2-e	▲ +97% +0.1 Mt CO_2-e	▲ +1% <+0.1 Mt CO_2-e
5.C Incineration and Open Burning of Waste	**<0.1 Mt**	-0.1 Mt CO_2-e ▼ -62%	▲ +12% <+0.1 Mt CO_2-e	▲ +0.4% <+0.1 Mt CO_2-e
5.D Wastewater Treatment and Discharge	**3 Mt**	-3 Mt CO_2-e ▼ -52%	-0.3 Mt CO_2-e ▼ -9%	-0.1 Mt CO_2-e ▼ -2%
5.E Other	**NE**	–	–	–

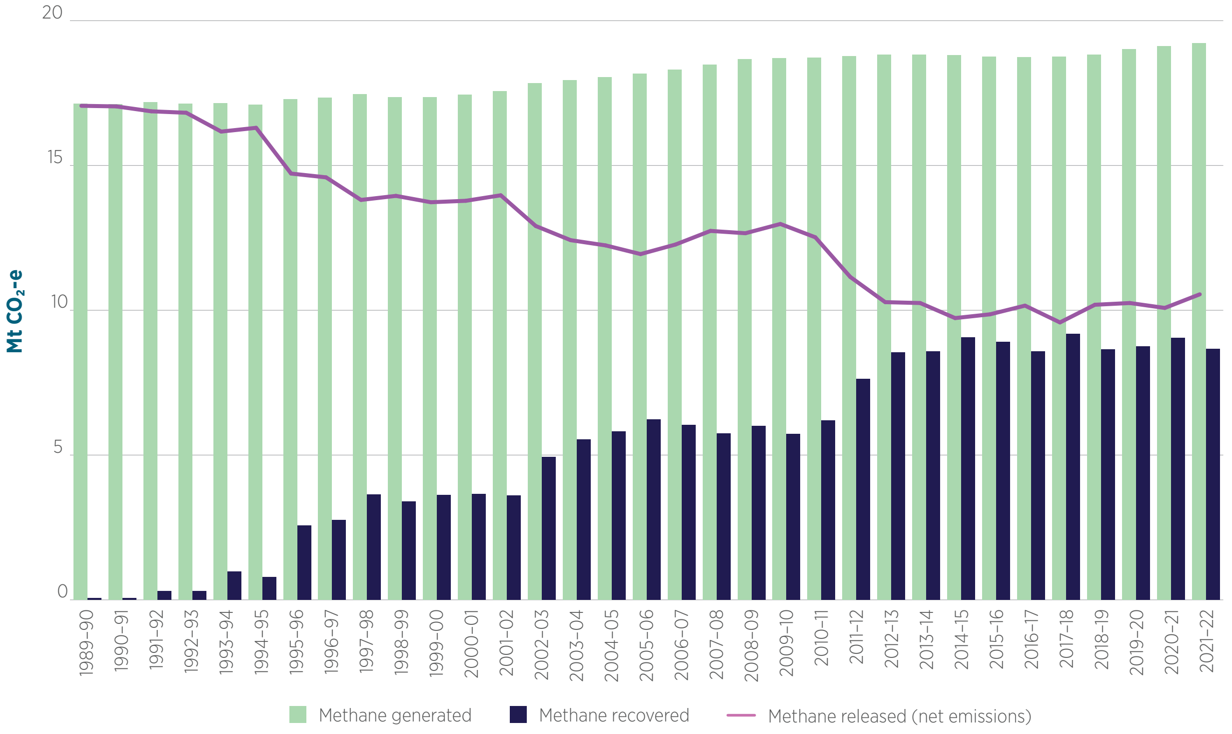
Note: NE = Not Estimated. Icons in this figure are sourced from Uniconlabs, kliwir art, juicy_fish, hindra, and Creatype on flaticon.com.

Total estimated waste emissions have decreased since 1989–90 (Figure 7.2). This decline has been driven by reductions in emissions from *solid waste disposal* and *wastewater treatment and discharge*.

As waste degradation is a slow process, estimates of methane generation from *solid waste disposal* reflect waste disposal levels and composition over several decades. In recent years, as rates of recycling have increased, paper disposal in particular has declined as a share of total waste disposed. Total waste disposal has also declined in recent years as alternative waste treatment options are becoming more viable, driven by state and territory waste management policy.

Rates of methane recovery from *solid waste* have improved substantially, increasing from a negligible amount in 1989–90 to almost half of total methane generation in recent years (Figure 7.3).

Figure 7.3 Trends in methane generation, recovery, and emissions from solid waste disposal, 1989–90 to 2021–22



Wastewater treatment and discharge emissions have decreased by around half since 1989–90, largely driven by changes in industry production, population loads on centralised treatment systems and the amount of methane recovered for combustion or flaring.

Table 7.1 Summary of methods and emission factors used to estimate emissions from waste

	CO_2		CH_4		N_2O	
	Method applied	Emission factor	Method applied	Emission factor	Method applied	Emission factor
5. Waste						
A. Solid waste disposal	NA	NA	T2/3	D	NA	NA
B. Biological treatment of solid waste	NA	NA	T1	CS	T1	CS
C. Incineration and open burning of waste	T2	CS	T2	CS	T2	CS
D. Wastewater treatment and discharge	NA	NA	T2/3	CS/D	CS	D

T1= Tier 1, T2 = Tier 2, CS = country specific, M = model, D = default, NE = not estimated, NA = not applicable, ▨ = key category

7.2 **Solid Waste Disposal** (CRT category 5.A)

7.2.1 Category description

The anaerobic decomposition of organic matter in a landfill is a complex process that requires several groups of microorganisms to act in a synergistic manner under favourable conditions. Emissions emanate from waste deposited over a long period (in excess of 50 years in the Australian inventory). The final products of anaerobic decomposition are CH_4 and CO_2. Emissions of CO_2 generated from solid waste disposal are considered to be from biomass sources and, therefore, are not included in the waste sector of the inventory. CO_2 produced from the flaring of methane from waste is also considered as having been derived from biomass sources.

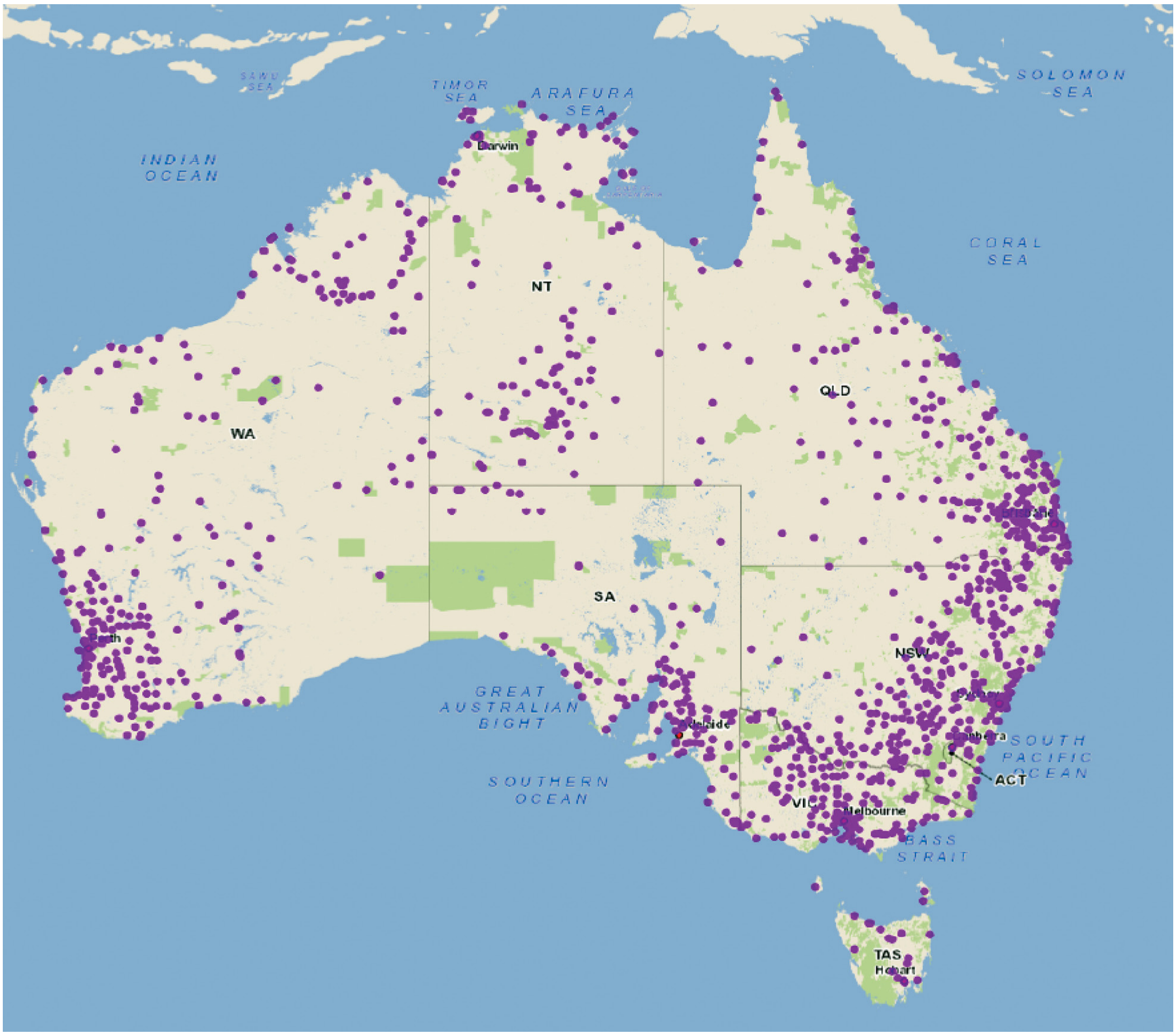
Common with the practice in many other developed economies, solid waste is processed in Australia via four main mechanisms:

- landfill;
- biological treatment/composting;
- incineration; and
- recycling/reuse.

There are approximately 1,168 operating landfills in Australia (disposal facilities). These landfills receive around a third of the estimated total waste generated in Australia with most of the remainder being recycled or reprocessed (including biological treatment/composting and a negligible amount is treated thermally (incinerated). Figure 7.3shows the physical locations of the major landfills in Australia. The map shows that landfills are clustered around the large population centres around Australia's coastline.

Australia's solid waste management task has become more concentrated in the last decade with many smaller landfills closing and larger centralised landfills taking the bulk of disposed waste. On the basis of the National Greenhouse and Energy Reporting (NGER) scheme data, a relatively small number of sites are responsible for the bulk of the waste received in Australia. Fifty per cent of Australia's waste disposal occurs in the 21 largest landfills. Around 11 per cent of landfills have a landfill gas collection system in place. However, this practice is more common in larger scale landfills, meaning that almost half of the methane generated by solid waste disposal is collected for either flaring or energy generation.

Figure 7.4 Australian landfill locations



Source: DCCEEW – National Waste Reporting Mapping Tool, 2013.

Additions to and losses from the pool of organic carbon in landfills, including both degradable and non-degradable organic carbon from all waste types, are presented in Table 7.2. Half of the carbon losses are assumed to result in the generation of methane (assuming that the share of carbon decay resulting in methane, F, is the IPCC default value of 0.5). The other half is assumed to be carbon dioxide.

The balance of emissions associated with Harvested Wood Products in Solid Waste Disposal Sites is reported in LULUCF (Chapter 6.10). All other CO_2 emissions are assumed to be related to biomass sources, the growth of which are either already accounted for in LULUCF or are assumed to be in equilibrium over the longer term, in accordance with default IPCC-based assumptions.

Table 7.2 Methane generation and emissions, Australia: 1989–90 to 2021–22

Year	Carbon additions to landfill (kt C)	Carbon loss (through emissions) (kt C)	Methane generated (Gg CH_4)	Methane captured (Gg CH_4)	Net methane (Gg CH_4)
1989–90	2,264	1,017	679	2	609
1994–95	2,344	1,011	675	28	582
1999–00	2,506	1,009	674	129	490
2004–05	2,659	1,038	693	207	437
2005–06	2,625	1,042	696	222	426
2006–07	2,572	1,052	703	216	438
2007–08	2,528	1,064	711	205	455
2008–09	2,435	1,073	717	215	452
2009–10	2,288	1,077	719	204	464
2010–11	2,364	1,075	718	221	447
2011–12	2,143	1,070	715	272	398
2012–13	2,090	1,068	713	305	367
2013–14	2,110	1,067	713	306	366
2014–15	2,062	1,063	710	324	348
2015–16	2,018	1,062	709	318	352
2016–17	1,956	1,062	710	306	363
2017–18	2,187	1,060	708	328	342
2018–19	2,220	1,067	713	309	364
2019–20	2,216	1,077	720	313	366
2020–21	2,258	1,082	723	323	360
2021–22	2,246	1,090	728	310	377

7.2.2 Methodological Issues

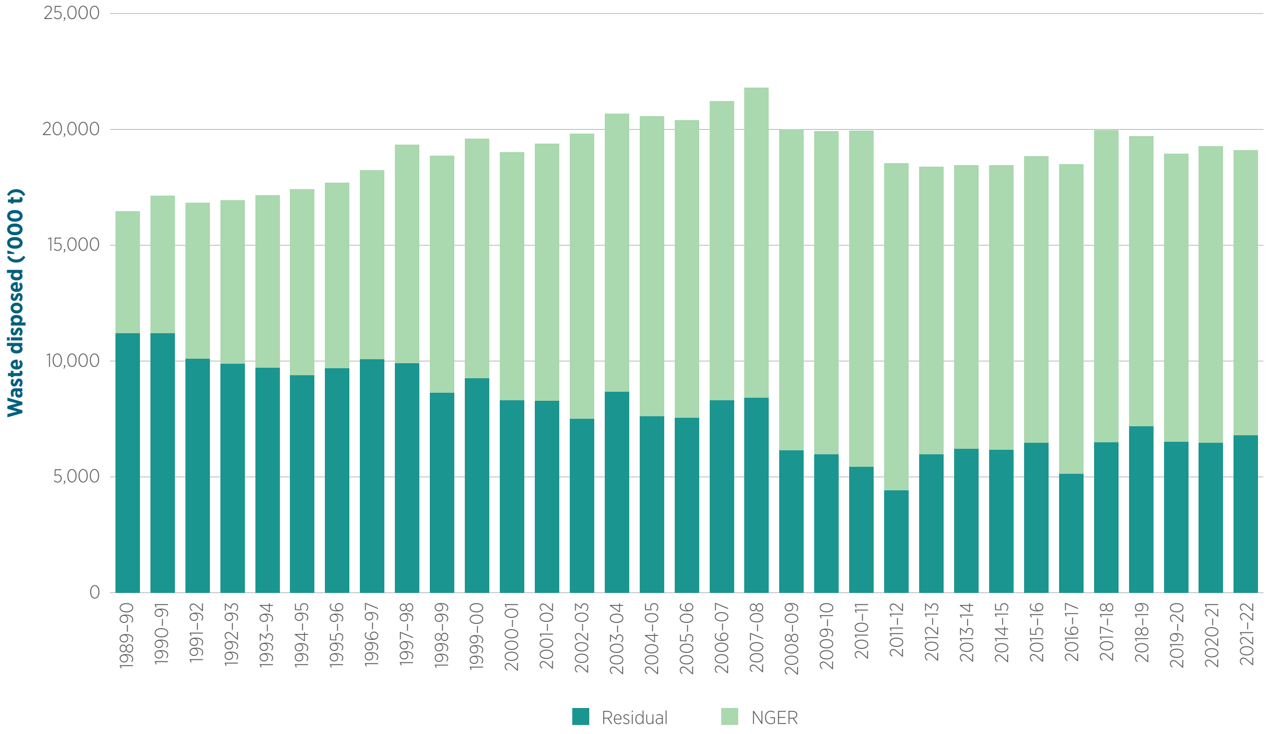
The Australian methodology for calculating greenhouse gas emissions from solid waste is consistent with the IPCC tier 2 First Order Decay (FOD) Model (IPCC) (2006). The methodology deployed utilises a dynamic model driven by landfill data provided by the relevant State/Territory Government agencies responsible for waste management together with facility-level data obtained under the NGER scheme. Although the structure of the methodology is constant across States, climate-specific parameters introduce variations in estimated emissions depending on location. The model tracks the stock of carbon estimated to be present in the landfill at any given time. Emissions are generated by the decay of that carbon stock and reflects waste disposal activity over many decades. The methodology is fully integrated with the results of the Harvested Wood Products (HWP) model reported in Chapter 6.10, including for the estimation of HWP in SWDS.

Australian waste generation and disposal to landfill

Quantities of waste disposed to landfill are collected by State Government agencies (and in most cases also published). Fluctuations in waste disposed to landfill has been observed in Australia's states and territories since the early 1990s reflecting, in part, differences in population growth and the impact of state government policies on waste management (Figure 7.6).

