Environment Protection Authority

Improving measurement of fugitive methane emissions

July 2025

Acknowledgement of Country

The NSW Environment Protection Authority acknowledges the Traditional Custodians of the land on which we live and work, honours the ancestors and the Elders both past and present and extends that respect to all Aboriginal people.

We recognise Aboriginal peoples' spiritual and cultural connection and inherent right to protect the land, waters, skies and natural resources of NSW. This connection goes deep and has since the Dreaming.

We also acknowledge our Aboriginal and Torres Strait Islander employees who are an integral part of our diverse workforce and recognise the knowledge embedded forever in Aboriginal and Torres Strait Islander custodianship of Country and culture.

Aboriginal artwork by Worimi artist Gerard Black

CSIRO’s contribution to this report

CSIRO, Australia’s national science agency, has extensive experience in making high-quality, long-term measurements of methane in the atmosphere, at global, regional and facility-level scales.

CSIRO conducted a scientific and technical review of methane measurement technologies for fugitive methane emissions (CSIRO review). The CSIRO review was co-authored by Dr Christopher Caldow, Dr Nasimeh Shahrokhi and Dr Zoe Loh, CSIRO. Sections 3, 4 and 5 of this report present a summary of the CSIRO review.

The EPA prepared this report, which includes the key findings of the CSIRO review and outlines how the EPA will consider CSIRO’s recommendations on facility-level fugitive methane monitoring. The EPA would like to thank CSIRO for its contributions to this report.

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Summary

1.1 Introduction

The NSW Environment Protection Authority (EPA) engaged the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to provide expert advice on how to improve the measurement of fugitive methane emissions.

The EPA has a critical role in protecting the environment from the threat of climate change and in delivering actions that will support NSW to achieve net zero emissions by 2050. The EPA is taking action to reduce greenhouse gas emissions, including carbon dioxide and methane emissions. Managing methane emissions is a key priority for the EPA to help meet national and state emissions reduction targets because methane can warm the Earth faster than carbon dioxide.

Fugitive methane, which is emitted by industrial activity, is inherently challenging to measure due to the diffuse and unpredictable nature of its sources. These emissions can occur intermittently and at varying magnitudes over space and time, making it difficult to consistently and accurately detect and quantify them.

In 2022, NSW methane emissions were 1,127,000 tonnes of methane (t CH_4). When expressed in terms of carbon dioxide equivalent (CO_2-e) emissions, this accounted for more than one-quarter (28%) of total greenhouse gas emissions.

1.2 Purpose of this report

The EPA is developing a phased regulatory approach to reduce fugitive methane emissions released by EPA-licensed facilities. As part of this work, the EPA commissioned CSIRO to conduct a review of methane measurement technologies for fugitive methane emissions. This includes prioritising key sectors with fugitive methane emissions licensed by EPA and feasible measurement approaches for these key sectors.

The aim of the CSIRO review is to provide independent expert advice to the EPA regarding the availability, feasibility and uses of facility-level fugitive methane monitoring, in order to improve quantification of emissions. Based on the findings from the review, CSIRO made recommendations on facility-level fugitive methane monitoring for the EPA's consideration.

This report presents the key findings of the CSIRO review, including priority sources of methane emissions, technologies for monitoring methane emissions, and the suitability of methods for different sectors (sections 3, 4 and 5, respectively). The report (section 6) outlines how the EPA will consider CSIRO recommendations on facility-level fugitive methane monitoring.

1.3 Priority sources of methane emissions

The assessment of priority sources of methane emissions is based on the definition of **fugitive methane** emissions provided in the EPA *Strategic Plan 2024–29*, which states:

> Fugitive methane is methane emitted by an industrial activity that is not from a point source of combustion but includes flaring. Examples include venting of gas from coal mines and gas processing facilities, leaks from pressurised gas lines, and surface emissions from waste facilities (such as landfills) and sewage treatment plants.

Priority sources of methane emissions are based on the **magnitude** of methane emissions produced by sectors and subsectors, and the **proportion** of emissions covered by EPA licences (i.e. 'EPA-covered emissions'). It is estimated that about 552,000 t CH_4/year is covered by EPA licences, based on 2022 data. This represents nearly half (49%) of methane emissions in NSW.

Priority fugitive methane emissions, based on the **magnitude** of emissions in NSW and the **proportion** of emissions covered by EPA licences (in order of priority) are:

1. underground coal mines – emitting 255,000 t CH_4/year, with emissions accounting for 46% of all EPA-covered emissions
2. solid waste disposal – emitting 122,000 t CH_4/year, accounting for 22% of all EPA-covered emissions
3. surface coal mining – emitting 65,000 t CH_4/year, accounting for 12% of all EPA-covered emissions.

The assessment of the magnitude of methane emissions is reliant on the data provided by Australia's National Greenhouse Accounts (ANGA). This is the only comprehensive dataset available that provides annual emissions estimates covering the relevant sectors and subsectors across NSW. With such reliance on ANGA, it is important to consider the uncertainties within ANGA, and the effect that this may have on the assessment of priority sources of fugitive methane emissions. These uncertainties are discussed in detail in section 3.3.

1.4 Technologies for monitoring methane emissions

The focus of the CSIRO review is to evaluate existing methane measurement technologies that can improve quantification of fugitive methane emissions at key EPA-licensed premises. These technologies are detailed in section 4.

In NSW, methane and other greenhouse gas emissions have traditionally been accounted for using bottom-up approaches, which are subject to considerable uncertainty. There is strong evidence that using a combination of bottom-up and top-down emissions monitoring approaches can improve the accuracy of estimations and help prioritise mitigation action over time (see sections 3.3 and 4.5). As such, both bottom-up and top-down approaches are considered.

> For the purpose of this report 'bottom-up' refers to use of activity and emission factors[1] associated with an emission source to estimate emissions; and 'top-down' refers to direct measurement of atmospheric composition and inverse modelling to infer emissions.

1.4.1 Bottom-up approaches

Bottom-up techniques are commonly applied to estimate methane emissions across facility, state, national and global scales. At the facility scale, the most commonly applied bottom-up techniques are prescribed in the *National Greenhouse and Energy Reporting (Measurement Determination) 2008*.

[1] Emission factors are used to convert a unit of activity into emissions.

Bottom-up techniques are widely implemented and have a number of advantages compared to top-down techniques, including that they are generally:

- relatively easy to apply, including at scales ranging from facility-level to national
- low cost, with low equipment requirements.

In the case of Intergovernmental Panel on Climate Change (IPCC) guidelines and Australian national inventory report methods, bottom-up approaches are aligned to international standards for reporting to the *United Nations Framework Convention on Climate Change* and thus can be used to meet international obligations. Also, in some cases, bottom-up monitoring may already be legislated (e.g. for safety), so there may be no additional burden in applying this technique.

The key limitations to bottom-up techniques are:

- limited accuracy when applying emission factors derived at broad global or national scales to smaller scales such as local or facility scale
- they capture only identified emission pathways and may not capture all sources of emissions
- limited independent verification by top-down methods that have been calibrated against controlled release studies
- limited data availability at scales finer than state-level, for specific gases such as methane, and for emissions that are below reporting thresholds such as the National Greenhouse and Energy Reporting (NGER) Scheme.

1.4.2 Top-down approaches

Techniques for top-down approaches have been developed for a broad range of spatiotemporal scales, ranging from annual global scale emissions determinations to hourly emissions from a single facility. Because the top-down approach measures an integrated signal in the atmosphere, it is particularly useful for quantifying fugitive emissions or detecting emissions from sources or processes that may otherwise be absent from or poorly accounted for in a bottom-up approach.

Critical to the use of top-down approaches is the need to robustly measure or represent the concentration of methane present in the air outside the boundary of the facility or the area being analysed (i.e. the ‘boundary condition’). At a facility scale, this is often best achieved by strategically placing monitoring instruments diametrically across a facility based on prevailing meteorology. This allows upwind and downwind measurements be to obtained, which can determine emissions due solely to the facility in question.

In addition, a fit-for-purpose modelling tool for the relevant spatial scale is needed to transform any observed increases in atmospheric gas concentration measured upwind and downwind of a facility, into an ‘emission flux’.

Generally, top-down approaches require a higher level of technical expertise to implement, as well as meteorological data relevant to the facility or collected by the facility.

Top-down approaches available for monitoring methane emissions include: atmospheric inverse approaches, atmospheric transport models, tracer release experiments, ground-based monitoring networks, mobile ground laboratories, uncrewed aerial vehicles, aircraft and satellite, a range of emerging technologies, and integrated greenhouse gas observing systems.

1.5 Suitability of methods for sectors

The benefits, limitations, costs and feasibility of bottom-up and top-down monitoring techniques are summarised in section 5. The appropriate technologies that can be used for fugitive methane emissions are identified for the priority sectors licensed by EPA. Factors to consider include: best-practice emissions estimation from continental to facility scale; capital costs; labour costs and technical feasibility; and suitability and feasibility of methods for sectors and subsectors.

1.6 Future regulatory policy considerations

Section 6 outlines how the EPA will consider the key recommendations on facility-level fugitive methane monitoring. These include regional greenhouse gas monitoring networks, a tiered approach to prioritise large emitters, facility-level fugitive methane measurement (for underground coal mines and other sectors), and top-down modelling to estimate emissions.

2

Introduction

The NSW Environment Protection Authority (EPA) has a critical role in protecting the environment from the threat of climate change and in delivering actions that will support NSW to achieve net zero emissions by 2050. The *EPA Climate Change Policy* (NSW EPA 2023a) and *Climate Change Action Plan 2023–26* (NSW EPA 2023b) outline a comprehensive regulatory approach and set of actions to address the causes and consequences of climate change in NSW. The EPA is taking action to reduce greenhouse gas emissions, including carbon dioxide and methane emissions.

NSW has legislated emissions reduction targets under the *Climate Change (Net Zero Future) Act 2023*. In addition, Australia is a signatory of the Global Methane Pledge[2] to reduce methane emissions by at least 30% from 2020 levels by 2030. Managing methane emissions is a key priority to help meet national and state emissions reduction targets.

Methane is a greenhouse gas that has high global warming potential and a short atmospheric lifetime compared to carbon dioxide. The higher global warming potential means that, molecule for molecule, methane can warm the Earth faster than carbon dioxide. The short lifetime means that cuts in methane emissions will result in near-term reductions in warming. Methane emissions in NSW have been gradually declining since 1990 (with an average decline of 33 kilotonnes [kt] of methane per year between 1990 and 2022). However, there remains considerable work to reduce emissions as NSW's methane emissions remain above 1,000 kt of methane per year.

Fugitive methane, which is emitted by industrial activity, is inherently challenging to measure due to the diffuse and unpredictable nature of its sources. These emissions can occur intermittently and at varying magnitudes over space and time, making it difficult to consistently and accurately detect and quantify them. In NSW, methane and other greenhouse gas emissions have traditionally been quantified using 'bottom-up' approaches, which are subject to considerable uncertainty. There is strong evidence that augmenting bottom-up methods with 'top-down' emissions monitoring approaches can improve the accuracy of estimations. For the purpose of this report 'bottom-up' refers to use of activity and emission factors associated with an emission source to estimate emissions, and 'top-down' refers to direct measurement of atmospheric composition and inverse modelling to infer emissions (section 4 describes these methods).

Accurate measurements are needed to help ground truth and provide transparency on the amount of fugitive emissions in NSW. These data will inform policy development and help industries understand and take further action to reduce fugitive methane emissions.

The EPA is developing a phased regulatory approach to reduce fugitive methane emissions released by EPA-licensed facilities. Actions we are taking or have taken include:

- working with experts to improve how fugitive methane emissions are measured, monitored, and independently and transparently verified
- trialling new methane measurement and monitoring techniques with experts to support more accurate assessment and verification of methane emissions from licensed facilities
- commissioning the University of NSW to conduct a greenhouse gas survey using car-based technologies in Western Sydney – the 2023 study is available at Summary – UNSW greenhouse gas survey in Western Sydney[3]

[2] https://www.globalmethanepledge.org/

[3] https://www.epa.nsw.gov.au/Your-environment/Climate-change/Greenhouse-gas-measurement/Report-summary

- working with the NSW Department of Climate Change, Energy, the Environment and Water (NSW DCCEEW) to progressively establish regional greenhouse gas monitoring networks.

As part of this work, the EPA commissioned the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to conduct a review of methane measurement technologies for fugitive methane emissions. This includes prioritising key sectors with fugitive methane emissions licensed by EPA and feasible measurement approaches for these key sectors.

The aim of the CSIRO review is to provide independent expert advice to the EPA regarding the availability, feasibility and uses of facility-level fugitive methane monitoring, in order to improve quantification of emissions. Monitoring fugitive methane concentrations in the atmosphere alone will not provide information on emissions from individual facilities or sources. Therefore, this project also details modelling methodologies to turn measurement into emission estimations from the source of the activity or process. Based on the findings from the review, CSIRO made recommendations on facility-level fugitive methane monitoring for the EPA's consideration.