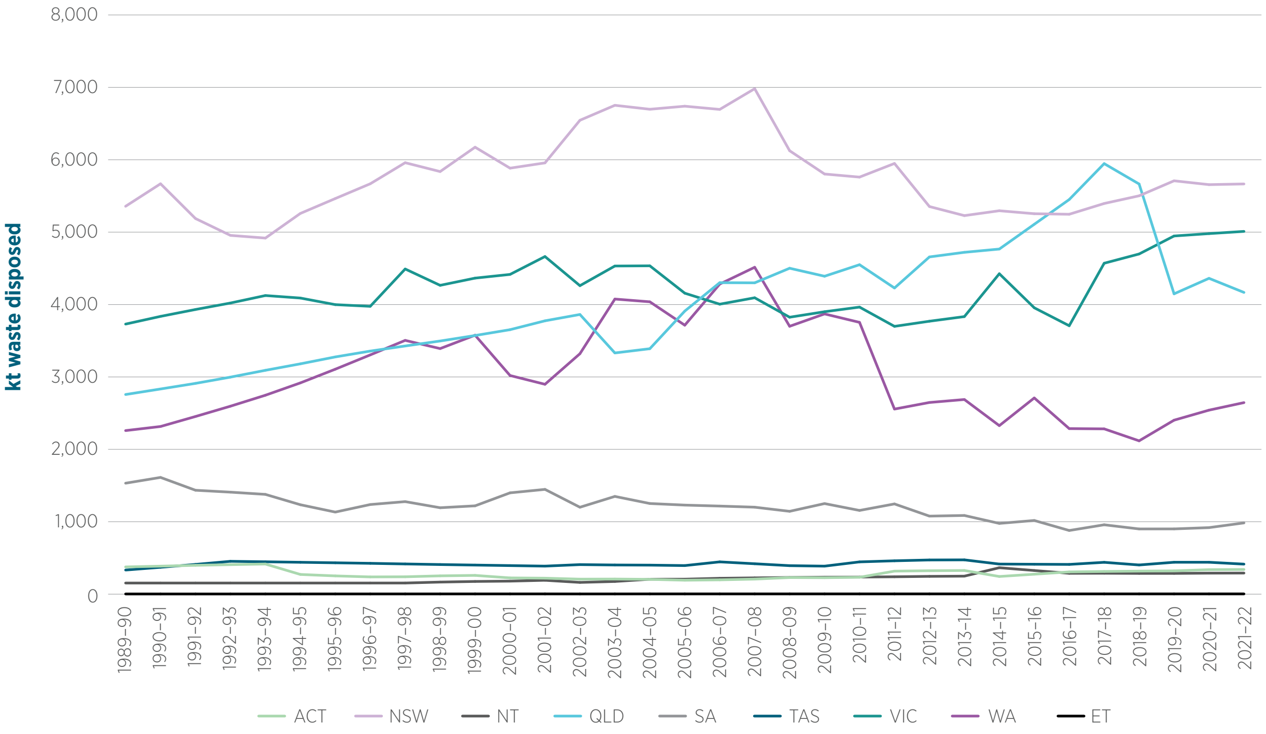
In addition to total disposal in each state and territory, disposal at individual landfills is obtained under the NGER scheme for landfills meeting the reporting thresholds. A majority of total disposal is covered by NGER scheme facility data (see Figure 7.5). The residual disposal not covered by the NGER scheme is calculated as the total disposal reported for each state and territory minus the sum of NGER disposal in each State and Territory.

Figure 7.5 NGER scheme waste disposal coverage 1989–90 to 2021–22



Activity data reported in this report and the accompanying Common Reporting Tables are for waste disposal to landfill as opposed to waste generated. State and territory landfill levy schemes are applied specifically to waste disposed and the NGER scheme reporting requirements have also been designed to be consistent with this principle.

Figure 7.6 Solid waste to landfill by state and territory 1989–90 to 2021–22



Waste streams

Total waste to landfill data is disaggregated into three major waste streams, defined according to relevant State and Territory Government legislation and broadly consistent with the following:

- **municipal solid waste** – waste generated by households and local government in their maintenance of civic infrastructure such as public parks and gardens;
- **commercial and industrial waste** – waste generated by business and industry, for example shopping centres and office blocks or manufacturing plants; and
- **construction and demolition waste** – waste resulting from the demolition, erection, construction, alteration or refurbishment of buildings and infrastructure. Construction and demolition waste may also include hazardous materials such as contaminated soil or asbestos.

State/Territory and NGER scheme data have been used to determine the stream percentages. Where disaggregated historical data cease, the stream shares have been held constant back to 1940 (Table 7.3).

Table 7.3 Waste streams: municipal, commercial and industrial, construction and demolition: percentages by State: 2021–22

	NSW	VIC	QLD	NT	SA	WA	TAS	ACT
Municipal Solid Waste	34.2%	44.1%	43.5%	42.8%	42.8%	36.2%	38.7%	31.2%
Commercial and Industrial	49.2%	28.3%	40.2%	14.3%	18.0%	41.1%	56.8%	61.8%
Construction and Demolition	16.6%	27.6%	16.3%	42.9%	39.2%	22.7%	4.5%	7.0%

Note: External Territories waste stream breakdown is assumed to be the same as QLD.

Some States include clean fill (uncontaminated inert solid material) in their waste to landfill estimates provided and this has an influence on the waste stream proportions. As this type of waste is largely inert, there is little effect on the final emissions estimate.

Individual waste types

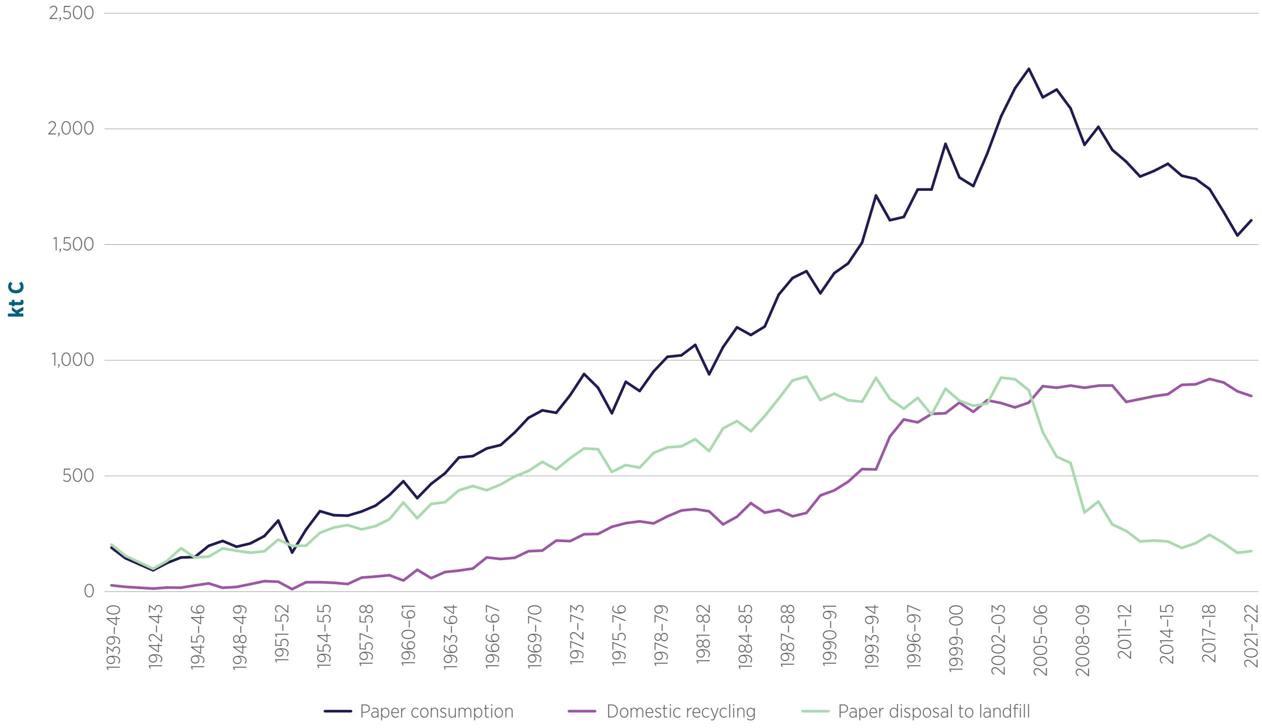
Each waste stream is further disaggregated into a mix of individual waste type categories that contain significant fractions of biodegradable carbon. The categories considered are as follows:

- Food;
- Paper;
- Garden and green;
- Wood;
- Wastes from the production of harvested wood products;
- Textiles;
- Sludge (including biosolids);
- Nappies;
- Rubber and leather; and,
- Inert (concrete, metal, plastics, glass, soil etc).

Harvested wood products – Paper wood and wood waste generation and disposal

The solid waste disposal estimates and composition are integrated with the wood, wood waste and paper disposal estimates output from the harvested wood products model. These quantities of disposal are used to adjust the waste mix percentages for NGER scheme facilities reporting default waste composition and the non-NGER scheme residual proportion of the waste load going to landfill. This adjustment is undertaken to ensure that the total wood, wood waste and paper disposed to all Australian landfills is consistent with the output of the harvested wood products model. This approach also ensures that paper recycling and wood waste diversion practices are reflected in the waste model. Figure 7.7 shows the improvement in paper recycling practices in Australia since 1940.

Figure 7.7 **Paper consumption, recycling, and disposal to landfill – Australia: 1939–40 to 2021–22**



Source: AFWPS (ABARES)

Back casting of total waste disposed to landfill

The data available from State Government agencies on total waste disposed to landfill does not extend to the period prior to 1989–90, nor are there any possibilities for filling in the gaps with future surveys. The technique chosen to determine the historical time series was a surrogate-data technique where the drivers used to determine total waste to landfill were the amount of waste generated from paper consumption and the estimated amount of waste generated from the production of harvested wood products. These data were chosen because published datasets of production and consumption of these variables, which are closely related to disposal, were available back to 1935–36. The surrogate technique applied was to assume that the total waste to landfill correlates with the sum of paper and wood wastes available for disposal to landfill for years prior to 1989–90. This assumption ensures that the more general underlying influences affecting waste generation impact these estimates since: a) rising per capita incomes and rising population are reflected in rising demand for paper consumption and consequent waste generation and b) changes in production functions over time (improvements in efficiency) are reflected in the amount of waste generated in HWP.

For disposal data reported under the NGER scheme, information is available on the entire operational life of the landfills extending to the period before 1989–90. Where these disposal data are available, they have been used. However, it must be noted that this represents only a small proportion of currently operating landfills.

Waste mixes disposed to landfill

Waste composition is determined in two ways. For landfills covered by the NGER scheme, their reported waste composition is used directly. Where these data are not available, country-specific waste mix percentages are used. These waste mix percentages are obtained as outlined below.

The base waste mix percentages are derived as a simple average of waste mixes presented in studies conducted by GHD (2008), and Hyder Consulting (2008). These mixes were confirmed in 2014 by a desktop audit of waste composition data conducted by Anne Prince Consulting. It is assumed that these waste mixes remain representative up to the current inventory year, other than for paper and wood. Table 7.4 shows the resulting waste mix percentages for the current final reporting year.

Table 7.4 Individual waste type mix: percentage share of individual waste streams disposed to landfill, 2021–22

	Municipal Solid Waste	Commercial & Industrial	Construction & Demolition
Food	39.4%	25.0%	0.0%
Paper [(a)]	2.1%	3.4%	0.3%
Garden and Green	18.6%	4.8%	2.0%
Wood [(a)]	1.0%	10.4%	10.4%
Waste from HWP production [(b)]	0.0%	0.0%	0.0%
Textiles	1.7%	4.7%	0.0%
Sludge	0.01%	1.7%	0.0%
Nappies	4.5%	0.1%	0.0%
Rubber and Leather	1.1%	5.2%	0.0%
Inert (concrete, metal, plastics and glass, soil etc)	31.0%	42.7%	87.3%

Source: Derived from GHD (2008), Hyder Consulting (2008) and Anne Prince Consulting (2014)

(a) Proportions vary over time, informed by the HWP model outputs.

(b) Waste generated in the production of HWP is handled at the manufacturing facility.

Table 7.5 Total waste and individual waste types disposed to landfill (kt): Australia

Year	Total waste to landfill	Food	Paper	Garden	Wood and wood waste	Textiles, Sludge, Nappies, Rubber and Leather	Other
	kt	kt	kt	kt	kt	kt	kt
1939–40	10,444	2,403	497	963	680	632	5,269
1989–90	16,500	3,267	2,223	1,373	904	835	7,898
2004–05	20,726	3,637	2,350	1,572	1,344	1,056	10,766
2007–08	21,947	4,142	1,454	1,749	1,521	1,208	11,872
2008–09	20,151	4,058	1,385	1,670	1,433	1,211	10,394
2009–10	20,068	4,231	851	1,757	1,462	1,251	10,516
2010–11	20,103	4,221	968	1,720	1,521	1,299	10,374
2011–12	18,700	4,011	712	1,629	1,407	1,223	9,718
2012–13	18,550	3,965	624	1,594	1,418	1,211	9,739
2013–14	18,610	4,106	510	1,667	1,444	1,272	9,611
2014–15	18,820	4,229	526	1,703	1,382	1,258	9,723
2015–16	19,064	4,112	519	1,724	1,385	1,229	10,094
2016–17	18,579	4,037	394	1,650	1,312	1,202	9,984
2017–18	20,198	4,490	455	1,793	1,419	1,400	10,643
2018–19	19,894	4,606	583	1,729	1,366	1,395	10,215
2019–20	19,160	4,791	515	1,798	1,334	1,427	9,296
2020–21	19,530	4,950	418	1,880	1,337	1,518	9,427

Year	Total waste to landfill	Food	Paper	Garden	Wood and wood waste	Textiles, Sludge, Nappies, Rubber and Leather	Other
	kt	kt	kt	kt	kt	kt	kt
2021–22	19,523	4,990	437	1,894	1,322	1,481	9,399

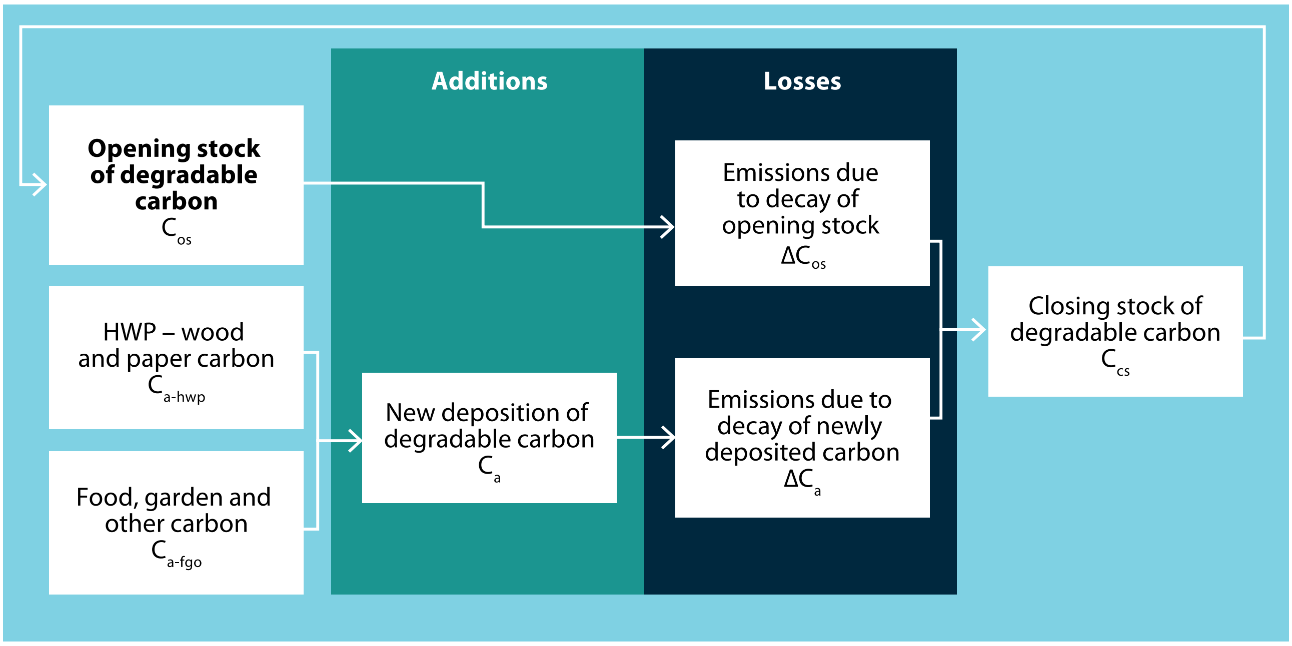
Note: The percentages derived from Table 7.5 will not align with those provided in Table 7.4 as these are based on the entire waste load entering landfill while Table 7.4 presents information by individual waste stream.

Emissions Estimation

The Australian methodology for the estimation of emissions from solid waste disposal utilises the tier 2 first order decay (FOD) model presented in the 2006 IPCC Guidelines (IPCC 2006).

The key parameters determining the amount of methane emissions are the fraction of degradable organic carbon in each individual waste type (DOC); the rate of decay assumed for each individual waste type (decay function ‘k’); the fraction of degradable organic carbon that dissimilates through the life of the waste type (DOC_f); the methane correction factor (MCF); and the amount of methane captured for combustion. The model takes account of the stock of carbon in a landfill by keeping track of additions of carbon through waste disposal and losses due to anaerobic decay. The approach is illustrated in Figure 7.8

Figure 7.8 Carbon stock model flow chart for solid waste to landfill



Carbon enters the landfill system via new deposition of waste (Ca). Deposition is based on wood and paper carbon transferred from the HWP carbon pool (Ca-hwp) and carbon in food, garden and other waste derived from data provided by State and Territory waste authorities (Ca-f). A portion of the newly deposited carbon decays in the first year (ΔCa) and the remainder contributes to the closing stock of carbon (Ccs). Additionally, the opening stock of carbon decays over the year (ΔCos) with the remainder going to the year’s closing stock. The closing stock then becomes the next year’s opening stock (Cos). The total change in carbon stock is used to estimate emissions of methane.

$$C_{cs} = C_{os} - D\,C_{os} + C_a - DC_a$$

In Australia, field work estimating methane generated at particular landfills (Bateman 2009, Dever et al. 2009 and Golder Associates 2009) has demonstrated that there is potentially a wide variation in methane generation rates across Australian landfills. In Australia, this is interpreted as principally reflecting:

- differences in waste composition at landfills, reflecting both the differing values of degradable organic carbon (DOC) of individual waste types and differing values of degradable organic carbon of individual waste types that is dissimilable (DOC_f); and
- differences in the decay rate ‘k’ reflecting differences in waste composition, management regimes or local climatic conditions.

Values for the degradable organic carbon (DOC) content for each waste mix category used in the model are listed in Table 7.6. The source for these parameters are the defaults provided by the 2006 IPCC Guidelines.