This report includes a summary of the CSIRO review, including:

- *priority sources of methane emissions in NSW* (section 3), which outlines the process for prioritising sectors with regard to the magnitude of methane emissions they emit and the proportion of these emissions that are covered by EPA licences
- *technologies for monitoring methane emissions* (section 4), which provides details on the variety of different monitoring techniques and technologies that are available
- *suitability of methods for sectors* (section 5), which provides guidance on the most appropriate technologies for priority sectors.

Section 6 *Future regulatory policy considerations* outlines how the EPA will consider CSIRO recommendations on facility-level fugitive methane monitoring.

3

Priority sources of methane emissions in NSW

3.1 NSW methane emissions by sector and subsector

3.1.1 Greenhouse gas emissions

At a state, federal and global level, methane and other greenhouse gas emissions are reported for different sectors and subsectors. These sectors are based on the *United Nations Framework Convention on Climate Change* (UNFCCC) (UN 1992) classification system and represent the main sources of anthropogenic greenhouse gas emissions, including energy, transport, agriculture, fugitive emissions, waste, industrial processes and land-use change. The emissions for each sector are the totals of emissions from their relevant subsectors. In general, methane emissions are dominated by agriculture, fugitive emissions from the oil, gas and coal industries and from the waste sector (landfills and wastewater treatment).

Australia estimates greenhouse gas emissions using Intergovernmental Panel on Climate Change (IPCC) methodologies in which activity data (e.g. how much coal was produced) are combined with emission factors representing the emissions intensity of each activity.[4] In some instances, the emission factors used can be country-specific.

In their review, CSIRO used the summary of emissions covered by EPA licences for sectors and subsectors provided in the *EPA Climate Change Policy* (EPA 2023a). Table 1 provides an overview of the main sources of greenhouse gas emissions by sector and subsector in NSW, and the relative amount of emissions that are covered by EPA licences. The transport and land-use sectors are not considered further in this report as they represent a very low portion under EPA's remit.

Table 1 NSW greenhouse gas emissions sources by sector and subsector, the activities covered by EPA licences, and the proportion covered by EPA licensees

Sector or Subsector*	Description	Activities in this sector that are covered by EPA licences	Proportion covered by EPA licences
Electricity generation (1.A.1.a.i Energy industries)	Emissions from the combustion of fossil fuels for electricity generation	The EPA licenses larger electricity generation activities that generate almost all of these emissions (e.g. coal-fired power stations). Local councils generally regulate smaller activities, which typically have much lower emissions.	Almost all
Transport (1.A.3 Transport)	Includes fossil fuel combustion emissions for use in transport activities (e.g. on-road vehicles, rail, domestic aviation and domestic shipping)	While some operators that the EPA licenses use on-road vehicles or rail rolling stock, emissions from these account for a very small proportion of total transport sector emissions.	Very low
Stationary energy (excluding electricity generation) (1.A.2, 4 and 5 various stationary energy)	Emissions from onsite fossil fuel combustion (e.g. to run boilers and furnaces) used in manufacturing and other activities	The EPA licenses larger industrial activities that generate most of these emissions (e.g. metallurgy). Local councils generally regulate smaller premises (e.g. some commercial, residential and smaller industrial premises).	Most

[4] Emission factors are used to convert a unit of activity into emissions.

Sector or Subsector*	Description	Activities in this sector that are covered by EPA licences	Proportion covered by EPA licences
Fugitive emissions (1.B Fugitive emissions from fuels)	Emissions from the extraction and distribution of coal and natural gas	In NSW fugitive emissions are mainly from coal and gas extraction activities, which are almost all licensed by the EPA (e.g. coal mines).	Almost all
Industrial processes (2. Industrial processes and product use)	Emissions from chemical and/or physical transformation of materials, and consumption of synthetic greenhouse gases	The EPA licenses larger industrial premises that generate most of these emissions (e.g. chemical production). Local councils generally regulate smaller activities; however, these typically have much lower emissions.	Most
Agriculture (3. Agriculture)	Includes emissions of methane and nitrous oxide from livestock, crops, and agricultural and forest soils	Most agricultural emissions are methane emissions from ruminant animals (mainly cattle and sheep). These animals are predominantly kept on grazing land, which is not licensed by the EPA. Some of these emissions are from livestock-intensive activities (e.g. feedlots), which the EPA does license.	Low
Land use, land-use change and forestry (4. LULUCF)	Emissions due to land use, land-use change and forestry (LULUCF) can either be an emission source (positive emissions) or sink (negative emissions)	EPA has a role in regulating some forestry activities (e.g. native forestry).	None
Waste (5. Waste)	Emissions due to waste disposal, treatment and processing, including domestic and industrial wastewater	Almost all waste activities are regulated by the EPA (e.g. landfills, sewage treatment plants).	Almost all

Table note:

* The corresponding sectors/subsectors based on the *United Nations Framework Convention on Climate Change* (UN 1992) classification system are shown in brackets.

3.1.2 NSW methane emissions

The data on methane emissions in NSW for sectors and subsectors presented here is based on the estimates of emissions provided by Australia's National Greenhouse Accounts (ANGA).[5] The assessment of priority sources of methane emissions is based on the definition of **fugitive methane** emissions provided in the EPA *Strategic Plan 2024–29* (NSW EPA 2024a), which states:

> Fugitive methane is methane emitted by an industrial activity that is not from a point source of combustion but includes flaring. Examples include venting of gas from coal mines and gas processing facilities, leaks from pressurised gas lines, and surface emissions from waste facilities (such as landfills) and sewage treatment plants.

[5] https://greenhouseaccounts.climatechange.gov.au/

In 2022, NSW methane emissions were 1,127 kilotonnes of methane (kt CH_4). When expressed in terms of carbon dioxide equivalent (CO_2-e) emissions, this accounted for more than one-quarter (28%) of total greenhouse gas emissions in NSW.[6] Total anthropogenic methane emissions for NSW declined from 2,177 kt CH_4 in 1990 to 1,127 kt CH_4 in 2022 (Figure 1). Between 2005 and 2022, NSW methane emissions declined by 30% (476 kt CH_4). The majority of this reduction was driven by reductions in the Energy sector (70% of total reduction), followed by the agriculture sector (18% of total reduction).

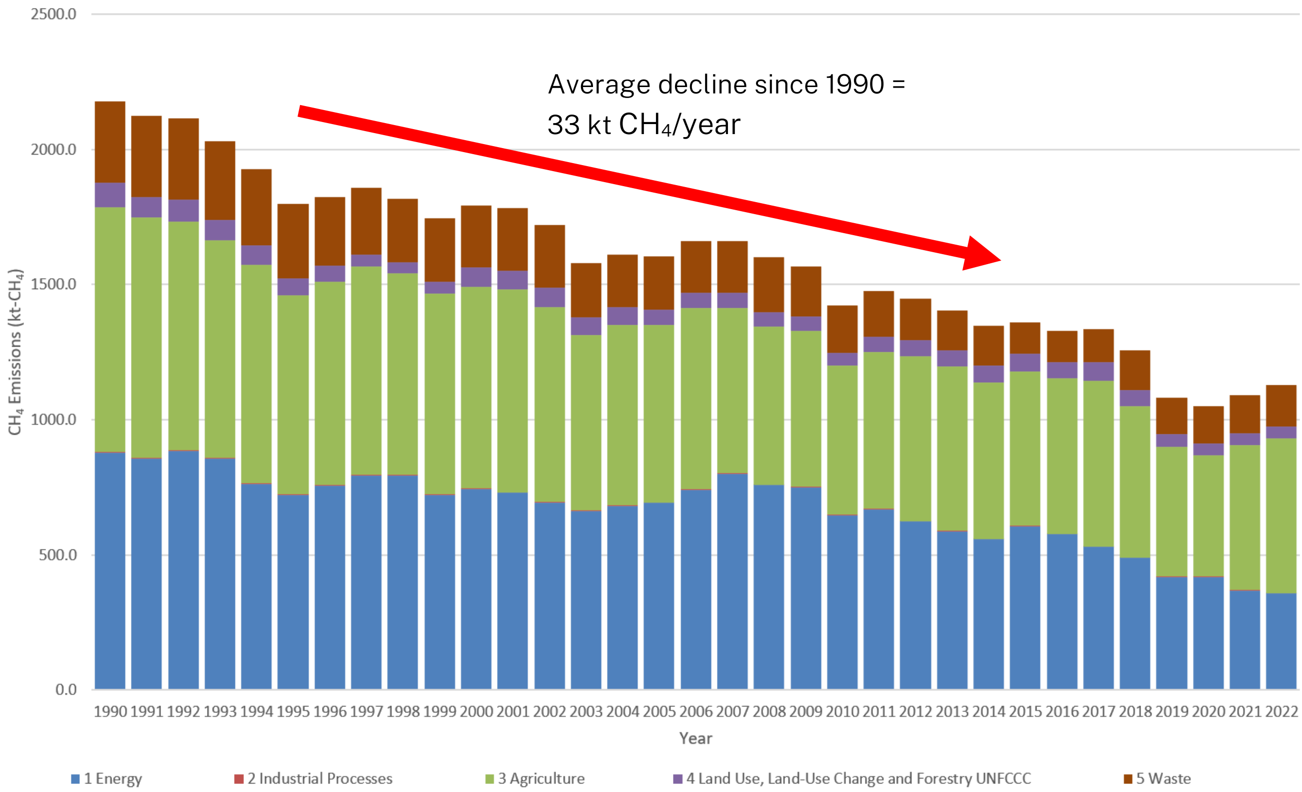

Figure 1 NSW methane emissions (kt CH_4) by sector for the years 1990 to 2022. (Source: Australia's National Greenhouse Accounts)

3.1.2.1 NSW methane emissions by sector

In 2022, the Agriculture and Energy sectors dominated total methane emissions, contributing 51% (572 kt CH_4) and 32% (357 kt CH_4), respectively (Figure 2). The Waste sector also contributed substantially (13%; 151 kt CH_4), and Land Use, Land-use Change and Forestry (LULUCF) had a minor contribution (4%; 44 kt CH_4). The Industrial Processes sector had a negligible contribution (~0.2%).

[6] https://greenhouseaccounts.climatechange.gov.au/

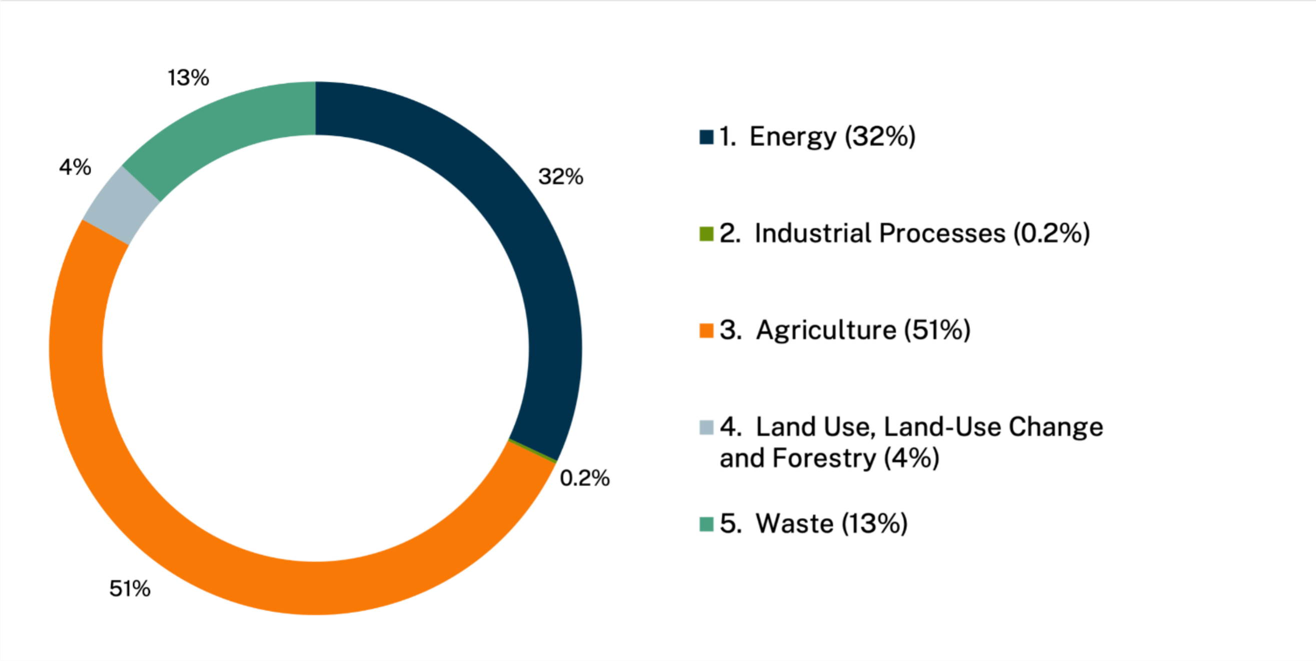

Figure 2 NSW methane emissions in 2022 by sector, expressed as a percentage of total NSW methane emissions. (Source: Australia's National Greenhouse Accounts)

3.1.2.2 NSW methane emissions by subsector

At the subsector level, NSW methane emissions were dominated by:

- 3.A Enteric Fermentation (513 kt CH_4), 46% of total emissions
- 1.B Fugitive Emissions from Fuels (340 kt CH_4), 30% of total emissions
- 5.A Solid Waste Disposal (122 kt CH_4), 11% of total emissions (Table 2; Figure 3).