Table 7.6 Key model parameters: DOC values by individual waste type

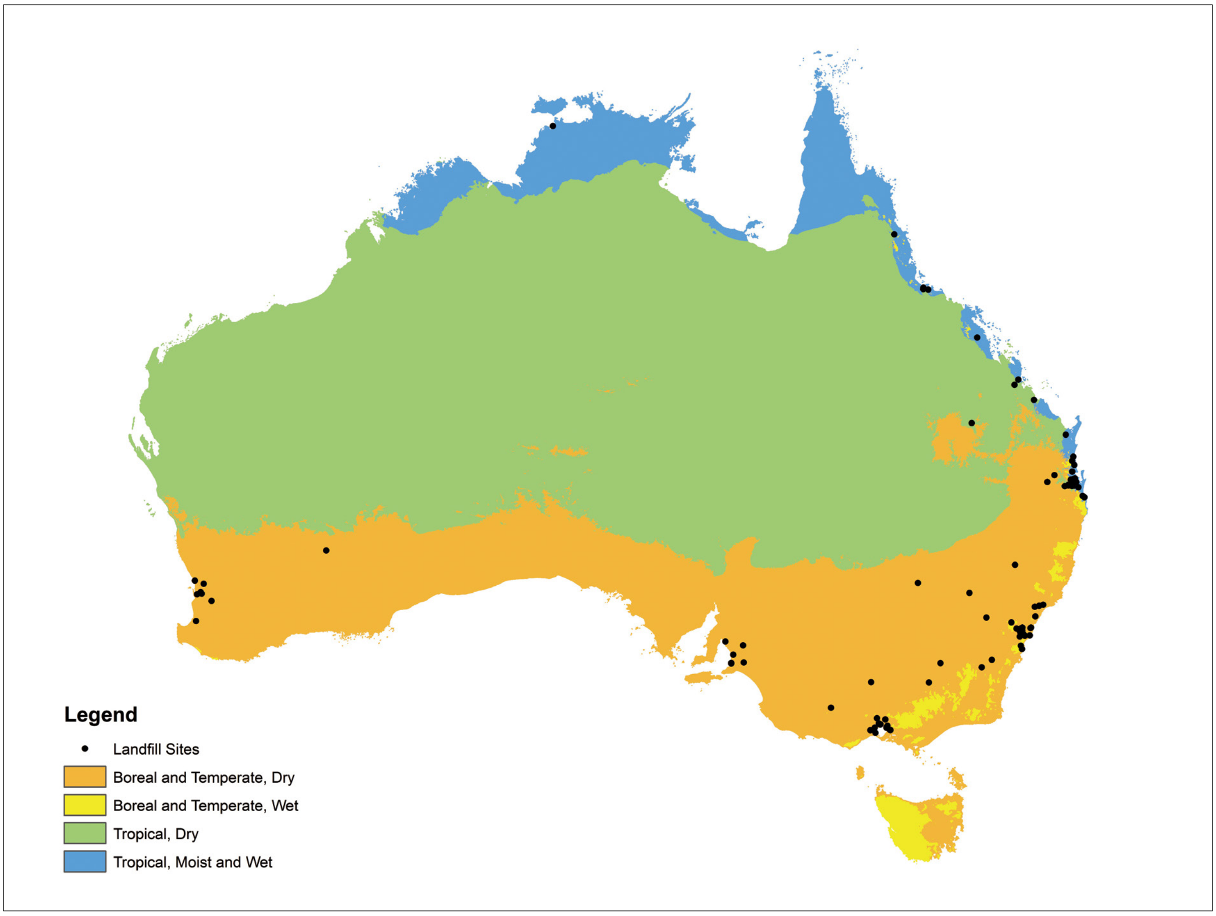
Waste Type (wet)	DOC
Food	0.2
Paper	0.4
Garden and Green	0.2
Wood and waste from HWP production	0.4
Textiles	0.2
Sludge	0.1
Nappies	0.2
Rubber and Leather	0.4
Other	-

The half-lives and associated decay rate constants ‘k’ values for each waste mix category applied in the FOD model are based on the climate conditions at the landfill location and are also consistent with the defaults provided in the 2006 IPCC Guidelines.

Decay rate constants are applied to disposed waste in two ways. For landfills covered by the NGER scheme, the geographical location of the landfill is used to determine which of the 4 IPCC climatic zones is applicable.

The distribution of the climate zones across Australia is illustrated in Figure 7.9. This map has been produced on the basis of average monthly grids of rainfall, pan-evaporation and average temperature from Bureau of Meteorology records between 1970 and 2010.

Figure 7.9 Australian climate zones and major landfill locations



For the proportion of disposed waste not covered by the NGER scheme, decay rate constants are assigned according to the prevailing climatic conditions at the landfill sites of the principal cities in each State and Territory. In each State, average annual temperature and annual rainfall data for the principal landfill sites were taken from data published by the Australian Bureau of Meteorology. The assumptions of climatic conditions for each State/Territory and 'k' values for each waste mix category are outlined in Table 7.7.

Table 7.7 Key model parameters: 'k' values by individual waste type and State Capital

	State / Territory and Climate Description		
	NSW	VIC, WA, SA, TAS, ACT	QLD, NT
Waste mix category	**Wet Temperate**	**Dry Temperate**	**Moist and Wet Tropical**
Food	0.2	0.1	0.4
Paper and Textiles	0.1	0.0	0.1
Garden and Green	0.1	0.1	0.2
Wood	0.0	0.0	0.0
Textiles	0.1	0.0	0.1
Sludge	0.2	0.1	0.4
Nappies	0.0	0.0	0.1
Rubber and leather	0.1	0.0	0.1

DOC_f is an estimate of the fraction of carbon in waste that is ultimately degraded anaerobically and released from solid waste disposal site (SWDS) and reflects the fact the some carbon in waste does not degrade or degrades very slowly under anaerobic conditions (IPCC 2006,Vol 5 p3.13) (IPCC 2006).

Values of DOC_f for individual waste types that are appropriate for Australia have been selected based on well documented research on DOC_f values contained in Barlaz 1998, 2005 and 2008 and Wang *etal.* 2011. These estimates provide an upper limit of an appropriate DOC_f value. The approach adopted, while conservative, is based on the recommendations of Guendehou (2010) after consultations with a range of experts in the industry GHD (2010), Hyder Consulting (2010) and Blue Environment (2010). The results of the Barlaz work are presented in Table 7. which shows reported values for the initial carbon content and carbon remaining after decomposition and the derived DOC_f value.

Table 7.8 DOCf values for individual waste types derived from laboratory experiments

Waste type	Initial total organic carbon (kg/dry kg)	Organic carbon remaining after decomposition (kg/dry kg)	DOCf (A-B)/A
	A	B	
Newsprint	0.49	0.42	0.15
Office paper	0.4	0.05	0.88
Old corrugated containers	0.47	0.26	0.45
Coated paper	0.34	0.27	0.21
Branches	0.49	0.38	0.23
Grass	0.45	0.24	0.47
Leaves	0.42	0.3	0.28
Food	0.51	0.08	0.84

For paper, the Barlaz work translates into a range of DOC_f values, for four classes of paper types meaning that it is important to understand the types of paper waste entering the landfill waste system to assign the appropriate weights for each of the Barlaz results. Newsprint contains high levels of lignin, which inhibits decomposition in anaerobic conditions, while office paper contains almost no lignin and therefore experiences high levels of decomposition even under anaerobic conditions. In addition, the Barlaz paper classes are not exhaustive of all paper types. Allowance must be made for non-identified paper classes. In these cases, consideration must be given to the possible chemical composition of the paper and theoretical approaches to the estimation of methane potential.

Consequently, it was necessary to make use of available waste audit data to compile a weighted average DOC_f value for the “paper and cardboard” waste mix category. Based on paper waste composition data presented in GHD (2008) and Lamborn (2009), the proportions of paper types corresponding to the Barlaz DOC_f categories have been derived for Australian landfills (Table 7.9).

Given that the classes of paper analysed by Barlaz were not comprehensive, a DOC_f value is also required to be assumed for ‘other’ paper. One factor important to the analysis of decomposition under anaerobic conditions relates to the amount of cellulose and hemicellulose in the product (see for example, Lamborn 2009). In the case of the paper types analysed with DOC_f values, the reported cellulose and hemicellulose proportions in the product range from 51.7 for coated paper up to 91.3 for office paper (Bariaz) (1998) . For the classification of ‘other’ paper, the value of cellulose and hemicellulose reported by Lamborn (2009) is 72.0 – which is very much in the middle of the range reported for the waste paper types for which DOC_f values are available.

Consequently, the assumption made is that the DOC_f for the 'other' paper is the weighted average of the paper types for which DOC_f values are available.

Table 7.9 Derivation of a weighted average DOC_f value for paper

Paper type	Composition (% of total paper in analysis) (a)	Cellulose and hemicellulose (%) (b)	DOC_f (c)(%)
Newspaper	4.0%	54.6	15.0
Office paper	11.0%	91.3	88.0
Cardboard	58.0%	67.2	450
Coated Paper	1.0%	51.7	21.0
Other paper	25.0%	72.0	49.0
Weighted average of above			**49.0**

(a) Lamborn (2009), (b) Bariaz (1998), (c) Hyder consulting 2009, except for 'other paper'.

Micales and Skog (1996) published a range of methane potentials for a comprehensive list of paper types (based on data in Doorn and Barlaz) (1995) which show that methane potentials range between 0.05 g CH_4/g refuse for newspaper and 0.131 g CH_4/g refuse for office paper. These results also suggest that the range of DOC_f values shown in Table 7.9 above derived from Barlaz data encompass the broad range of paper types that may be present in Australian landfills and the degradabilities observed in the experimental data.

For wood products, Australia has selected a value of 0.1 to apply to all wood deposited in landfills in Australia based on the mid-point of observations of DOC_f values for various wood species examined in Wang et al. 2011 which included results for softwood, hardwood, plywood and MDF as well as some Australian wood species. Results from these laboratory-based experiments suggest that, particularly for the Australian wood species examined, very little anaerobic degradation occurs. Follow up studies by Australian researchers (Ximenes et al. 2013) for a range of engineered wood products (particleboard, MDF and high pressure laminate) observed carbon loss factors no higher than 1.6 per cent while previous field studies (Gardner et al. 2008b and Gardner et al. 2004) (Gardner 2004) also indicate that low DOC_f values are likely for timber products.

For food waste the DOC_f value of 0.8 based on the work of Barlaz 1998 has been used. For garden and park waste a DOC_f value of 0.5 based on the work of Barlaz 1998 has been used. This value assumes the upper estimate calculated by Barlaz for "leaves" and "grass". On this assumption, it represents a conservative upper limit on the likely true DOC_f value for this category. For the remaining waste categories in the inventory the IPCC default value of 0.5 has been retained. This includes values for textiles, sludge, nappies, and rubber and leather which require additional research to be undertaken before waste type specific values are adopted. The complete list of DOC_f values for each inventory waste mix type is presented in Table 7.10.

Table 7.10 Key model parameters: DOCf values by individual waste types

Waste type	DOC_f value
Food	0.8
Paper and paper board	0.5
Garden and park	0.5
Wood	0.1
Wood waste	0.1
Textiles	0.5
Sludge	0.5
Nappies	0.5

Waste type	DOC_f value
Rubber and Leather	0.5
Inert waste (including concrete, metal, plastic and glass)	0.0

An important parameter for the emissions calculation is the methane correction factor (MCF) which is intended to represent the extent of anaerobic conditions in landfills. It is assumed that all *solid waste disposal on land* in Australia is disposed to well-managed landfills, hence a methane correction factor of 1.0 has been applied to all years. Data from a Waste Management Association of Australia (WMAA) (2007) survey on waste management practices undertaken in 2007 was reviewed for this inventory and considered to provide strong evidence that the landfills in Australia adopt management practices that are consistent with the IPCC characterisation of well-managed landfills. 71 per cent of landfills, receiving an estimated 95 per cent of waste, operate with some form of permanent cover. The balance of landfills are assumed to operate within the meaning of well-managed landfills, as defined by the IPCC.

The IPCC default delay time of six months (M =13) has been used to reflect the fact that methane generation does not begin immediately upon deposition of the waste. Under this assumption, and given that all waste is assumed to be delivered at the mid-point of the year, anaerobic decay is set to start, on average, on the first day of the year following deposition.

The IPCC default fraction of decomposition that results in methane (F) of 0.5 is assumed for this inventory, reflecting the assumption that the decomposition of organic carbon under anaerobic conditions is equally split between the generation of methane and the generation of carbon dioxide.

The IPCC default oxidation factor (OF) of 0.1 is assumed for this inventory, reflecting the proportion of methane generated by the decomposition of organic carbon under anaerobic conditions that is oxidised before the gas reaches the surface of the landfill.

Net emissions are derived after accounting for methane recovery undertaken at the landfill site. The quantity of methane recovered for flaring and power is based upon methane capture reported under the NGER scheme for 2008–09 onwards and industry survey for the years 1989–90 to 2007–08. Methane capture reported by landfill gas capture companies is measured according to the gaseous fuels measurement provisions set out in the *National Greenhouse and Energy Reporting (Measurement) Determination 2008* (the Determination) . Under these provisions, a range of options are available to reporters including indirect measurement based on invoices or electricity dispatched or direct measurement at the point of consumption using gas measuring equipment operated in accordance with set standards. Under these reporting provisions, landfill gas companies must also specify whether the collected gas is combusted for power generation, flared, or sent offsite for other uses.

Methane recovered (R(t)) is 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.

Emissions from the combustion of landfill gas for power generation are reported in the energy sector (1.A.1.a – public electricity and head production).

Small quantities of non-methane volatile organic compounds (NMVOC) are contained in landfill gas emitted from landfills in Australia. Some of these NMVOC are generated by the decomposition process and others are residuals from the types of waste dumped in the landfill. The CSIRO Division of Coal and Energy Technology in Sydney (Duffy et al. 1995) investigated NMVOC emissions from four landfills in the Sydney region. They found significant concentrations, up to 10 parts per million by volume (ppmv), for approximately 60 different compounds. Researchers in the UK (Baldwin and Scott 1991) have found between 2,200 and 4,500 milligrams per cubic metre (mg/m^3) of NMVOC present in landfill gas. In Australian landfills, liquid waste is rarely disposed of with solid waste whereas co-disposal is common practice in the UK. On this basis the lower range of 2,000 mg/m^3 found by the UK researchers is used for NMVOC emissions from Australian landfills unless other site-specific information is available. It is assumed that NMVOC emissions from landfills comprise 0.2 per cent of total landfill gas emissions; the average methane fraction of landfill gas as generated before release to the atmosphere is 0.5. This quantity is a weighted mean for all previous years of waste data used to calculate any inventory year's data and the proportion of methane emitted after oxidation is 0.9.

7.2.3 Uncertainty assessment and time-series consistency

The uncertainty analysis in Annex II provides estimates of uncertainty according to IPCC source category and gas. Time-series consistency is ensured by use of consistent models, model parameters and datasets for the calculations of emissions estimates. Where changes to emission factors or methodologies occur, a full time-series recalculation is undertaken.

The use of NGER scheme data has required careful consideration of time-series consistency issues. Facility-level activity data and emission factors are available from 2008–09 onwards. To preserve time-series consistency, facility-level activity data obtained under the NGER scheme has been back-cast as a fixed proportion of total population serviced in each state. Constant facility level MCF values and the proportion of methane generated that was captured in 2008–09 have been used with the back-cast activity data. This approach to maintaining time series consistency was based on the consideration that the larger-scale facilities covered by the NGER scheme utilise well established infrastructure and treatment processes that have not undergone significant changes since 1989–90.

The residual portion of the sector, for which no NGER scheme facility-specific data is available, has been handled as described above for the entire time-series.

7.2.4 Category-specific QA/QC and verification

The solid waste sector category is covered by the general QC measures undertaken for inventory preparation. Emissions are estimated subject to the application of carbon balance constraints that ensures completeness; that carbon is tracked from harvest to disposal and that consistency between the harvested wood product and landfill pools is maintained. Estimates of carbon stored in wood products and in landfills are provided in Annex 4.

Quality assurance in relation to key parameters and the overall method for the sector was provided through review by an international external expert not involved in the inventory process (Guendehou) (2009). Independent external review provides assurance that the approach adopted by Australia is consistent with the approaches adopted by other parties.

As part of a systematic quality control process the emission estimates obtained for the Australian inventory are compared with those reported by other parties. Methane generation at landfills in Australia was assessed against the reported estimates of methane generated at landfills across all Annex I parties. It was concluded that the implied emission factor for Australian landfills was not significantly different to the mean implied emission factor for all Annex I parties.

Additionally, methane recovery, utilisation and flaring at landfills is reported under the NGER scheme by landfill operators. Often this methane is subsequently sold to energy companies for utilisation. Under the NGER scheme, such energy companies are also required to report the amount of methane utilised. In this way, two independent reports on the recovery and utilisation of methane are generated. This information is used to verify the amount of methane collected for utilisation.

Key parameters such as waste type fractions have been the subject of consultations with industry and industry experts. External experts have been utilised or review of available waste audit data, MCF, DOC_f and oxidation rates.

Analysis of available waste audit data utilised in this inventory was undertaken independently by two external expert consultancies (Hyder consulting,(2008) GHD 2008 (2008)).

The methane correction factor (MCF), which is intended to represent the extent of anaerobic conditions in landfills, was reviewed for this inventory by GHD 2010. The assessment of GHD confirmed that an MCF factor of 1.0 is appropriate for Australian landfills.

Country specific values for DOC_f for individual waste types were selected after consultation with independent consultants (GHD (GHD 2010), Hyder consulting 2010, Blue Environment (2010)) and reviewed by an international expert reviewer not involved in the preparation of the inventory (Guendehou 2010 (2010)). Guendehou concluded that the approach adopted lead to a significant improvement in the emission estimates.

Oxidation rates were reviewed (GHD (2010)). Following the review, it was decided to retain the IPCC default assumption of 10 per cent until further research can be undertaken.

When NGER scheme data were used for methane capture for the first time in the inventory in 2009–10, it was important to ensure time-series consistency was maintained. To ensure this was the case, the DCCEEW engaged the external consultant who was previously used to collect methane capture information from landfill gas capture companies to undertake a QC analysis of the NGER scheme capture data. Data were assessed for completeness and consistency with previously reported values. Capture estimates were compared with data available from the renewable energy certificate register as well as the NSW Greenhouse Gas Reduction Scheme register. The analysis confirmed that methane capture for energy generation was complete and consistent with previously reported data. For methane flaring, the analysis highlighted a completeness issue with respect to flaring occurring at local council landfills (in general, councils are not required to report under the NGER scheme (2008–09 onwards)). Therefore, this portion of flaring activity data had to be estimated for 2008–09 based on previously reported data. Through this QC project, the former DoEE was able to ensure continuity of expertise and knowledge used in the compilation of previous inventory submissions.