The Enteric Fermentation subsector (46%) is almost entirely due to cattle and sheep, predominantly on pasture (44%), with 2% contributed by beef cattle in feedlots. The Fugitive Emissions from Fuels subsector (30%) was dominated by coal mining (28% of NSW total, predominantly underground coal mines) with a minor contribution from oil and natural gas (2% of NSW total). The Solid Waste Disposal subsector was comprised entirely of Managed Waste Disposal sites (11% of NSW total).

There were also minor contributions from Manure Management (4% of NSW total), Wastewater Treatment and Discharge (2%), Fuel Combustion (2%) and LULUCF (4%), among other subsectors.

Table 2 2022 NSW methane emissions (kt CH_4) by sector and subsector (Source: ANGA)

The subsectors presented here represent the major contributors to NSW methane emissions and/or they have been presented to differentiate fugitive methane emissions licensed by the EPA. As such, the sector values may not be the sum of the subsectors. Italicised data indicates sub-subsectors.

Sector/subsector*	NSW emissions (kt CH_4)	% of total NSW CH_4 emissions (1,127 kt CH_4)
1 Energy	**357**	**31.7%**
1.A Fuel Combustion^	17	1.5%
1.B Fugitive Emissions from Fuels	340	30.2%
1.B.1.a Coal Mining	*320*	*28.4%*
1.B.1.a.i Underground Coal Mines	*255*	*22.6%*
1.B.1.a.ii Surface Coal Mines	*65*	*5.8%*
1.B.2 Oil and Natural Gas	*19*	*1.7%*
2 Industrial Processes	**2**	**0.2%**
3 Agriculture	**573**	**50.8%**
3.A Enteric Fermentation (including cattle, sheep and pigs)	513	45.5%
3.A.1.c.i Beef Cattle - Feedlot	*21*	*1.9%*
Other Enteric Fermentation	*492*	*44%*
3.B Manure Management (including cattle, sheep, pigs)	43	3.8%
3.B.1.c Beef Cattle - Feedlot	*0.8*	*0.1%*
3.B.3 Swine	*11*	*1.0%*
Other Manure Management	*31.2*	*2.9%*
3.C Rice Cultivation	10.2	0.9%
4 Land Use, Land-use Change and Forestry (including forest land, grassland, wetland)	**44**	**3.9%**
5 Waste (including solid waste disposal)	**151**	**13.4%**
5.A Solid Waste Disposal	*122*	*10.8%*
5.D Wastewater Treatment and Discharge (including domestic and industrial)	*27*	*2.4%*

Table notes:

* Sectors and subsectors names are consistent with international guidelines adopted by the *United Nations Framework Convention on Climate Change* (UN 1992), and those used by Australia's National Greenhouse Accounts (ANGA).

^ The 1.A Fuel Combustion sector includes various subsectors including 1.A.1 Electricity generation, and 1.A.2, 4 and 5 Stationary energy.

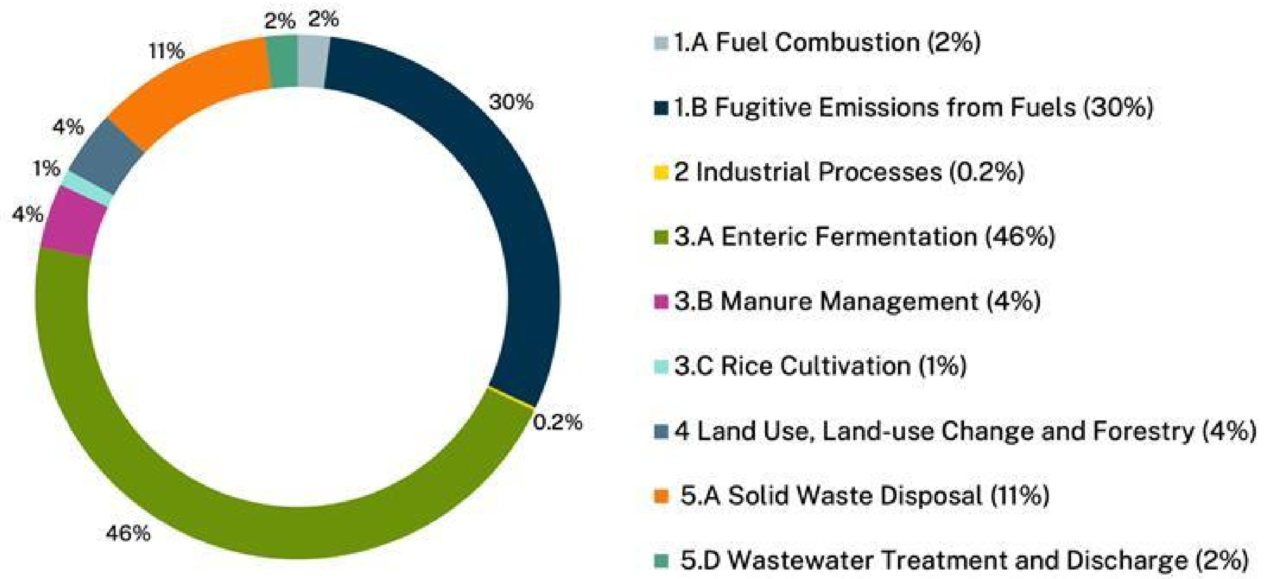

Figure 3 NSW methane emissions for 2022 by sector/subsector, expressed as a percentage of total emissions. (Source: ANGA)

3.2 Methane emissions covered by EPA licences

The aim of the review is to provide advice on fugitive methane emissions monitoring for facilities that are licensed by the EPA.

The prioritisation of fugitive methane emissions for sectors or subsectors licensed by the EPA depends on the combination of:

1. the magnitude of methane emissions in NSW for each sector or subsector
2. the proportion of the emissions for each sector or subsector that are covered by EPA licences.

The assessment of the magnitude of methane emissions for each sector and subsector is reliant on the data provided by Australia's National Greenhouse Accounts (ANGA). This is the only comprehensive dataset available that provides annual emissions estimates covering the relevant sectors and subsectors across NSW. With such reliance on ANGA, it is important to consider the uncertainties within ANGA, and the effect that this may have on the assessment of priority sources of fugitive methane emissions licensed by the EPA. These uncertainties are discussed in detail in section 3.3.