7.2.5 Category-specific recalculations

Recalculations to Solid Waste Disposal are detailed in Table 7.11 and are due to:

A. Revised Activity Data

Revised activity data in the harvested wood products model contributed to revisions in emissions of between -0.56 and 0.35 per cent between 1989–90 and 2020–21.

Table 7.11 Solid Waste: recalculation of emissions (Gg CO_2–e)

	2023 Submission	2024 Submission	Change	
Year	Gg CO_2–e	Gg CO_2–e	Gg CO_2–e	%
1989–90	17,064.7	17,064.6	-0.1	0.00
1994–95	16,316.8	16,304.2	-12.7	-0.08
1999–00	13,748.9	13,729.9	-19.0	-0.14
2004–05	12,267.8	12,242.4	-25.3	-0.21
2005–06	11,963.3	11,941.1	-22.2	-0.19
2006–07	12,293.0	12,271.7	-21.2	-0.17
2007–08	12,756.4	12,739.0	-17.5	-0.14
2008–09	12,677.6	12,661.6	-16.0	-0.13
2009–10	12,994.5	12,979.5	-15.0	-0.12
2010–11	12,539.1	12,524.9	-14.2	-0.11

Year	2023 Submission	2024 Submission	Change	
	Gg CO_2-e	Gg CO_2-e	Gg CO_2-e	%
2011–12	11,159.0	11,145.4	-13.6	-0.12
2012–13	10,296.6	10,283.1	-13.6	-0.13
2013–14	10,260.4	10,246.0	-14.4	-0.14
2014–15	9,750.7	9,734.8	-15.8	-0.16
2015–16	9,880.7	9,863.5	-17.2	-0.17
2016–17	10,180.2	10,161.9	-18.3	-0.18
2017–18	9,629.5	9,575.6	-53.9	-0.56
2018–19	10,215.8	10,191.2	-24.6	-0.24
2019–20	10,218.3	10,254.4	36.1	0.35
2020–21	10,075.9	10,079.1	3.2	0.03

7.2.6 Category-specific planned improvements

Facility-level data used in this submission are limited to waste disposal quantities and composition and methane capture for all landfill facilities triggering NGER scheme reporting thresholds. Decay rate constants have been assigned to each landfill based on their individual geospatial coordinates and BOM climate data.

Initial testing of the methods at landfills has demonstrated the value of ensuring that local climate and management practices are explicitly considered. The methods to be used to determine 'k' are provided in the Determination. Under the NGER scheme, operators of landfills are encouraged to undertake audits of waste data received and to collect data on methane generation rates to enable the operator to determine a facility-specific 'k' value so that 'k' will reflect both localised climate and management conditions. However, to date, no landfills have undertaken these measurements. The DCCEEW will continue to review the availability of data and where available these will be used to ensure that the decay functions applied at individual landfills reflect both local climatic conditions and facility management practices. The latter is particularly important as practices can vary considerably – for example, two in every five landfills practice leachate control which would significantly increase the value of 'k' at a landfill facility.

For the residual disposal not covered by the NGER scheme reporting, the DCCEEW will continue to explore methods of aligning state and territory reported data as well as the possibility of estimating emissions at a more spatially disaggregated level. This would enable climatic variation to be accounted for in the residual estimates. The implementation of this planned improvement will depend on the availability of disposal data at a more disaggregated level than is currently available.

A desktop audit of waste mix percentages was conducted in 2014 to confirm the representativeness of the CS waste mix percentages used in the inventory. The DCCEEW will explore the possibility of conducting a new desktop audit of available waste composition data to either confirm or update the CS waste mix percentages applied to landfills not reporting their own composition under the NGER scheme.

The DCCEEW will also continue to review the 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2019) for supplementary methodologies, parameters and/or guidance applicable to Australia's inventory.

7.3 Biological Treatment of Solid Waste (CRT category 5.B)

7.3.1 Category description

Biological treatment of solid waste through processes such as windrow composting and enclosed anaerobic digestion is considered an emerging treatment pathway in Australia, where a small amount of activity data has become available under the NGER scheme (2008–09 onwards) and annual industry surveys by the University of New South Wales (2003–04 to 2009–10).

Table 7.12 Emissions from biological treatment of solid waste, Australia: 1989–90 to 2021–22

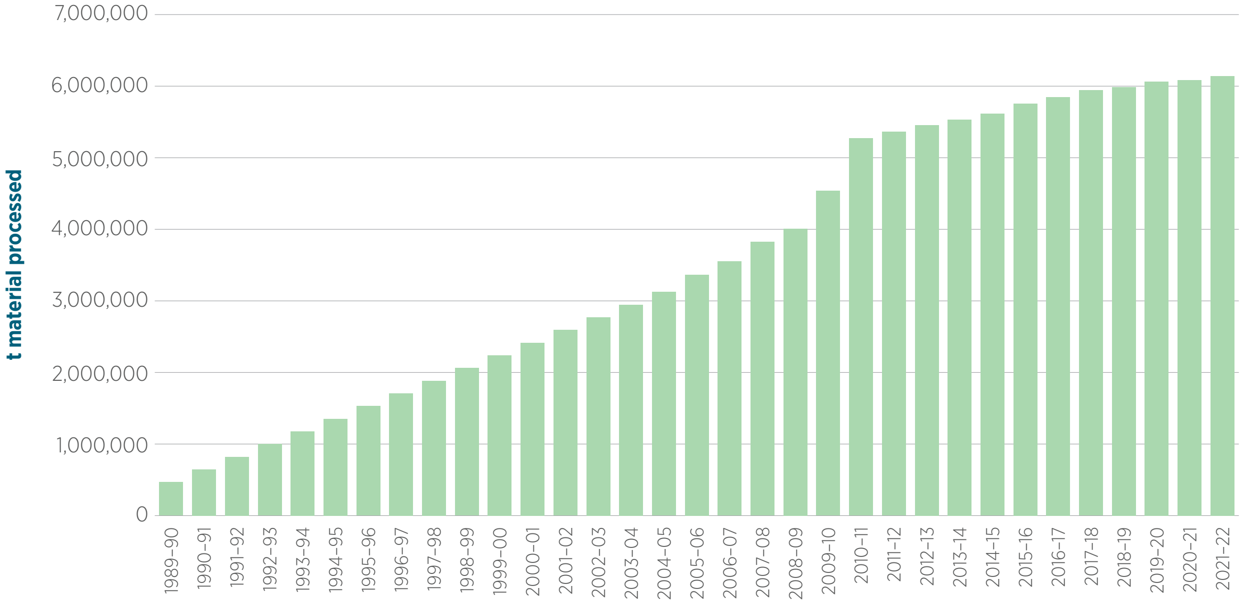
Year	Methane emissions (kt CH_4)	Nitrous oxide emissions (kt N_2O)	Total emissions (kt CO_2–e)
1989–90	9.8	11.9	21.7
1994–95	28.4	34.4	62.8
1999–00	47.0	56.9	103.9
2004–05	65.6	79.5	145.1
2005–06	70.6	85.6	156.2
2006–07	74.6	90.3	164.9
2007–08	80.3	97.3	177.6
2008–09	84.2	102.0	186.3
2009–10	95.3	115.4	210.7
2010–11	110.7	134.1	244.8
2011–12	112.6	136.4	249.0
2012–13	114.5	138.7	253.3
2013–14	116.2	140.8	257.0
2014–15	117.9	142.8	260.6
2015–16	120.9	146.5	267.4
2016–17	122.8	148.8	271.6
2017–18	124.8	151.2	275.9
2018–19	125.7	152.3	278.0
2019–20	127.3	154.3	281.6
2020–21	127.7	154.8	282.5
2021–22	129.0	156.2	285.2

7.3.2 Methodological issues

Composting

Australia has applied the tier 2 method from the 2006 IPCC Guidelines (IPCC 2006) and country-specific emission factors to derive estimates of emissions based upon the total amount of material processed through composting and anaerobic digestion. Activity data are obtained from an annual industry survey undertaken by the Recycled Organics Unit at the University of New South Wales are. Survey data cover the years 2003–04 to 2009–10, with extrapolation used to derive activity data for the years 1989–90 to 2002–03. From 2008–09 onwards, activity data are from the NGER scheme. The time-series of quantities of waste material processed via composting is shown in Figure 7.10.

Figure 7.10 Quantities of material processed via composting 1989–90 to 2021–22



Australia has adopted country-specific emission factors for CH_4 and N_2O emissions from composting based on research conducted by Amlinger (2008) covering the composting of bio-waste, loppings and home composting material. The emission factors are shown in Table 7.13.

Table 7.13 Composting emission factors (t CO_2–e /t material processed) used in the Australian inventory [(a)]

	CH_4 emission factor (t CO_2–e /t material processed)	N_2O emission factor (t CO_2–e /t material processed)
Composting	0.019	0.030

(a) In raw-gas terms, these emission factors are 0.00075 t CH_4/ tonne of material processed and 0.000096 t N_2O/ tonne of material processed.

The country-specific emission factors have been drawn from the document *Update of emission factors for N_2O and CH_4 for composting, anaerobic digestion and waste incineration* (DHV (2010)) which itself cites Amlinger (2008) as the source of its recommended emission factors. DHV (2010)presents a synthesis of all available research data covering emissions from the biological treatment of solid waste.

Anaerobic digestion at biogas facilities

To date, no facilities have reported emissions associated with the anaerobic digestion of solid waste at biogas facilities under the NGER scheme. According to the Australian Clean Energy Finance Corporation, bioenergy projects are not widely deployed in Australia (CEFC 2015). There are three known facilities in operation in Australia that could be classed as anaerobic digestion facilities. The Richgro facility in Jandakot Western Australia became operational in 2015 and has the capacity to process up to 140 tonnes of food waste per day. Another facility known as Earthpower has been operating in Sydney since 2003 and can process up to 130 tonnes of organic waste per day. As with the Richgro facility, emissions of less than 1,000 tonnes of CO_2–e are estimated. A third facility was commissioned in the Yarra valley in Victoria as of May 2017. The facility has the capacity to process around 90 tonnes of food waste per day.

When the IPCC default CH_4 EF of 0.8 g CH_4/kg wet waste treated is applied to the maximum quantity of waste that could be processed at these three facilities, it results in annual emissions of around 2.9 kt of CO_2–e . This is well below the significance threshold for reporting. Accordingly, this source is Not Estimated (NE).

There are several biogas facilities associated with agricultural activities in operation in Australia. Emissions associated with these operations are reported under 3.B manure management or 5.D.2 Industrial wastewater treatment where appropriate.

7.3.3 Uncertainty assessment and time-series consistency

The uncertainty analysis in Annex 2 provides estimates of uncertainty according to IPCC source category and gas. Time-series consistency is ensured by use of consistent models, model parameters and datasets for the calculations of emissions estimates. Where changes to emission factors or methodologies occur, a full time-series recalculation is undertaken.

7.3.4 Category-specific QA/QC and verification

The composition emission factors are considered suitable for use in Australia's inventory due to the following:

1. Emission factors fall within the IPCC default ranges.

   While the CH_4 and N_2O emission factors chosen are towards the lower end of the default range, it has been concluded by Alminger (2008) that values exceeding 0.065 t CO_2–e / t material processed likely indicate some kind of system mismanagement such as insufficient aeration or mechanical turning. The mid-range IPCC default factors according to this conclusion would suggest a level of system mismanagement not thought to occur in Australia.

2. Waste types considered by Amlinger (2008) are representative of waste types commonly processed via biological treatment in Australia (namely bio-waste and greenwaste).

   GHD (2010) cites typical materials treated by the various biological processes in Australia:

   - Source separated garden organics;
   - Source separated garden organic organics with biosolids;
   - Source separated garden organics with food waste;
   - Source separated garden organics with food waste and biosolids;
   - Source separated food waste; and
   - Mixed residual waste containing food waste and paper.

3. The technologies examined (windrow composting processes) are reflective of those commonly used in Australia. The Recycled Organics Unit identifies aerobic windrow composting as the dominant form of biological treatment of solid waste currently employed in Australia.

7.3.5 Category-specific recalculations

There are no recalculations to biological treatment of solid waste in this submission.

7.3.6 Category-specific planned improvements

Australia continues to review the use of population data as a proxy. The DCCEEW will continue to investigate other potential data and asses their applicability as a proxy over the coming year.

7.4 Incineration and Open Burning of Solid Waste (CRT category 5.C)

7.4.1 Category description

Emissions are reported for the incineration of solvents and municipal and clinical waste. Incineration estimates include a quantity of solvent generated through various metal product coating and finishing processes. In this instance, incineration is used as a method to minimize emissions of solvents and volatile organic compounds to the atmosphere and leads to emissions of CO_2.

Between 1989–90 and 1995–96 there were three incinerators receiving municipal solid waste, located in New South Wales and Queensland. All three incinerators ceased operations in the mid-1990s.

In addition to the incineration of municipal solid waste, a quantity of clinical waste is incinerated in four major facilities located in Queensland, New South Wales, South Australia, and Western Australia.

7.4.2 Methodological issues

Data on the incineration of solvents prior to 2003–04 is based on company data, after which emissions from this source have been based on data estimated by the DCCEEW. Carbon dioxide emissions from incineration of solvents are estimated by converting the volume of solvent incinerated (Litres) to the weight of solvent (using specific volume factor of 1,229 L/t), deriving the energy content of the mass of solvent (using the energy content of 44 GJ/t), and using a carbon dioxide emission factor per petajoule of solvent (69.6 Gg/PJ).

Data on the quantities of municipal solid waste incinerated are based upon published processing capacities of the three incineration plants prior to decommissioning. Data on the quantities of clinical waste incinerated have been obtained from a per capita waste generation rate derived from data reported under the NGER scheme, by O’Brien (2006b) and an estimate of State population reported by the Australian Bureau of Statistics.

The quantity of CO_2 emitted as a result of the incineration of municipal and clinical waste is based upon the quantity of waste incinerated, the carbon content of the waste and the proportion of that carbon which is of fossil origin and the efficiency of the combustion process (oxidation factor). The country-specific fossil carbon content of municipal waste of 7 per cent is based upon empirical data presented in NGGIC (1995) for incineration activities occurring in 1989–90. Of this 7 per cent of fossil carbon in municipal waste, it is estimated that 80 per cent of this carbon is combustible (NGGIC (1995)). Emissions of N_2O from the incineration of municipal solid waste are also estimated based on a country-specific emission factor of 0.00015 Gg of N_2O/Gg of waste taken from NGGIC (1995). The carbon content factors used in the emissions estimation are shown in Table 7.14. Emissions of methane from the incineration of municipal solid waste have been calculated based on the energy content of “Non-Biomass municipal materials if recycled and combusted to produce heat or electricity” of 12.2 GJ/t MSW used for the NGER scheme and a CH_4 emission factor of 30 kg CH_4/TJ MSW taken from the 2006 IPCC Guidelines (2006).

The 2006 IPCC guidelines (2006) do not provide default CH_4 and N_2O emission factors for the incineration of clinical waste and solvents. Furthermore, when the highest 2006 IPCC default EFs for CH_4 and N_2O listed for municipal solid and general industrial waste incineration are applied to the AD for clinical waste and solvents incineration, emissions estimates contribute around 0.0001 per cent (0.7 kt CO_2–e) of total emissions from all sectors. Accordingly, emissions of CH_4 and N_2O from this source are not estimated in the inventory on the grounds that they fall below the significance threshold established in paragraph 37(b) of the UNFCCC Reporting Guidelines.

Table 7.14 Parameters used in estimation of waste incineration emissions

	Municipal Solid Waste [(a)]	Clinical Waste [(b)]
Proportion of waste that contains fossil carbon	0.07	
Proportion of waste that is carbon		0.60
Proportion of fossil carbon containing products that is carbon	0.80	
Fossil carbon content as a proportion of total carbon		0.40
Oxidation factor	1.00	1.00
Energy content of non-biomass municipal materials if recycled and combusted to produce heat or electricity (GJ/t)	12.20	

Source: (a) NGGIC (1995); NGER scheme; (b) IPCC (2006).

Incineration of waste other than solvents, municipal and clinical waste

Emissions resulting from the incineration of waste other than solvents, municipal and clinical waste are not estimated on the basis that the likely level of emissions is below the significance threshold established in paragraph 37(b) of the UNFCCC Reporting Guidelines. In the absence of suitable AD, analysis was undertaken using data obtained from all Annex-1 parties reporting sewage sludge incineration. A per capita value for sewage sludge was used and a 100% fossil carbon content was assumed. When the highest 2006 IPCC default EFs for CO_2 and N_2O listed for waste lubricant, hazardous waste and biosolids are applied to the AD, emissions are likely to contribute around 52 kt CO_2–e , or 0.01% of total emissions from all sectors.

Accidental Fires at Solid Waste Disposal Sites

Emissions of CO_2, CH_4 and N_2O resulting from unintentional (accidental) fires at solid waste disposal sites (SWDS) are uncommon in Australia, however they have been assessed for significance. Emission estimates were derived using emission factors consistent with those described for the incineration of municipal solid waste. The total amount of waste open-burned was estimated based on population, number of waste fires recorded, waste generation rates and approximate fire duration.

Emissions from this source were estimated to be 17.3 kt CO_2–e, or 0.004% of total national emissions from all sectors. Accordingly, emissions from this source are not estimated in the inventory on the grounds that they fall below the significance threshold established in paragraph 37(b) of the UNFCCC Reporting Guidelines.

7.4.3 Uncertainty assessment and time-series consistency

The uncertainty analysis in Annex II provides estimates of uncertainty according to IPCC source category and gas. Time-series consistency is ensured by use of consistent models, model parameters and datasets for the calculations of emissions estimates. Where changes to emission factors or methodologies occur, a full time-series recalculation is undertaken.

7.4.4 Category-specific QA/QC and verification

The incineration and open burning of solid waste category is subject to general QC measures undertaken during inventory preparation. Activity data is reviewed and compared with other relevant data sources and checked against previous years to ensure consistency over time, including amount of waste incinerated.

7.4.5 Category-specific recalculations

There are no recalculations to incineration and open burning of solid waste in this submission.

7.4.6 Category-specific planned improvements

The DCCEEW will continue to investigate methods to improve the accuracy and reporting of emissions from accidental fires at SWDS and will aim to include this in a future submission to enhance completeness.

The DCCEEW will also continue to review the 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2019) for supplementary methodologies, parameters and/or guidance applicable to Australia's inventory.

7.5 Wastewater Treatment and Discharge (CRT category 5.D)

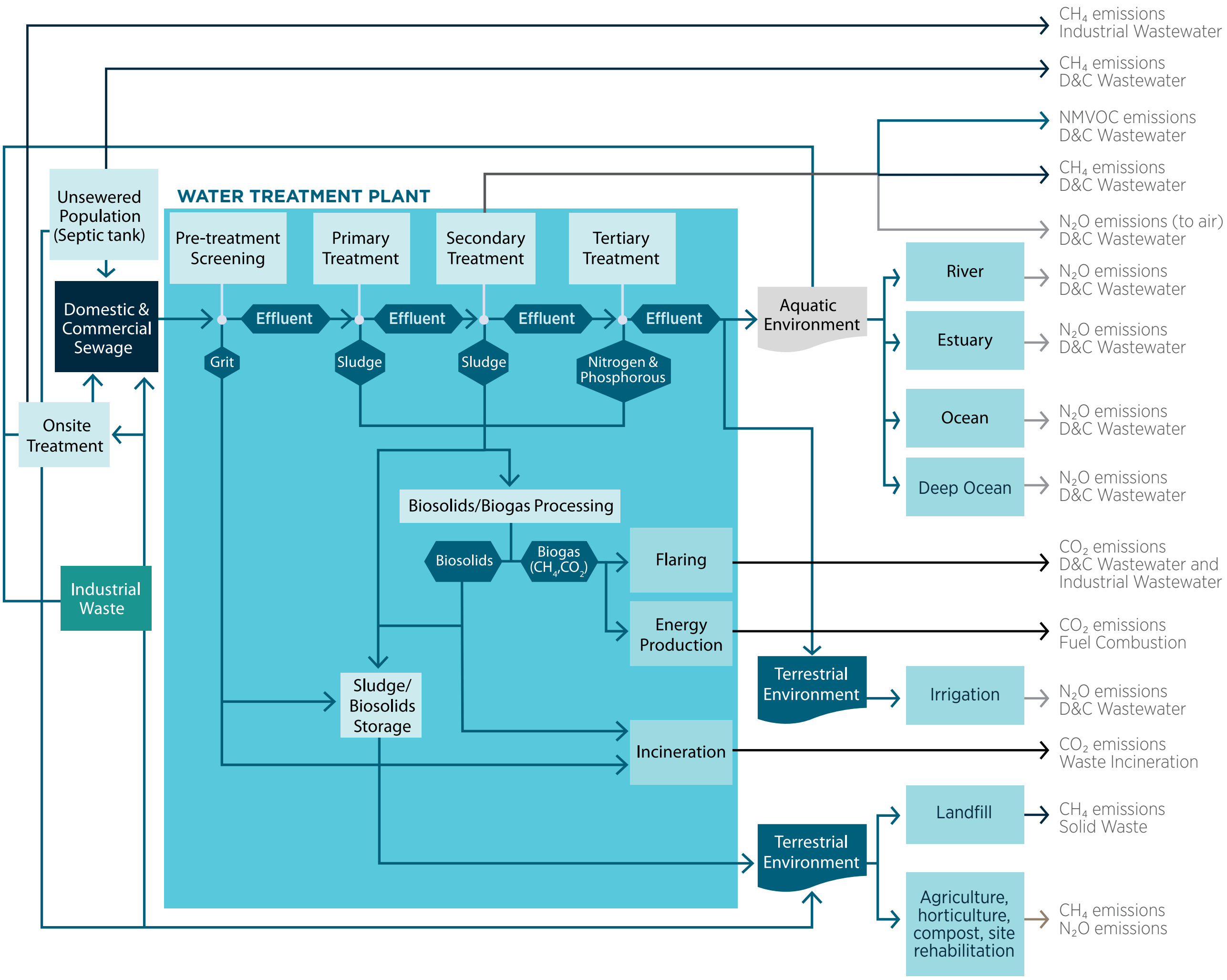
7.5.1 Category description

The anaerobic decomposition of organic matter in wastewater results in emissions of methane while chemical processes of nitrification and denitrification in wastewater treatment plants and discharge waters give rise to emissions of nitrous oxide.

Large quantities of CH_4 are not usually found in wastewater, as even small amounts of oxygen are toxic to the anaerobic bacteria that produce the CH_4. In wastewater treatment plants, however, there are several processes that foster the growth of these organisms by providing anaerobic conditions.

Municipal wastewater treatment plants in Australia treat a major portion of the domestic sewage and commercial wastewater, and a significant part of industrial wastewater. Approximately 5 per cent of the Australian population is not connected to the domestic sewer and instead utilise on-site treatment of wastewater such as septic tank systems (WSAA (2005)). Some industrial wastewater is treated on-site and discharged either to an aquatic environment or to the domestic sewer system which then feeds into a municipal wastewater treatment plant. A schematic diagram of the pathways for the treatment of wastewater in Australia is shown in Figure 7.11.

Figure 7.11 Pathways for Wastewater



Methane emissions from effluent discharge to receiving waters is not reported in the inventory. Similarly, N_2O emissions from any form of industrial wastewater discharge and from discharge of municipal wastewater to ocean and deep ocean waters or used in irrigation are considered negligible and are not reported in the inventory.

Sludge removed from wastewater treatment plants is either disposed to landfill or can be further treated to produce biosolids and then used in a land application such as agriculture, horticulture, composting or site rehabilitation. Emissions of methane from disposal of sludge in a landfill are included in the solid waste sector. Emissions of nitrous oxide from land application are included in the agriculture sector under *3.D Agricultural soils.*

7.5.2 Methodological issues

As methane is generated by the decomposition of organic matter, the principal factor which determines the methane generation potential of wastewater is the amount of organic material in the wastewater stream. This is typically expressed in terms of Chemical Oxygen Demand (COD). COD is a measure of the oxygen consumed during total chemical oxidation (both biodegradable and non-biodegradable) of all material in the wastewater (IPCC (2006)). COD has been used as the data input as this is preferred parameter measured by companies reporting under the NGER scheme. This aligns best with domestic licensing provisions and is consistent with the 2006 IPCC Guidelines (2006), which also provide a default factor in terms of COD.

Nitrous oxide, N_2O, is also generated from municipal wastewater treatment plants. Nitrogen, which is present in the form of urea in urine and as ammonia in domestic wastewater, can be converted to nitrate (NO3). Nitrate is less harmful to receiving waters since it does not take oxygen from the water. The conversion of nitrogen to nitrate is usually done by secondary and tertiary wastewater treatment plants using special bacteria in a process called nitrification. Following the nitrification step some facilities will also use a second biological process, known as denitrification. Denitrification further converts the nitrogen in the nitrates to nitrogen gas, which is then released into the atmosphere. Nitrification and denitrification processes also take place naturally in rivers and estuaries. N_2O is a by-product of both nitrification and denitrification.

The emission factor for N_2O was revised in the 2021 submission from 4.9 to 2.082 tonnes of nitrous oxide (CO_2–e) per tonne of nitrogen produced. This change reflects the update made to the emissions factor within the Determination and aligns with the 2006 IPCC Guidelines (2006).

Methane generated at wastewater treatment facilities may be captured and combusted for energy purposes or flared. The amount of CH_4 captured or flared is subtracted from the total CH_4 generated. Quantities of sludge biogas combusted to produce energy and the associated non-CO_2 emissions are reported in the *stationary energy* sector.

Discharge of treated effluent to aquatic environments is regulated by state and territory governments. As a result, wastewater treatment facilities in Australia predominantly process wastewater to a secondary or tertiary treatment level before discharging the wastewater into an aquatic environment. As the treatment level increases from primary to secondary to tertiary, the number of unit operations used to treat the wastewater and the amount of organic matter and nitrogen removed before discharge to an aquatic environment increases. Consequently, such aquatic environments are considered unlikely to be sources of CH_4.

Effluent discharged by wastewater treatment plants in Australia enters one of four classes of aquatic environment which are defined as follows:

- River means all waters other than estuarine, ocean or deep ocean waters;
- Estuarine waters means all waters (other than ocean or deep ocean waters):
  - that are ordinarily subject to tidal influence, and
  - that have a mean tidal range greater than 800 mm (being the average difference between the mean high-water mark and the mean low-water mark, expressed in millimetres, over the course of a year);
- Ocean means all waters except for those waters enclosed by a straight line drawn between the low-water marks of consecutive headlands and deep ocean waters; and
- Deep ocean means all waters, except for river and estuarine waters, that are more than 50 metres below the ocean surface.

The type of discharge environment is critical to emissions of N_2O from discharge. Table 7.15. shows the nitrogen discharged to each receiving environment and indicates that the majority of effluent is discharged to either ocean or deep ocean outfalls, typically more than two kilometres from the coastline at a depth of 50 metres or more.

Table 7.15 Effluent discharged from wastewater treatment plants by type of aquatic environment for 2021–22

Type of aquatic environment	Nitrogen discharged (t N)	
River	6,647	33%
Estuary	4,345	21%
Ocean or deep ocean	9,241	46%
Total	**20,234**	**100%**

Source: NGER scheme 2023.

Sludge treatment and disposal practices include transfer to landfill or agricultural land. The proportion sent to each destination are shown in Table 7.16. Emissions from sludge sent to landfills are included in the solid waste sector while emissions from biosolids (treated sludge) used in a land application are included in Agriculture.

Table 7.16 Sludge reuse and disposal in 2021–22

	Nitrogen (t)	% Contribution
Sludge to Landfill	2,201	13%
Sludge Reused in Land Application	14,751	87%
Total	**16,952**	**100%**

Source: NGER scheme 2023.

Methane from municipal wastewater

Methane emissions from the treatment of wastewater at municipal wastewater treatment plants are estimated according to the default method set out in the 2006 IPCC Guidelines (2006), which relates emissions to the total quantity of organic waste treated at the MWTP. The emission factors applied to this quantity of organic waste are derived from a consideration of the type of treatment process used at the MWTP and the degree to which the organic waste is treated anaerobically.

Quantities of organic waste in wastewater treated at individual MWTPs have been obtained under the NGER scheme (2008–09 onwards). Around 80 per cent of facilities reporting under the NGER scheme (numbering 30 in total and servicing around 50 per cent of Australia's population) measured the quantity of COD entering their facility directly. The weighted average per capita COD entering these facilities is 0.0685 tonnes of COD per person per year.

For the remainder of the category's facilities, a country-specific value of 0.0585 tonnes of COD per person per year (NGGIC (1995)) was used for the amount of organic waste in wastewater received at their sites.

Utilities reporting under the NGER scheme are also required to report the quantities of COD leaving their facility in effluent and treated in the form of sludge. As with the COD entering the facilities, NGER scheme facility-specific data on COD sludge leaving the facility has been used where this variable has been measured directly. Where this data was unavailable, a country-specific fraction of COD removed and treated as sludge of 0.54 has been applied (NGGIC (1995)).

To estimate CH_4 emissions generated by the treatment of domestic wastewater, the amount of COD treated separately as sludge, and the amount of untreated COD discharged into aquatic environments, is subtracted from the overall COD entering the treatment facility. This method ensures a balance of organic carbon influent, emissions and effluent.

Emissions generated from the treatment of COD in wastewater are estimated according to the following equation:

$$CH_{4(t)} = (COD_{in} - COD_{sl} - COD_{out}) * Ef_{t}$$

Where $CH_{4(t)}$ is the estimated CH_4 emissions from the treatment of sewage at wastewater plants

COD_{in} is the amount of COD input entering into wastewater treatment plants

COD_{sl} is the amount of COD treated separately as sludge

COD_{out} is the amount of COD effluent discharged from wastewater treatment plants into aquatic environments

EF_{t} is the emission factor for wastewater treated by wastewater plants

Emissions generated from the treatment of sludge are estimated according to the following equation:

$$CH_{4(t)} = (COD_{sl} - COD_{trl} - COD_{tro}) * Ef_{sl}$$

Where $CH_{4(t)}$ is the estimated CH_4 emissions from the treatment of sewage at wastewater plants

COD_{sl} is the amount of COD treated separately as sludge

COD_{trl} is the amount of COD as sludge removed and sent to landfill

COD_{tro} is the amount of COD as sludge removed and sent to a site other than landfill

EF_{sl} is the emission factor for sludge treated by wastewater plants

Under the NGER scheme reporting provisions, wastewater facilities must characterise the type of treatment process used in terms of the fraction of COD (as both sludge and wastewater) treated anaerobically. This parameter is defined as the methane conversion factor (MCF). The 2006 IPCC default MCF values and the definition of the corresponding treatment processes associated with these defaults in Australia are shown in Table 7.17. Facilities reporting under the NGER scheme select the most appropriate MCF value for their operational circumstances.

Table 7.17 MCF values listed by wastewater treatment process

Classes of wastewater treatment in 2006 IPCC Guidelines	MCF Values	Applicable Wastewater Treatment Processes
Managed Aerobic Treatment	0.0	• Preliminary treatment (i.e. screens and grit removal) • Primary sedimentation tanks (PST) • Activated sludge processes, inc. anaerobic fermentation zones and anoxic zones for biological nutrient removal (BNR) • Secondary sedimentation tanks or clarifiers • Intermittently decanted extended aeration (IDEA), intermittently decanted aerated lagoons (IDAL) and sequencing batch reactors (SBR) • Oxidation ditches and carrousels • Membrane bioreactors (MBR) • Mechanically aerated lagoons • Trickling filters • Dissolved air flotation • Aerobic digesters • Tertiary filtration • Disinfection processes (e.g. chlorination inc. contact tanks, ultraviolet, ozonation) • Mechanical dewatering (e.g. centrifuges, belt filter presses)
Unmanaged Aerobic Treatment	0.3	• Gravity thickeners • Imhofftanks
Anaerobic Digester / Reactor	0.8	• Anaerobic digesters High-rate anaerobic reactors (e.g. UASB)

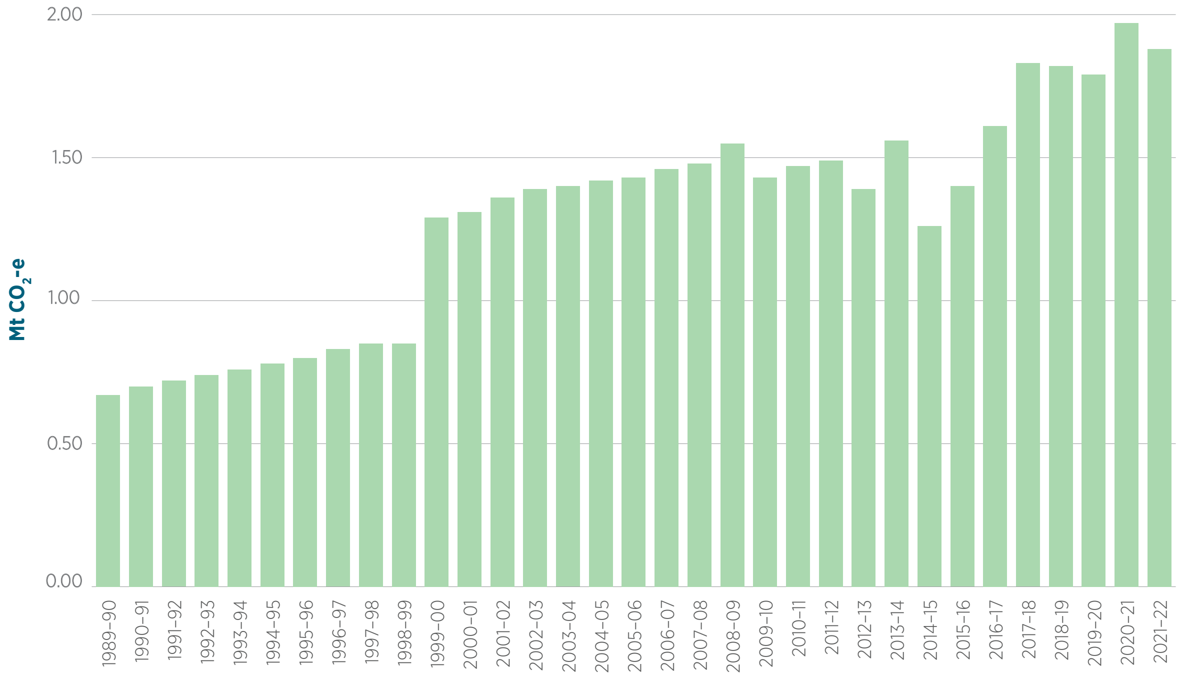
Classes of wastewater treatment in 2006 IPCC Guidelines	MCF Values	Applicable Wastewater Treatment Processes
Anaerobic Shallow Lagoon (< 2 m deep)	0.2	Facultative lagoons Maturation / polishing lagoons Sludge drying pans
Anaerobic Deep Lagoon (> 2 m deep)	0.8	Sludge lagoons Covered anaerobic lagoons

Source: IPCC 2019 page 6.21 (IPCC 2019), WSAA 2011

Emission factors for each facility for wastewater and sludge are derived using equation 6.2 in the 2006 IPCC Guidelines (2006). The IPCC default maximum methane producing capacity (B0) of 0.25 kg CH_4/kg COD is used for all facilities.

Methane recovered for combustion for energy or flared is deducted from the estimated methane generated and is based on directly measured quantities of methane captured for combustion and flaring reported under the NGER scheme for the years 2008–09 onwards. For 1989–90 to 2007–08, recovery is based upon a consideration of historical changes in methane capture capacity at individual wastewater treatment plants. A capture time-series for each wastewater utility has been established based on capture rates for 1989–90 reported in NGGIC (1995) and on subsequent reported commissioning of cogeneration plants, odour control system upgrades, and general plant capacity upgrades. Figure 7.12shows the time-series for methane capture from domestic and commercial wastewater treatment. The significant increase in capture from the year 1999–00 corresponds to an improvement in capture capacity due to the commissioning of cogeneration facilities at a number of key wastewater treatment facilities serving particularly large populations. The small decline in capture in 2009–10 reflects a combination of changes to treatment processes (i.e. a shift to aerobic treatment) and reported declines in flaring and combustion of sludge biogas for energy production. The decline in capture in 2014–15 is due to declines in capture levels reported under the NGER scheme at that time.