The scheduled activities that are licensed by EPA are described in detail in Schedule 1 of the *Protection of the Environment Operations Act 1997*. See also Table 1 for the corresponding sector/subsectors for greenhouse gas reporting that are covered by EPA licences.

Methane emissions covered by EPA licences are referred to as 'EPA-covered emissions'. Percentages of EPA-covered emissions reported here for sectors and subsectors refer to the emissions by sector as a proportion of all EPA-covered emissions.

It is estimated that approximately 552 kt CH_4/year is covered by EPA licences, about 49% of methane emissions in NSW.

The sectors or subsectors which make up the highest proportion of EPA-covered emissions (which together account for 94% of all EPA-covered emissions) are:

- Fugitive Emissions from Fuels subsector (62%)
- Waste sector (27%)
- Agriculture sector (6%).

The highest-priority subsector based on the proportion of all EPA-covered emissions is by far the Fugitive Emissions from Fuels subsector (1.B), which accounts for approximately 62% of EPA-covered emissions. The Coal Mining subsector (1.B.1.a) itself represents 58% of EPA-covered emissions, which includes Underground Coal Mines (1.B.1.a.i) and Surface Coal Mining (1.B.1.a.ii) comprising 46% and 12% of EPA-covered emissions, respectively.

The next-highest-priority sector is Waste (5), which accounts for 27% of EPA-covered emissions. This is dominated by the Solid Waste Disposal (5.A) subsector which alone accounts for 22% of EPA-covered emissions. The Wastewater Treatment and Discharge (5.D) subsector also contributes significantly, comprising 5% of total covered emissions.

The Agriculture (3) sector makes a minor, yet still significant, 6% contribution to EPA-covered emissions. This is mostly from Beef Cattle in Feedlots (3.A.1.c.i and 3.B.1.c.; 4%) and Manure Management of Swine (3.B.3; 2%). Australia's National Greenhouse Accounts provide the ability to separately quantify emissions from livestock-intensive activities related to beef cattle as there is a separate subsector for feedlots. However, this is not possible for other livestock-intensive activities such as sheep (i.e. lamb) in feedlots, dairy cattle in accommodation, and pigs (swine) in accommodation. For the purposes of this assessment, it was assumed that only a very small proportion (5% of total, equates to 4 kt CH_4) of the NSW emissions related to dairy cattle, and lambs and hoggets, would be related to livestock-intensive activities. On the contrary, it was assumed that for swine manure management, that the majority would be related to livestock-intensive activities (90% of total, equates to 10 kt CH_4). These proportions are similar to those determined independently by the EPA. When combined with the emissions from beef cattle in feedlots (21 kt CH_4) this leads to an approximate estimate of ~35 kt CH_4 emissions from the Agriculture sector being licensed by the EPA. This equates to approximately 3% of total NSW methane emissions, or 6% of the NSW EPA's covered emissions (see Table 3).

3.2.1 Priority fugitive emissions

The top fugitive emissions, based on the magnitude of emissions **and** the proportion of emissions covered by EPA licences, in order of priority are (highlighted in Table 3 and shown in Figure 4):

1. Underground coal mines (1.B.1.a.i) – emitting 255 kt CH_4/year in NSW and emissions accounting for 46% of all EPA-covered emissions.
2. Solid waste disposal (5.A) – emitting 122 kt CH_4/year in NSW and emissions accounting for 22% of all EPA-covered emissions.

3. Surface coal mining (1.B.1.a.ii) – emitting 65 kt CH_4/year in NSW and emissions accounting for 12% of all EPA-covered emissions.

Table 3 Summary of priority sectors and subsectors that are covered by EPA licences, including the EPA-covered emissions (kt CH_4/year) and their percentage contribution to all EPA-covered emissions (552 kt CH_4 yr^{-1}). Priority emissions are highlighted in **bold**

The sectors included here have been broken down further into subsectors (and sub-subsectors) to highlight those with a large contribution to total CH_4 emissions covered by the EPA remit.

Sector/subsector	EPA-covered emissions (kt CH_4/year)	% of all EPA-covered emissions
1.B.1.a.i Underground Coal Mines	255	46%
1.B.1.a.ii Surface Coal Mines	65	12%
1.B.2 Oil and Natural Gas	19	3%
5.A Solid Waste Disposal	122	22%
5.D Wastewater Treatment and Discharge (including domestic and industrial)	27	5%
3 Agriculture (e.g. intensive agriculture such as feedlots)	35	6%
Other (electricity generation, stationary energy, etc.)	<28	5%

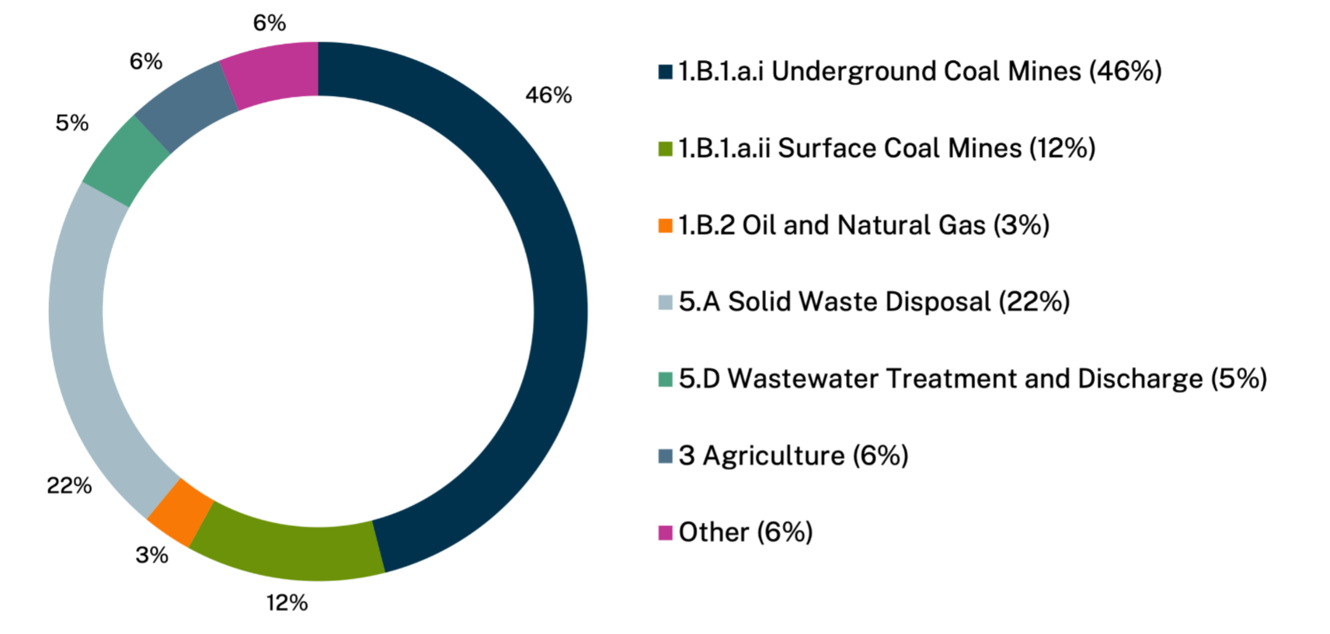

Figure 4 Methane emissions sectors/subsectors as a percentage (%) of all EPA-covered emissions. (Source: ANGA)