Figure 7.12 Methane capture from domestic and commercial wastewater treatment 1989–90 to 2021–22



No data is available on the precise split of methane recovery between wastewater and sludge treatment. For the purposes of reporting in Common Reporting Table 5.B.s1, methane recovery is allocated between wastewater and sludge such that emissions generated from the treatment of sludge are captured and the balance of reported capture is then allocated to wastewater treatment.

Efs by facility are derived according to equation 6.2 in the 2006 IPCC Guidelines (2006), where MCFs by facility are applied to the maximum CH_4 producing capacity (B0) of 0.25 kg CH_4/kg COD.

There is a proportion of the wastewater treatment sector where no facility-specific data is available under the NGER scheme. The choice of parameters applicable to the residual portion of the sector was made in accordance with the decision tree described in Chapter 1.3.1. As treatment processes employed at individual facilities are highly technology specific, it was not considered reasonable to extrapolate the factors obtained from NGER scheme data to the facilities in the residual portion of the sector. Consequently, the per capita COD and region-specific MCF values from NGGIC (1995) were used for 2008–09 for the residual of the category where no facility-specific data under the NGER scheme was available.

Methane from on-site domestic and commercial wastewater treatment

Default methods from the 2006 IPCC Guidelines (2006) are applied. The total unsewered population on a State-by-State basis is calculated according to the Australian Bureau of Statistics (ABS (2020)) and WSAA data (WSAA (2005)). It is assumed that each person in unsewered areas in Australia produces 0.0585 tonnes of COD per person per year (NGGIC (1995)). The amount of COD that settles out as solids and undergoes anaerobic decomposition (MCF) is assumed to be 50 per cent, which is the IPCC default fraction for total urban wastewater (IPCC (2019)). The default emission factor of 0.25 kg CH_4/kg COD is used.

Sludge is also generated by on-site domestic and commercial wastewater treatment. Septic tank systems must be emptied occasionally of the sludge that accumulates inside the system. This sludge is typically transferred to a municipal wastewater treatment facility for further treatment.

Nitrous oxide emissions from domestic and commercial wastewater

The methodology used to estimate N_2O emissions from domestic and commercial wastewater treatment utilises a detailed IPCC 2006 methodology. The methodology comprises estimates of emissions from sewage treatment at a wastewater plant; emissions from discharge of effluent into aquatic environments; and emissions from disposal of treated sludge to land.

$$\text{Total } N_2O\text{-}N = N_2O_{(t)}\text{-}N + N_2O_{(d)}\text{-}N + N_2O_{(l)}\text{-}N$$

Where N_2O-N is the estimated N_2O emissions from domestic and commercial wastewater treatment
$N_2O_{(t)}$-N is the estimated N_2O emissions from sewage treatment at a wastewater plant
$N_2O_{(d)}$-N is the estimated N_2O emissions from discharge of effluent
$N_2O_{(l)}$-N is the estimated N_2O emissions from application of treated sludge to land

The emissions of N_2O from sewage treatment at wastewater treatment plants are estimated using the following equation:

$$N_2O_{(t)}N = (N_{in} - N_{out} - N_{trl} - N_{tro}) * EF_6$$

Where $N_2O_{(t)}$-N is the estimated emissions from the treatment of sewage at wastewater plants
N_{in} is the amount of nitrogen input entering into wastewater treatment plants

N_{out} is the amount of nitrogen effluent discharged from wastewater treatment plants into aquatic environments

N_{trl} is the amount of nitrogen removed from wastewater treatment plants as sludge and disposed to landfill

N_{tro} is the amount of nitrogen removed from wastewater treatment plants as sludge and disposed at a site other than landfill (reused in land applications) and

EF_6 is the emission factor for sewage treated by wastewater plants

The total nitrogen input entering wastewater treatment plants for Australia is obtained from facility specific measurements under the NGER scheme. In total, facility level data obtained under the NGER scheme covers 146 facilities.

Estimates of the remainder of the nitrogen entering the national system is based on the residual population not covered by the facilities reporting under the NGER scheme and the average nitrogen input received by the wastewater plants per person serviced by the plants derived from the NGER scheme (2008–09 onwards). Together with the IPCC default factor for the fraction of nitrogen in protein, 0.16 kg N/kg protein, the facility level data translates into a per capita protein consumption level of 85.6 g per person per day in 2021–22.

Estimates of nitrogen leaving the system as effluent or as sludge disposed to landfill or to a land application, N, N_{trl} and N_{tro} have also been obtained by facility under the NGER scheme.

The emission factor for the estimation of N_2O emissions from wastewater treatment is the 2006 IPCC Guidelines' (2006) default of 0.01 kg N_2O-N/kg N.

Nitrous oxide emissions from discharge of effluent

The effluent discharged into an aquatic environment may enter directly into a river, estuary, ocean surface waters or deep ocean environment depending on the location of the wastewater outfall of each treatment plant.

The emissions of N_2O from the discharge of effluent are estimated using the following equation:

$$N_2O_{(d)}N = N_{out}r x (EF_5r + EF_5e) + N_{out}e \times (EF_5e)$$

Where $N_2O_{(d)}$-N is the emissions from discharge of effluent

$N_{out}r$ is the amount of nitrogen discharged into rivers which then flows into an estuary

$N_{out}e$ is the amount of nitrogen discharged into estuaries

EF_5r is the emission factor for rivers

EF_5e is the emission factor for estuaries

The amount of nitrogen discharged by aquatic environment is obtained by facilities reporting under the NGER scheme.

The default IPCC initial emission factors are 0.0025 kg N_2O-N/kg N for wastewater discharged into rivers (EF_{5r}) and 0.0025 kg N_2O-N/kg N for wastewater discharged into estuaries (EF_{5e}) (IPCC 2006 page 11.24). For wastewater discharged into rivers, the final emission factor is cumulative, (EF_{5r} + EF_{5e}), as it is assumed that the wastewater passes from the river system, through the estuaries and then into the sea. For wastewater discharged directly into an estuary, only (EF_{5e}) is applied.

While the 2006 IPCC Guidelines state that nitrous oxide emissions resulting from sewage nitrogen are estimated from 'nitrogen discharge to aquatic environment' (IPCC (2006) page 6.25), they only provide an N_2O emission factor based on discharge to rivers and estuaries. Consequently, it is considered that there is no IPCC default method available for the estimation of emissions from effluent discharged directly to ocean waters (as opposed to being passed from river and estuary systems into the sea). Nor is there any empirical literature available on emissions from disposal to ocean waters in Australia – such a study would be prohibitively expensive at this time. It is noted, however, that the 2019 Refinement to the 2006 IPCC Guidelines expands the application of the N_2O emission factor emission to 'freshwater, estuarine and marine discharge' (IPCC (2013) page 6.39). Further discussion of the 2019 Refinement is provided in the planned improvements section of this chapter.

The results of the limited number of studies conducted that relate to ocean bodies outside of Australia are not considered appropriate to Australian marine conditions. They are, nonetheless, reviewed in the QA/QC section of this Chapter.

Ocean waters are defined to include only those bodies of water that are beyond the straight line drawn between the low-water marks of consecutive headlands. Waters within the headlands, such as bays and basins, are included as part of the estuarine waters. Consequently, the delineation of ocean waters is considered conservative.

Table 7.18 IPCC emission factors for disposal of effluent by type of aquatic environment

Type of Aquatic Environment	Emission factor for initial disposal
River (EF_{5-r}).	0.0025 kg N_2O-N/kg N
Estuary (EF_{5-e}).	0.0025 kg N_2O-N/kg N

Source: (a) IPCC (2006) page 11.24

Nitrous oxide emissions from the application of treated sludge to land

The emissions of N_2O from the application of treated sludge to land is estimated using the following equation:

$$N_2O_{(l)}N = N_{tro} \times EF_7$$

Where $N_2O_{(l)}$-N is the emissions from treated sludge applied to the land

N_{tro} is the amount of nitrogen removed as treated sludge and applied to the land

EF_7 is the emission factor for treated sludge applied to land

The amount of nitrogen applied to land is obtained by facility under the NGER scheme (2008–09 onwards). The emission factor for the application of treated sewage to land is 0.009 kg N_2O-N/kg N applied and is consistent with the N_2O emission factors for manure applied to crops and pastures (Bouwman et al. 2002). Emissions from the application of sludge to agricultural land are reported under agricultural soils (3.D) consistent with good practice.

Non-methane volatile organic compounds (NMVOC)

There has been little research into the release of NMVOC from wastewater treatment plants. BOD values obtained and used for calculations of methane emissions are used for the calculation of NMVOC from domestic and commercial wastewater and for industrial wastewater. A default value of 0.3 kg NMVOC/ tonne BOD for municipal wastewater treatment plants is used.

Methane from Industrial wastewater

Technologies for dealing with industrial wastewater in Australia are varied. Some industrial wastewater is treated entirely on-site, while a large amount is treated entirely off-site at municipal wastewater treatment plants. Increasingly, industrial wastewater is partially treated on-site before being recycled or discharged to the sewer and treated at municipal wastewater treatment plants. This is due to trade waste discharge licence compliance requirements for a certain quality of wastewater to be achieved prior to sewer discharge.

Most of the industrially produced COD in wastewater comes from the manufacturing industry. Sectors like food and beverage manufacturing produce significant amounts of COD, some of which is anaerobically treated. Some concentrated industrial wastewater is removed from factories in tankers operated by specialised waste disposal services. This wastewater is usually transported to a special treatment facility.

The methodology to determine the amount of CH_4 generated from industrial wastewater is based on the 2006 IPCC Guidelines and focuses on the 9 industrial sectors which are considered to generate the most significant quantities of wastewater in Australia:

- Dairy production;
- Pulp and paper production;
- Meat, poultry and seafood processing;
- Organic chemicals production;
- Sugar production;
- Beer production;
- Wine production;
- Fruit processing; and
- Vegetable processing.

Quantities of organic waste in wastewater treated at industrial facilities have been obtained under the NGER scheme for 2008–09 onwards. Where available, the quantity of COD treated at each facility has been taken from direct measurements reported under the NGER scheme. NGER scheme data are used where coverage is considered sufficient to provide a representative picture of wastewater treatment practices in a given industry. Where facility-specific data under the NGER scheme are unavailable, estimates are based on country-specific wastewater and COD generation rates shown in Table 7.20.

An analysis has been undertaken of the proportions of current production and facility numbers covered by the NGER scheme. Where company/facility coverage is complete or there is robust information about the composition and operational circumstances of the industry, it is possible to conclude that any residual production is not subject to onsite anaerobic wastewater treatment. This is the case for pulp & paper, sugar and beer production. For the remaining commodities considered under industrial, wastewater treatment, NGER scheme coverage is not complete and emissions from residual wastewater are estimated using national statistics on production levels and commodity-specific parameters. Table 7.19 provides further details of the consideration of residual commodity production and associated onsite wastewater treatment.

Table 7.19 Commodity production, coverage and residual wastewater treatment 2021–22

	Total commodity production (litres)	NGER scheme commodity production (tonnes)	% NGER scheme coverage	Residual treatment
Dairy Production	8,554,200,000	837,926	10	Residual based on total national production and commodity – specific parameters
Pulp and Paper Production	3,015,687	1,411,163	47	All facilities covered by NGER scheme. Residual production not subject to onsite WW treatment or aerobic processes
Meat, Poultry and Seafood Production	4,710,535	3,079,804	65	Residual based on total national production and commodity – specific parameters
Organic Chemicals Production	1,837,591	C	C	Residual based on total national production and commodity – specific parameters
Sugar Production	4,123,000	3,643,597	88	All facilities covered by NGER scheme. Residual production not subject to onsite WW treatment or aerobic processes
Beer Production	1,811,455,822	835,796	46	2 of 3 major producers covered by NGER scheme. The remaining producer does not have on-site wastewater treatment.
Wine Production	1,307,000,000	646,805	49	Residual based on total national production and commodity – specific parameters
Fruit Processing	2,551,740	C	C	Residual based on total national production and commodity – specific parameters
Vegetable Processing	3,706,754	C	C	Residual based on total national production and commodity – specific parameters

Note: Facility-level parameters obtained for organic chemical, fruit, and vegetable production under the NGER scheme are confidential (C).

Table 7.20 Country-specific COD generation rates for industrial wastewater, 2021–22

Commodity	Wastewater generation rate (m^3 wastewater/t commodity produced)	COD generation rate (kg COD/m^3 wastewater generated)
Dairy	5.7	1.2
Pulp and Paper	26.7	0.5
Meat, Poultry and Seafood	13.7	2.9
Organic Chemicals (a)	67.0	C
Sugar	0.4	4.0
Beer	5.3	1.1
Wine	23.0	1.3
Fruit	20.0	0.2
Vegetables (a)	20.0	C

Source: NGER 2022 (a) facility-level parameters obtained for organic chemical and vegetable production under the NGER scheme are confidential (C).

Emission factors for each facility for wastewater and sludge are derived using equation 6.2 from the 2006 IPCC Guidelines (2006). The IPCC default maximum methane producing capacity (B0) of 0.25 kg CH_4/kg COD is used for all facilities. Under the NGER scheme reporting provisions, industrial wastewater facilities must characterise the type of treatment process used in terms of the fraction of COD (as both sludge and wastewater) treated anaerobically. This parameter is defined as the methane conversion factor (MCF). As with COD, data on facility specific MCF values at industrial wastewater facilities are available for all listed commodities. Country-specific MCF values outlined in Table 7.21 are the weighted average MCF values based on data reported under the NGER scheme and residual treatment not reported under the NGER scheme.

Table 7.21 Methane conversion factors for industrial wastewater emissions, 2021–22

Commodity	MCF wastewater	MCF Sludge
Dairy	0.5	0.7
Pulp and Paper	0.7	0.7
Meat, Poultry and Seafood	0.7	0.3
Organic Chemicals (a)	C	C
Sugar	0.3	0.1
Beer	0.8	0.8
Wine	0.3	0.7
Fruit	1.0	0.2
Vegetables (a)	C	C

Source: NGER scheme 2022 (a) facility-level parameters obtained for organic chemical and vegetable production under the NGER scheme are confidential (C).

Note: These values represent weighted averages where facility-level MCF values are reported.

A proportion of the COD generated in the industrial wastewater is ultimately treated as sludge. Quantities of COD treated as sludge have been obtained for the dairy, paper, meat, poultry and seafood, sugar, beer, wine, fruit, and vegetable processing industries from the NGER scheme. For the organic chemicals, a constant fraction of COD of 0.15 is assumed to be treated separately as sludge (NGGIC (1995)).

Estimates of the quantities of methane captured have been obtained from the NGER scheme for dairy, paper, meat, poultry and seafood, sugar, beer, wine, fruit and vegetable processing facilities for 2008–09 onwards and derived from facility-level data in O'Brien (2006) and NGGIC (1995) for the years 1989–90 to 2007–08. For organic chemicals for which NGER scheme data has not been used, the sources are O'Brien (2006) and NGGIC (1995).

As with domestic and commercial wastewater treatment, no data is available on the precise split of methane recovery between wastewater and sludge treatment. For the purposes of reporting in Common Reporting Table 5.B.s1, methane recovery is allocated between wastewater and sludge on the basis of emissions generated from sludge treatment as a proportion of total capture with the balance being allocated to wastewater.

Table 7.22 Methane recovered as a percentage of industrial wastewater treatment 2021–22

Commodity	Fraction of methane recovered/flared (%)
Dairy	40.7
Pulp and Paper	85.9
Meat, Poultry and Seafood	39.3
Organic Chemicals	1.9
Sugar	0.0
Beer	63.6
Wine	50.9
Fruit	0.5
Vegetables	4.6

Source: NGER scheme 2022.

Nitrous oxide emissions from industrial wastewater

Nitrogen generated and discharged to the sewer system is ultimately treated at centralised municipal wastewater treatment plants. As N_2O emissions estimates at these plants are estimated based on the measurement of nitrogen entering the plant, this value is also inclusive of any nitrogen originating from industrial sources. Therefore, emissions of N_2O from *industrial wastewater* are included in the estimate of N_2O emissions from *domestic wastewater.*

7.5.3 Uncertainty assessment and time-series consistency

Facility level data on nitrogen entering the domestic and commercial wastewater system is used for the years 2007–08 onwards, as reported in DCC 2009 and under the NGER scheme (2008–09 onwards). Time-series consistency has been maintained for the estimates of Australia's protein per capita intake through the following assumptions. The protein per capita consumption value for the years 1989–90 to 1992–93 of 99.4 g/day (36.28 kg/year) is sourced from the Australian Institute of Health and Welfare (AIHW) (de Looper and Bhatia 1998). The values for 1993–94 to 1997–98 are based upon data presented in AIHW (2002). Linear interpolation was used to derive values for 1998–99 to 2006–07, which is the period for which no data are available. The following table shows the time series for values used for protein per capita consumption.

Table 7.23 Estimates of implied protein per capita: Australia: 1989–90 to 2021–22

Year	Protein per capita g/capita/day
1989–90	99.4
1994–95	96.6
1999–00	100.0
2004–05	97.6
2005–06	97.1
2006–07	96.6
2007–08	96.1
2008–09	98.3
2009–10	87.3
2010–11	85.2
2011–12	90.6
2012–13	89.7
2013–14	94.4
2014–15	103.6
2015–16	109.0
2016–17	92.8
2017–18	88.8
2018–19	88.9
2019–20	86.0
2020–21	82.6
2021–22	85.6

Source: de Looper and Bhatia 1998 (1989–90 to 1992–93), AIHW (2002) (1993–94 to 1997–98), DCC (2009) (2007–08), NGER scheme 2008–09 onwards. Note: interpolation used for years 1998–99 to 2006–07 inclusive.

Time-series consistency has been maintained through the interpolation of MCF values and proportions of methane captured for pulp and paper, sugar, dairy, meat, poultry and seafood, wine and fruit and vegetables for 1989–90 to 2007–08. For the beer industry, facility specific MCF values and quantities of methane captured were available for the years 2002–03 to 2004–05. For the years 1989–90 to 2001–02 in the beer time series, the 2002–03 values for MCF and proportion of methane generated that was captured have been used. For the years 2005–06 to 2007–08, the 2008–09 NGER scheme MCF and proportion of methane captured have been applied. This introduces a step change in the methane capture estimates for beer in 2005–06 where the amount of methane captured doubles, reflecting a doubling in treatment plant capacity in the beer industry during 2005–06.

For the organic chemicals where NGER scheme data have not been used, time-series consistency is ensured using a consistent methodology and associated parameters.

7.5.4 Category-specific QA/QC and verification

The quality of the data utilised in this report has been assessed against facility data available through the State Government EPA licensing system. The Australian wastewater industry is heavily regulated by State Governments, which administer relevant state legislation such as the *Environmental Protection Act* 1994 in Queensland and the *Protection of the Environment Operations Act* 1997 in New South Wales. Under this legislation the State Governments issue environment protection licences to each premises treating wastewater.

The licences require compliance with strict conditions including limits on odours, noise and organic matter and nutrients (nitrogen and phosphorus) discharged to water catchments. Annual reports must be submitted by wastewater facility operators to their state government to demonstrate their compliance and some of this information is publicly available through public registers, the National Pollutant Inventory and, in some cases, the operator's own website.

The protein per capita consumption for the 2020–21 Inventory is derived from NGER scheme facility data. Facility data received under the NGER scheme for the first 5 years of reporting indicates a degree of volatility associated with this factor. Those facilities reporting the underlying data, however, do undertake frequent sampling and analysis and must also adhere to legislated requirements to ensure the data is representative and free from bias. Nitrous oxide emissions are concentrated in rivers and estuaries where the processes for N_2O production can take place in both the water column and the sediments. N_2O emissions also arise from ocean waters in the continental shelf region; however, while these emissions may occur from human activity, they also occur naturally and are very difficult to isolate empirically.

A good understanding of how N_2O emissions occur in the continental shelf region and the influences of human activity on them is still being formed. Nitrous oxide formation is very dependent on regional conditions and chemistry and location of outfalls. Some studies have been undertaken which attempt to measure or characterise the N_2O in the continental shelf regions of Europe (Bange (2006), Barnes and Owens 1998), Canada (Punshon and Moore (2004)) and North China (Zhang et al. (2008)). A literature survey of four such studies determined an average emission rate for continental shelf/oceanic coastal waters of 0.0018 kg N_2O-N/kg N discharged. The regions studied, however, are influenced by very different marine conditions to those in Australian waters and also do not consider the effects of treated wastewater discharges (Foley and Lant, (2007)). The regional marine conditions are a major influence on the production of N_2O (Zhang et al. (2008)). An appropriate method and emission factor for estimating N_2O emissions from wastewater discharged to coastal and continental shelf waters would require further research.

The wastewater sector source categories are also covered by the general QA/QC of the greenhouse gas inventory in Annex 4.

7.5.5 Category-specific recalculations

Recalculations to Wastewater Treatment and Discharge are detailed in Table 7.24 and are due to:

A. Revised Activity Data for Industrial Wastewater

Improved reporting of commodity production across some industrial sectors resulted in revised activity data for Industrial Wastewater. These improvements contributed to revisions in emissions of 0.70% and 6.87% in 2019–20 and 2020–21, respectively.

B. Revised Activity Data for Domestic Wastewater

Minor revisions to activity data in 2021 has contributed to a revision in emissions of 0.25 per cent in 2020–21 in Domestic Wastewater.

Table 7.24 Wastewater Treatment and Discharge: recalculation of emissions (Gg CO_2–e)

Year	2023 Submission	2024 Submission	Change		Reasons for Recalculation (Gg CO_2–e)	
	Gg CO_2–e	Gg CO_2–e	Gg CO_2–e	%	A	B
1989–90	6,289.5	6,289.5	0.0	0.00	0.0	0.0
1994–95	5,631.2	5,631.2	0.0	0.00	0.0	0.0
1999–00	4,706.9	4,706.9	0.0	0.00	0.0	0.0
2004–05	3,297.5	3,297.5	0.0	0.00	0.0	0.0
2005–06	3,333.4	3,333.4	0.0	0.00	0.0	0.0
2006–07	3,385.1	3,385.1	0.0	0.00	0.0	0.0
2007–08	3,422.4	3,422.4	0.0	0.00	0.0	0.0
2008–09	3,312.2	3,312.2	0.0	0.00	0.0	0.0
2009–10	2,818.3	2,818.3	0.0	0.00	0.0	0.0
2010–11	2,778.9	2,778.9	0.0	0.00	0.0	0.0
2011–12	2,822.8	2,822.8	0.0	0.00	0.0	0.0
2012–13	2,706.6	2,706.6	0.0	0.00	0.0	0.0
2013–14	2,688.9	2,688.9	0.0	0.00	0.0	0.0
2014–15	2,680.6	2,680.6	0.0	0.00	0.0	0.0
2015–16	2,904.2	2,904.2	0.0	0.00	0.0	0.0
2016–17	2,854.6	2,854.6	0.0	0.00	0.0	0.0
2017–18	2,929.0	2,929.0	0.0	0.00	0.0	0.0
2018–19	2,741.5	2,741.5	0.0	0.00	0.0	0.0
2019–20	2,958.9	2,967.1	8.1	0.28	8.1	0.0
2020–21	2,967.5	3,052.6	85.1	2.87	80.6	4.5

7.5.6 Category-specific planned improvements

The DCCEEW will also continue to review the 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2019) for supplementary methodologies, parameters and/or guidance applicable to Australia's inventory.

The DCCEEW will also keep industrial wastewater model parameters and methods under review based on facility level data reported under the NGER scheme.

An independent review of wastewater emissions from meat processing facilities was undertaken in 2021 by an external consultancy (Point Advisory, 2021). Based on this review, wastewater emissions generated by seafood processing industries were included in the inventory. The DCCEEW will continue to investigate how the findings of this review can support future improvements within the wastewater treatment and discharge model.

We are considering how to respond to previous review recommendation W.8 (2022) on clarifying total organically degradable carbon in wastewater (TOW) removed as sludge to wastewater treatment plant (WWTP) operators. Further information will be provided in a future update.

8. Other (CRT Sector 6)

Australia does not report any emissions under CRT sector 6, ‘Other’.

9. Indirect CO_2 and nitrous oxide emissions

For the purpose of paragraph 29 of decision 24/CP.19, Australia has elected not to report indirect CO_2 and nitrous oxide emissions. Information on indirect CO_2 and nitrous oxide emissions in the *Energy and Agriculture* sectors can be found in Chapters 3 and 5 respectively.

10. Recalculations and improvements

Emissions processes are complex and, consequently, emissions estimation techniques and data sources for the Australian inventory continue to be refined, updated and improved.

More generally, the development effort behind recalculations is undertaken in line with the *Inventory Improvement Plan* for the Australian inventory. This plan is aimed at improving transparency, accuracy, completeness, consistency and comparability, with a focus on those areas where the Australian community is undertaking efforts to introduce new emissions-reducing approaches and technologies. These generally align with key categories. The improvement plan also responds to international expert reviews and changes in international practice. Some of the elements of the improvement program are set out in this chapter.

10.1 Explanations and justifications for recalculations, including in response to the review process

Key reasons for recalculations in this inventory are given in the sectoral chapters and are summarised in Table 10.1. To ensure the accuracy of the estimates, and to maintain consistency of the series through time, recalculations of past emission estimates are undertaken for all previous years in the time series.

Table 10.1 Recalculations in this Report (NIR 2022), compared with the previous report (NIR 2021)

Sector	Subsector	Category & NIR Chapter	Reason for Recalculation
Energy – Fuel combustion	Energy Industries	Category 1.A.1 Chapter 3.2.4	Australia's official statistics on energy production and use receives periodic updates to support improved understanding of Australia's energy systems, including for time series consistency. These updates are reflected in the inventory. Recalculations between 1999 and 2003 relate to the treatment of residual diesel combustion in electricity generation. The process of balancing total AES diesel consumption with facility data in circumstances where facility data exceeded the AES total led to negative balance in residual facilities in certain states and certain years. This has been corrected to ensure residual facilities balance to zero where negative balances are identified.
	Manufacturing Industries and Construction	Category 1.A.2 Chapter 3.2.5	Australia's official statistics on energy production and use receives periodic updates to support improved understanding of Australia's energy systems, including for time series consistency. These updates are reflected in the inventory. Historic activity data has been updated to align with the Australian Energy Statistics in the Chemicals and Non-ferrous metals categories. An energy conversion error has been rectified for 2020–21 within Mining (excluding fuels) and quarrying for natural gas consumption.
	Transport	Category 1.A.3 Chapter 3.2.6	Activity data for 1.A.3.e.i Pipeline transport is sourced from the Australian Energy Statistics' reporting of the amount of natural gas consumed by ANZSIC Sub-divisions 50–53 Other transport, services and storage for gas transportation purposes. Previous submissions' estimates of pipeline transport emissions have included natural gas consumed by ANZSIC subdivisions 50–53 for purposes other than gas transportation, emissions which are already reported under 1.A.4.a Commercial/Institutional. This has been corrected in this submission, resulting in a downward revision to pipeline transport emissions between 2002–03 and 2016–17. A correction to Domestic Navigation black coal consumption in 2007–08 has resulted in a recalculation. A correction to domestic aviation gasoline consumption in 2008–09 has resulted in a recalculation. A time series correction to the allocation of ethanol consumption between Domestic Navigation, Road Transport and Off-road Vehicles in 1.A.3 Transport and lawnmowers in 1.A.4.b has resulted in minor recalculations between 2005–06 and 2020–21. A revision of road transport natural gas consumption in 2020–21 has resulted in a recalculation. Motor vehicle stock data used to calculate road transport non-CO_2 emissions were revised by the Bureau of Infrastructure and Transport Research Economics for the 2020–21 inventory year. This has been corrected for this submission and results in a recalculation in non-CO_2 emissions in road transport in 2020–21. Several minor corrections to AD across several transport modes and fuels have been implemented to accurately reflect the latest release of the Australian Energy Statistics.

Sector	Subsector	Category & NIR Chapter	Reason for Recalculation
	Other Sectors	Category 1.A.4 Chapter 3.2.7	Australia's official statistics on energy production and use receives periodic updates to support improved understanding of Australia's energy systems, including for time series consistency. These updates are reflected in the inventory. A time series reallocation of emissions from the combustion of lubricants from 2.D Non-Energy Use of Fuels to 1.A.3 transport and 1.A.4.b residential sectors has been completed for this submission. This includes Motorcycles, domestic marine, residential (mowers etc), and off-road vehicles. In response to ERT recommendation, Australia has adopted a Swiss assumption of 0.05% of lubricants are assumed combusted in the transport and residential sectors.
	Other (Military Transport)	Category 1.A.5 Chapter 3.2.8	Recalculations in this sector are a result of minor corrections to military transport fuel consumption activity data to accurately reflect the latest release of the Australian Energy Statistics.
Energy – Fugitive emissions	Solid Fuels	Category 1.B.1 Chapter 3.3.1	The recalculations relate to correcting data relating to four decommissioned underground mines in 2020–21.
	Oil and Gas	Category 1.B.2 Chapter 3.3.2	A recalculation was applied to resolve an error in the application of global warming potentials in the calculation of Method 2 reporting facilities in 1.B.2.b.v gas distribution. Additionally, updated historic facility-specific UAG% data were applied in NSW and Victoria for 2014–15 to 2019–20. Recalculations to estimates for 1.B.2.b.vi.1 Post-meter gas to use the updated 2021 Residential Baseline Study activity data. An update was made to the activity data in 1.B.2.c.i Venting for the condensate venting estimate to use updated activity data for 2019–20 to 2021–22. A recalculation to remove a double-count in 1.B.2.c.ii flaring activity in 2020–21 at a facility that reported the same activity for both crude oil production flaring and gas flaring. The source data associated with abandoned oil and gas wells have been updated, resulting in a small recalculation for the full time series of estimates.
Energy – Carbon Dioxide Transport and Storage	CCS Injection and Storage	Category 1.C Chapter 3.5	There are no recalculations to carbon dioxide transport and storage in this submission.
Industrial Processes and Product Use	Mineral Industry	Category 2.A Chapter 4.2	Updates to construction activity data received from the ABS resulted in minor revisions to emissions estimates in *2.A.4 Other process uses of carbonates* from the year 2010–11 onwards. Revised carbonate consumption data in the production of ceramics has resulted in a revision to emissions estimates *2.A.4 Other process uses of carbonates* for the year 2020–21.
	Chemical Industry	Category 2.B Chapter 4.3	Nil
	Metal Industry	Category 2.C Chapter 4.4	Revised activity data associated with the consumption of petroleum coke in the production of carbon anodes at one facility has resulted in a revision to CO_2 emissions estimates from the production of aluminium in 2020–21.
	Non-energy Products from Fuels and Solvent Use	Category 2.D Chapter 4.5	Nil
	Product Uses as Substitutes for Ozone Depleting Substances	Category 2.F Chapter 4.7	Emissions have been revised in the year 2020–21 due to updated vehicle stock data from the ABS.

Sector	Subsector	Category & NIR Chapter	Reason for Recalculation
	Other Product Manufacture and Use (Electrical Equipment)	Category 2.G Chapter 4.8	Emissions have been revised in 2007–08 and subsequent years due to revised CSIRO emission estimates used to calibrate SF_6 operational leakage rates in electrical equipment.
	Other (Food & Beverage Industry)	Category 2.H Chapter 4.9	Nil
Agriculture	Enteric Fermentation	Category 3.A Chapter 5.2	A recalculation to the 2021 emissions estimate was made, updating the statistics for the number of lactating cows. This affects the calculation of feed intake, and hence the estimate of enteric fermentation.
	Manure Management	Category 3.B Chapter 5.3	Emission factors for fertiliser use on crop and pasture land were updated based on a new meta-analysis of N_2O emissions from Australian agriculture from 2003 to 2021 (Grace, et al. 2023). Although they are primarily used in estimating emissions from *agricultural soils* (3.D), these source-specific EFs are also used to calculate the indirect emissions from manure management. From 2015 onward, MMS allocation for Dairy cattle was updated based on the Dairy Australia's Land, Water and Carbon Survey Report (2020). Additionally, in response to ERT recommendation A.16 (2022) the Methane Conversion Factor (MCF) for anaerobic lagoons and drains to paddocks has been estimated for each year using the annual temperature of dairy regions in each State and Territory. As for Dairy (as described in the previous paragraph) the Methane Conversion Factor (MCF) for anaerobic lagoons and drains to paddocks has been estimated for each year using the annual temperature of piggery regions in each State and Territory.
	Rice Cultivation	Category 3.C Chapter 5.4	There are no recalculations associated with rice cultivation in this submission.
	Agricultural Soils	Category 3.D Chapter 5.5	This submission introduces use of crop residue emission factors from the 2019 Refinement to the 2006 IPCC Guidelines (Chapter 11). Instead of a single default value, there are now two new disaggregated emission factors, for wet and dry climates. These new default values were applied as a single weighted factor, calculated using the mass of nitrogen produced in wet climates compared to dry climates for each crop. The resulting EF reflects the dominance of dry climates in Australian cropland. Emission factors for fertiliser use on crop and pasture land were updated based on a new meta-analysis of N_2O emissions from Australian agriculture from 2003 to 2021 (Grace, et al. 2023). As described in Chapter 6 (LULUCF), the estimates for soil carbon are recalculated for the entire time series in every inventory. This leads to small changes in the estimates of nitrogen mineralisation due to loss of soil carbon.
	Field Burning of Agricultural Residues	Category 3.F Chapter 5.7	There are no recalculations associated with the field burning of agricultural residues in this submission.
	Liming	Category 3.G Chapter 5.8	There are no recalculations associated with liming in this submission.
	Urea Application	Category 3.H Chapter 5.9	There are no recalculations associated with urea application in this submission.

Sector	Subsector	Category & NIR Chapter	Reason for Recalculation
LULUCF	Cross-cutting	Category 4 Chapter 6	Significant improvements have been made to the way the FullCAM model reflects climate impacts on crop and grass production and soil carbon. Refinements have also been made to a range of parameters used in FullCAM, including updates to grazing pressure, crop and grass regimes and crop yield tables, as well as minor enhancements including for implementation of perennial grass parameters in the savanna fire model. These improvements are described in more detail in Chapters 6.5.1 and 6.6.1 and below. Activity data updates implemented in this submission include addition of activity data and climate data for 2021–22, and annual updates to spatial datasets (Woody Change, Plant Type and Land Use spatial layers) based on recent satellite observations. These result in a re-allocation of lands between land use categories, resulting in recalculations across most subsectors.
	Forest Land remaining Forest Land	Category 4.A.1 Chapter 6.4.1	The spatial methodology introduced in the 2019 inventory to estimate emissions from native forestry on public lands has been extended in this report to include the state of Queensland. The changes in reported emissions have two causes. Firstly, using a spatial model with specific, reported timber harvesting events and locations changed reported emissions for public multiple use forests. These changes also reflect the effects of the weather record on tree growth, and particularly on the soil carbon pool which responds strongly to inter-annual variability in rainfall. Secondly, revisions to the activity data have been received from the publicly owned NSW Forestry Corporation, resulting in higher harvesting rates prior to 2000. The multiple use forest extent in New South Wales has been expanded, improving completeness of spatial harvesting activity data captured within the modelling.
	Land converted to Forest Land	Category 4.A.2 Chapter 6.4.2	Recalculations are limited to the cross-cutting issues.
	Cropland remaining Cropland	Category 4.B.1 Chapter 6.5.1	Changes to FullCAM this year include the revision of the yield model. Yield response to rainfall has been revised through improvements to the water balance sub-model used in calculation of yields. The ranges of crop yields aligned better with those reported in ABS Agricultural Commodities statistics, especially in wetter climates. Annual grass growth was also modified to accept input yields as monthly growth increments rather than a single yearly value; this captured better the pasture growth and its response to climate. Annual grasses now grow for 9–12 months. Minor modifications were also made to the handling of turnover, which is included in growth increments. These changes have led to large recalculations in some years, particularly over 2020–2021 where the onset of La-Nina brought more rain, lower evaporation and temperatures; overall this increased crop production and as a result more carbon was retained within the soil. Updates and refinements were also made to a range of parameters used in FullCAM, including updates to grazing pressure, crop and grass regimes and crop yield tables. Grazing pressure tables now reflect revised yields. Grazing is handled as a fraction of the crop mass. Annual grasses regimes were modified so the growth season is a minimum of 9 months to better reflect trends in annual pasture cultivations. Crop and grass yield tables were updated according to the revised yield model.
	Land converted to Cropland	Category 4.B.2 Chapter 6.5.2	Recalculations are limited to the cross-cutting issues.