The Underground Coal Mines subsector is the highest priority for action as it accounts for around 46% of all EPA-covered emissions. Although reported emissions from underground coal mining are generally considered to have relatively low uncertainty (see section 3.3), some relatively minor and cost-effective monitoring would substantially improve the accuracy of reported emissions.

The Solid Waste Disposal subsector contributes around 22% of relevant fugitive methane emissions, with relatively high uncertainty associated with bottom-up emission factors (see section 3.3). These uncertainties are due to the inhomogeneity of emissions across a facility and the effect of environmental variables (rainfall, temperature, windshear, etc.) on those emissions.

Surface coal mining contributes 12% of emissions with relatively high uncertainty, largely due to the variation in gas content between mines.

Wastewater treatment (~5%), intensive agriculture (~6%) and the oil and gas sector (~3%) are all relatively minor components of EPA-covered emissions and will have a lower priority for action. However, the same technical approach recommended for the solid waste and open-cut coal mining sectors would be suitable for these sectors.

3.3 Uncertainties in the assessment

As mentioned above, the assessment of the magnitude of methane emissions in NSW is reliant on the data provided by Australia's National Greenhouse Accounts (ANGA). There have been multiple studies which have examined methane emissions from various subsectors or facilities in NSW (e.g. Buchholz et al. 2016; Sadat-Noori et al. 2018; Phillips et al. 2016; Tait et al. 2015; Day et al. 2016). However, these generally do not provide the same level of coverage that ANGA provides in terms of both temporal (annual emissions) and broader sectoral and subsectoral coverage.

The uncertainty of ANGA, at the national scale, is provided and described for some sectors and subsectors within the *National Inventory Report 2022* (Cth DCCEEW 2024d, Volume 2, Annex II: Uncertainty Analysis) and the associated uncertainty tables (Cth DCCEEW 2024c). These uncertainties are sector or subsector wide for national emissions, and therefore are only indicative of typical uncertainties that may apply at state (i.e. NSW) or facility scale.

The overall impact of uncertainty on the assessment will depend not just on the uncertainty of each sector or subsector, but also the relative magnitude of emissions for each sector or subsector. For example, the uncertainty of the Fugitive Emissions from Fuels subsector will have the highest influence on the assessment, as this subsector represents ~60% of all methane emissions covered by EPA licences. This is also true for the Coal Mining subsector as it covers 94% of the emissions from its parent Fugitive Emissions from Fuels subsector. On the other hand, uncertainty in the Industrial Processes sector will have negligible impact on the assessment as the methane emissions from this sector (~0.2% of NSW total) are extremely low relative to other sectors.

Uncertainty estimate provided in the *National Inventory Report 2022* (NIR 2022) (Cth DCCEEW 2024b), combined with National Greenhouse and Energy Reporting (NGER) Scheme data provide a sense of the uncertainties in the initial estimates of fugitive emissions. For example, applying these uncertainties to the magnitude of NSW methane emissions across subsectors within Fugitive Emissions from Fuels, results in total uncertainty of around ±17% or ±60 kt CH_4 for this subsector. Underground Coal Mines has uncertainty around ±10.2% (±26 kt CH_4) and Surface Coal Mines has larger uncertainty of about ±33.2% (±22 kt CH_4).

For the Waste sector, uncertainty estimates provided in NIR for subsector Solid Waste Disposal are ±54%; and for subsector Wastewater Treatment and Discharge are ±50%. If applied to NSW emissions, this translates to a total uncertainty for the Waste sector of ±79 kt CH_4 of the total 149 kt CH_4.

In addition to the uncertainties provided in the NIR 2022, there are also other indicators that can be applied to estimate uncertainty. For example, a recent study by Sadavarte et al. (2021) used satellite measurements of methane to estimate methane emissions from coal mines in Queensland. One of their main findings was that for two of the three locations, their satellite-based estimates of methane were significantly higher than those reported to the Australian Government (Sadavarte et al. 2021; Sadavarte et al. 2024; Sturgiss 2024). For one of these locations, the Hail Creek surface mine, they found their satellite-based emissions were 38 times higher than those reported to the Australian Government, or 12 times higher than even the total carbon dioxide equivalent (CO_2-e) emissions reported for this mine under the Safeguard Mechanism (Sadavarte et al. 2021; Sadavarte et al. 2024). Importantly, the emergence of satellite-based estimates of greenhouse gas emissions, including the Sadavarte et al. 2021 study, prompted the Australian Government to review inventory methods for open-cut coal mines in Queensland (DISER 2022b). This led to a 'significant improvement in the method' which resulted in a 44% increase (1.6 megatonne [Mt] CO_2-e/year) in methane emission estimates from Queensland open-cut coal mines (Figure 5; DISER 2022b). This 44% increase is about 11% larger than the NIR 2022 estimate of uncertainty for Surface Mining (± 33.2%), underscoring the fact that estimates of uncertainty on inventory methods are highly uncertain unless they can be benchmarked against measurement-based assessments of emissions.