Sector	Subsector	Category & NIR Chapter	Reason for Recalculation
	Grassland remaining Grassland	Category 4.C.1 Chapter 6.6.1	Changes to FullCAM this year include the revision of yield model. Yield response to rainfall has been revised through improvements to the water balance sub-model used in calculation of yields. Significant changes were made to the handling of grasses this year. Perennial grass handling has been modified so that yields are provided as a monthly growth increment, rather than a total standing dry matter mass. The die off component has been removed and FullCAM now handles removal of turnover at each time step. Annual grass growth was also modified to accept input yields as monthly growth increments rather than a single yearly value; this captured better the pasture growth and its response to climate. This aligns both perennial and annual grass growth, the major difference now being their growth periods: multiple years for perennial grasses and 9–12 months for annuals Minor modifications were also made to the handling of turnover, which is included in growth increments. Updates and refinements were made to a range of parameters used in FullCAM, including updates to grazing pressure, crop and grass regimes and crop yield tables. Grazing pressure tables now reflect revised yields. Grazing is handled as a fraction of the crop mass. Annual grasses regimes were modified so the growth season is a minimum of 9 months to better reflect trends in annual pasture cultivations. Crop and grass yield tables were updated according to the revised yield. Recalculations for soil carbon due to the above lead to a recalculation of nitrogen leaching and N_2O emissions from N-mineralisation due to loss of soil carbon. Minor enhancements have also been made to the grass productivity parameters in the savanna fire model.
	Land converted to Grassland	Category 4.C.2 Chapter 6.6.2	Recalculations are limited to the cross-cutting issues.
	Wetlands remaining Wetlands	Category 4.D.1 & Category 4.H Chapter 6.7.1	Refinements were made to the model used to estimate farm dam emissions. The 2023 model (Malerba, et al. n.d.) introduces a local weather and satellite-based method to model methane emissions from agricultural ponds accounting for fluctuations in water surface area and temperature-dependent methane flux.
	Land converted to Wetlands	Category 4.D.2 Chapter 6.7.2	Recalculations are limited to the cross-cutting issues.
	Settlements remaining Settlements	Category 4.E.1 Chapter 6.8.1	Recalculations are limited to the cross-cutting issues.
	Land converted to Settlements	Category 4.E.2 Chapter 6.8.1	Recalculations are limited to the cross-cutting issues.
	Harvested Wood Products	Category 4.G Chapter 6.10	Recalculations are due to time-series revisions to the underlying source data on forestry and wood products produced by ABARES, and revisions in the Waste sector which impact HWP in SWDS.

Sector	Subsector	Category & NIR Chapter	Reason for Recalculation
Waste	Solid Waste Disposal	Category 5.A Chapter 7.2	Revisions to the harvested wood products activity data contributed to revisions of between -0.56 and 0.35 per cent between 1989–90 and 2020–21.
	Biological Treatment of Solid Waste	Category 5.B Chapter 7.3	There are no recalculations to biological treatment of solid waste in this submission.
	Incineration and Open Burning of Solid Waste	Category 5.C Chapter 7.4	There are no recalculations to incineration and open burning of solid waste in this submission.
	Wastewater Treatment and Discharge	Category 5.D Chapter 7.5	Improved reporting of commodity production across some industrial sectors resulted in revised activity data for industrial wastewater. These improvements contributed to revisions of 0.70% and 6.87% in 2019–20 and 2020–21, respectively. Minor revisions to activity data in domestic wastewater contributed to a revision of 0.25 per cent in 2020–21.

10.2 Implications for emission and removal levels

Table 10.2 gives the estimated recalculations for this submission for each category for 1989–90, 2004–05 and the past ten years.

Table 10.2 Estimated recalculations for this submission (compared with last year's submissions 1989–90, 2004–05, 2011–12 to 2020–21)

	1989–90	2004–05	2011–12	2012–13	2013–14	2014–15	2015–16	2016–17	2017–18	2018–19	2019–20	2020–21
Sector	**Emissions (Mt CO_2-e)**											
1.A Fuel Combustion	0.0	0.0	-0.4	-0.2	-0.3	0.1	0.1	0.1	0.2	-0.1	-0.2	0.5
1.A.1, 2, 4, 5 Stationary Energy	0.0	0.0	-0.4	-0.2	-0.3	0.1	0.1	0.2	0.2	-0.1	-0.2	0.6
1.A.3 Transport	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
1.B Fugitives	0.0	0.0	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.3	-0.2
2 Industrial Processes	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
3 Agriculture	-0.9	-1.1	-1.5	-1.3	-1.3	-1.3	-1.2	-1.7	-1.4	-1.3	-1.1	-1.6
4 LULUCF	-19.9	-5.7	-22.7	-2.7	-16.1	-6.3	-20.7	20.4	-11.8	-14.1	-18.7	-24.7
5 Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	-0.1
Total Recalculation	**-20.9**	**-6.8**	**-24.4**	**-4.0**	**-17.5**	**-7.2**	**-21.4**	**19.1**	**-12.6**	**-15.2**	**-19.7**	**-26.0**

10.3 Implications for emission and removal trends, including time series consistency

The most significant recalculations occur in LULUCF. The overall trend of national emissions is largely unaffected, and the standards of time series consistency are preserved in all recalculations.

The full time series of recalculations is set out in Table 10.3.

Table 10.3 Estimated recalculations for this submission (compared with last year's submission 1989–90 to 2020–21)

	Including LULUCF				Excluding LULUCF			
	Previous estimate	Current Estimate	Difference		Previous estimate	Current Estimate	Difference	
	Mt CO_2-e	Mt CO_2-e	Mt CO_2-e	%	Mt CO_2-e	Mt CO_2-e	Mt CO_2-e	%
1989–90	636.3	615.4	-20.9	-3.3%	438.1	437.1	-0.9	-0.2%
1990–91	621.5	595.0	-26.5	-4.3%	438.0	437.2	-0.8	-0.2%
1991–92	556.8	554.5	-2.3	-0.4%	441.8	441.0	-0.7	-0.2%
1992–93	535.3	533.5	-1.8	-0.3%	442.3	441.3	-0.9	-0.2%
1993–94	531.0	523.4	-7.6	-1.4%	442.6	441.6	-1.0	-0.2%
1994–95	514.2	511.0	-3.2	-0.6%	451.1	450.3	-0.8	-0.2%
1995–96	522.3	512.2	-10.1	-1.9%	457.6	456.4	-1.1	-0.2%
1996–97	522.9	510.3	-12.5	-2.4%	469.8	468.5	-1.3	-0.3%
1997–98	524.3	527.9	3.6	0.7%	484.0	483.0	-1.1	-0.2%
1998–99	539.6	548.3	8.7	1.6%	490.0	488.9	-1.1	-0.2%
1999–00	566.4	569.8	3.5	0.6%	501.6	500.5	-1.1	-0.2%
2000–01	586.6	586.5	-0.2	0.0%	509.5	508.4	-1.0	-0.2%
2001–02	582.5	591.0	8.5	1.5%	513.2	512.0	-1.1	-0.2%
2002–03	591.5	590.5	-1.0	-0.2%	511.7	511.2	-0.5	-0.1%
2003–04	584.9	574.7	-10.2	-1.7%	528.8	528.0	-0.9	-0.2%
2004–05	616.3	609.4	-6.8	-1.1%	535.6	534.5	-1.1	-0.2%
2005–06	626.8	644.9	18.1	2.9%	540.0	538.7	-1.3	-0.2%
2006–07	641.5	626.1	-15.4	-2.4%	546.7	545.9	-0.8	-0.2%
2007–08	630.3	614.6	-15.6	-2.5%	549.1	548.8	-0.3	-0.1%
2008–09	630.9	607.9	-23.0	-3.7%	552.1	550.6	-1.5	-0.3%
2009–10	613.3	609.2	-4.2	-0.7%	547.2	545.9	-1.3	-0.2%
2010–11	594.0	577.6	-16.4	-2.8%	549.0	547.5	-1.5	-0.3%
2011–12	579.1	554.7	-24.4	-4.2%	552.3	550.6	-1.7	-0.3%
2012–13	561.1	557.1	-4.0	-0.7%	543.8	542.5	-1.3	-0.2%
2013–14	555.8	538.3	-17.5	-3.1%	535.5	534.1	-1.4	-0.3%
2014–15	540.9	533.7	-7.2	-1.3%	544.2	543.3	-0.9	-0.2%
2015–16	512.5	491.1	-21.4	-4.2%	552.4	551.6	-0.8	-0.1%
2016–17	509.8	528.9	19.1	3.7%	559.6	558.3	-1.3	-0.2%
2017–18	514.2	501.7	-12.6	-2.4%	560.8	560.0	-0.8	-0.1%
2018–19	505.9	490.7	-15.2	-3.0%	555.2	554.2	-1.0	-0.2%
2019–20	494.2	474.5	-19.7	-4.0%	536.7	535.8	-1.0	-0.2%
2020–21	464.8	438.7	-26.0	-5.6%	528.6	527.3	-1.4	-0.3%

10.4 Areas of improvement and/or capacity building in response to the review process

Priorities for the inventory development process have been set out in the *National Inventory Systems Inventory Improvement Plan* and have been informed by analysis of key sources and key trends. Information on planned improvements are outlined for each sector in the relevant chapter.

More broadly, Australia is progressively implementing updated IPCC methods for sources identified in the *2019 Refinement to the 2006 IPCC Guidelines*, and in the *2013 Wetlands Supplement*. Continued investment in IT software systems including the AGEIS, and for *LULUCF* the FullCAM, is also a critical part of the improvement plan.

New information generated by publicly funded research programs or other sources also provide opportunities to test the validity of existing parameters, to consider changes to model structures, or to develop new methods. Australia is closely following the development of new atmospheric measurement technologies and associated techniques for opportunities to further enhance national inventory system quality assurance processes.

Summary of Responses to the simplified review for the 2023 inventory submission

Australia was the first Party to participate in a simplified review of its national inventory under the Paris Agreement: Report on the simplified review of the national inventory report of Australia submitted in 2023. The simplified review was conducted by the secretariat in accordance with paragraphs 15–19 of the conclusions and recommendations from the 2023 joint meeting of lead reviewers, available at https://unfccc.int/documents/627213. In its review, the secretariat undertook automated checks on completeness and consistency. As set out in Section III to the Report on the simplified review, Australia observed the 2023 simplified review compared Australia's first national inventory submission under the Paris Agreement with its last submission under the UNFCCC. As a consequence, many findings reflected differences between the CRF and the CRT, rather than a discrepancy in inventory completeness or consistency. With regard to other findings in the simplified review report, Australia confirms that all the new key categories identified in findings IDs I.2.80-96 were estimated using IPCC tier 2 or 3 methods, consistent with IPCC guidelines. Some findings reflected Australia's misinterpretation of the CRT (IDs I.1.32–37), which it has shared with the secretariat to assist other Parties in their completion of the new CRT, and issues associated with the manual population of the CRT due to the new CRT reporter tool being under development. Recalculations implemented last submission were documented in the NIR 2021 in Volume 1, Chapters 3–7 and summarised in Chapter 10.

Summary of Responses to UNFCCC ERT Recommendations and Comments

As part of the national inventory development process all issues identified by the UNFCCC ERT review teams are assessed for their implications for the national inventory. Recommendations from the previous reviews which are in the process of being addressed are summarised below.

Table 10.4 Status of issues raised by previous UNFCCC Technical Expert Review Teams

Sector	Issue ID#	ERT Recommendation	Australian Response	Reference Chapters
General	G.2, 2022 (G,5, 2021)	Include the information required by the 2006 IPCC Guidelines (vol. 1, chap. 3, section 3.2.2.3, and vol. 1, chap. 2, section 2.2 and annex 2A.1 on expert elicitation) when using expert judgment in the uncertainty analysis.	We have made substantial progress against this recommendation. We are continuing to review uncertainty values and will provide further details on values determined using expert judgment in future annual submissions.	A2
Energy	E.8, 2022	The ERT recommends that the Party include in the NIR a description of the two methods for estimating fugitive CH_4 emissions available to natural gas distributors under the NGER scheme, including, for both methods, the assumptions made, the required AD and EFs, and relevant references.	We have focussed on ensuring that the general explanations in methodological issues are sufficient. The text at page 94 of Volume 1 has been updated to provide further clarity on the estimation approaches.	3.3.1.2 3.3.1.5
IPPU Petrochemical and carbon black production	I.2, 2022 (I.11, 2021)	Indicate in CRF table 9 under which category CO_2 emissions from methanol production (category 2.B.8.a), reported as "IE" in the CRF tables, are included.	Methanol production data is confidential. All emissions associated with petrochemical and carbon black production, which includes methanol production, is reported under CRT category 2.B.8.g.ii (Other), and Table 9 of the CRTs has been updated accordingly.	CRT 2(I).A-H
IPPU Magnesium production	I.4, 2022 (I.13, 2021)	Correct the description of the AD in CRF table 2(II)B-Hs1 and replace the notation key "NE" used for AD with the estimates for 1996–2000.	Activity data for SF_6 emissions associated with magnesium production are now shown as the volume of SF_6 used.	CRT 2(II).B-Hs1
Agriculture General	A.2, 2022 (A.20, 2021)	Add an appropriate unit for all AD, parameters and EFs included in the NIR, including for the following in volume 1: the number of dairy cattle in each class for each state and season (N_{ij}) in equation 3A.1a_4 (p.310), additional intake for milk production (MA_{ijk}=4) in equation 3A.2_3 (p.313), the inorganic fertilizer EF for non-irrigated cropping (EF_{ij}) in equation 3B.5d_2 (p.335), the mass of limestone and dolomite applied to soils (M_y) in equation 3G_1 (p.361), the default EFs for limestone (EFj=1) and dolomite (EFj=2) in equation 3G_1 (p.361), the mass of urea applied to soils (Mi) in equation 3H_1 (p.362) and the default EF for urea in equation 3H_1 (p.362).	Units have been added to activity data, including all those identified by the expert review team.	5
Agriculture Animal manure applied to soils	A.10, 2022 (A11, 2021) (A18, 2020)	Explain in the NIR the estimation of the N_2O EF for animal manure applied to soils.	We note that outstanding concerns from the technical expert review team on this issue relates specifically to manure from swine. We are reviewing this choice of emission factor.	5.3.2 A5.5.5

Sector	Issue ID#	ERT Recommendation	Australian Response	Reference Chapters
Agriculture MMS – Anaerobic lagoons; drains to paddocks	A.16, 2022 (new)	Either (1) report data on average annual temperature by state/territory for the entire reporting period in the NIR (e.g. in tabular format in an appendix) in order to justify the appropriateness of the current MCFs for anaerobic lagoons and drains to paddocks, which have been selected to estimate CH_4 emissions from swine and dairy cattle MMS or (2) adjust the MCF values of the two M MS anaerobic lagoons and drains to paddocks (the latter of which is assumed to be similar to a liquid/slurry system) in accordance with the data collected on average annual temperature by state/territory for the entire reporting period and recalculate CH_4 emissions from MMS of swine and dairy cattle, as necessary.	We are considering how to respond to this recommendation and further information will be provided in a future update.	5.3.5
Agriculture MMS – Swine	A.17, 2022 (new)	Report information on the PigBal model in accordance with paragraph 50(a) of the UNFCCC Annex I inventory reporting guidelines.	The explanation of the PigBal model in the NIR has been extended.	5.3.2 A5.5.5
LULUCF General	L.1, 2022 (L.1, 2021) (L.2, 2020) (L.3, 2019) (L.4, 2017) (L.29, 2016)	Provide separate AD and estimates for the following categories and pools currently reported as "IE": cropland, wetlands and settlements converted to forest land (all pools except organic soils); cropland converted to grassland (all pools); and cropland and grassland converted to settlements (all pools). Until this is done, provide in the NIR an update of the status of efforts to provide estimates for these pools.	We note that this recommendation has been reviewed by numerous technical expert review teams since 2016. Croplands, wetlands and settlements converted to forest land are now reported and previous reviews have assessed these elements as resolved. Previous reviews have agreed that it is reasonable for cropland converted to grassland to be reported as IE on the basis that it is not practical to identify these transitions where mixed cropping and grazing rotations frequently occur as a part of normal farming operations in Australia. Identifying cropland and grassland converted to settlements will require an extension of Australia's Approach 3 land identification systems to distinguish changes in land uses other than forest cover. While it is not mandatory for Australia to extend beyond Approach 1 land representation in this respect, it is nevertheless a planned improvement to do so as competing priorities and resources permit.	6.4.2 6.5.1.1 6.8.2.5
LULUCF General	L.7, 2022 (new)	Provide in the NIR information on new data updates and associated calibration and validation of the model, FullCAM, or a comparison of estimates derived using the model with estimates derived from an alternative method for SOC changes in forest land and grassland.	We are considering how to respond to this recommendation and further information will be provided in a future update.	

Sector	Issue ID#	ERT Recommendation	Australian Response	Reference Chapters
LULUCF Forest Land	L.8, 2022 (new)	Report in the NIR annual emissions associated with natural disturbances disaggregated from subsequent annual removals.	Table 6.3.5, in chapter 6, shows separate time series of emissions and removals associated with natural disturbances.	6.3.2
Waste Solid waste disposal	W.7, 2022 (new)	Provide in the NIR a more detailed explanation of QA/QC procedures for data on CH_4 recovery, utilization and flaring, including how the amount of CH_4 used for energy generation or flaring is verified, preferably including a table with the results, at an aggregated level, of a comparison of data from landfill operators with those from energy companies.	Additional information has been provided regarding the NGER scheme data collection process and how it supports verification.	7.2.4
Waste Wastewater	W.8, 2022 (new)	Either: (1) better explain the definition of TOW removed as sludge to WWTP operators and improve the QA/QC procedures for data collected on wastewater treatment and discharge under the NGER scheme to ensure that accurate values of sludge are reported; or, alternatively, (2) recalculate CH_4 emissions from wastewater treatment using data on more common WWTP parameters that are available from the WWTP operators and include a description of the methodology in the NIR.	We are considering how to respond to this recommendation and further information will be provided in a future update.	7.5.6

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