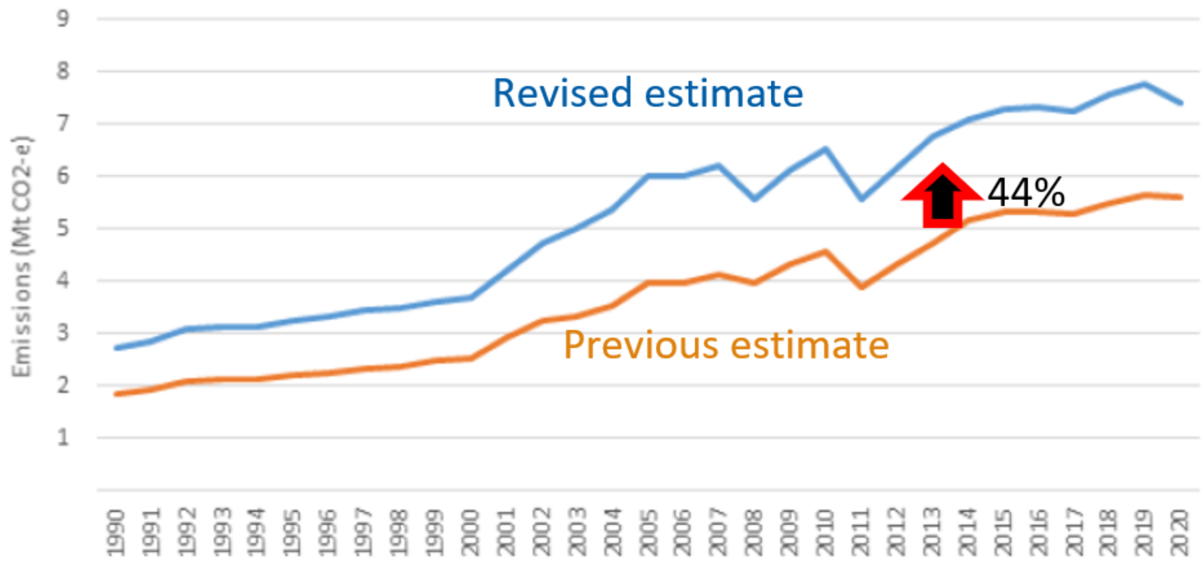

Figure 5 Fugitive emissions estimates for Queensland open-cut coal mines determined using national inventory methods. (Source: DISER 2022b)

The International Energy Agency (IEA) Global Methane Tracker 2024 (IEA 2024) provides independent estimates of Australian methane emissions from multiple sectors and compares them to those reported in the NIRs submitted to the UNFCCC, alongside other independent estimates. For the Australian coal and the oil and gas sectors, the IEA estimates for 2022 are 1,668 kt CH_4 and 440 kt CH_4, which are 66% and 47% higher than those reported in the NIR 2022. The Global Methane Tracker 2024 also presents a comparison of methane emission estimates for the oil and gas sector derived from top-down and bottom-up country-level reporting and company level reporting, which highlights large discrepancies depending on the method (IEA 2024).

Another example of the effect of method updates on calculated emissions is detailed in the *National Inventory Report 2015* (Commonwealth of Australia 2017a). In this report, it is shown that method updates between NIR 2014 and NIR 2015 led to an average increase of 63% (2.1 Mt CO_2-e/year) in emissions from the Natural gas – Total subsector (Figure 6; Commonwealth of Australia 2017a). The quoted uncertainty for the Natural gas subsector in both the NIR 2014 and NIR 2015 was 9% CO_2-e (Commonwealth of Australia 2016; Commonwealth of Australia 2017b), which is far less than the 63% (CO_2-e) increase observed between NIR 2014 and NIR 2015. These examples suggest that the uncertainty in the NIR and thus ANGA, may include larger sources of uncertainty than what is quoted in the NIR 2022.

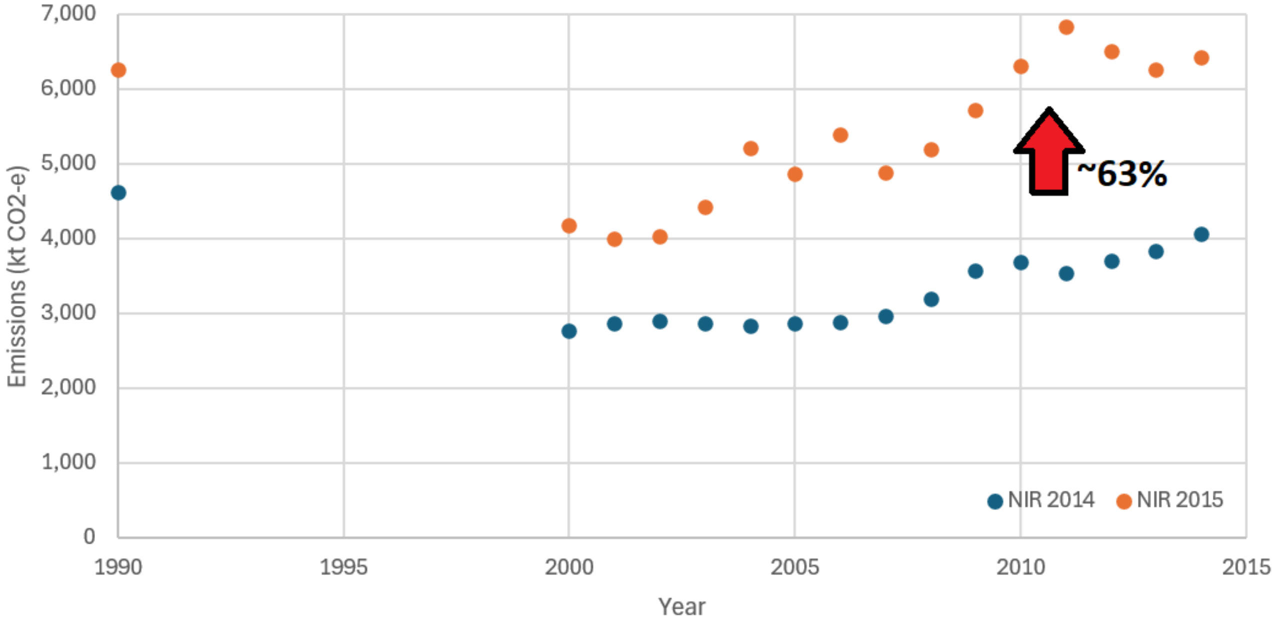

Figure 6 Emissions from the Natural gas – Total sector calculated using the National Inventory Report (NIR) 2014 and NIR 2015 methods. (Source: Commonwealth of Australia 2017a)

The NIR 2015 methods resulted in an average increase of 63% for the data points shown above.

4

Technologies for monitoring methane emissions

4.1 Context

The focus of this review is to evaluate existing methane measurement technologies that can improve quantification of fugitive methane emissions at key EPA-licensed premises.

The term 'monitoring' is ambiguous in the context of methane (and other greenhouse gas) emissions. Common air pollutants (dust, ozone, nitrogen dioxide, carbon monoxide and sulphur dioxide) are regulated based principally on human health criteria, with action triggered by concentration exceedances. In contrast, the long-lived greenhouse gases (carbon dioxide, methane and nitrous oxide) are unreactive and thus pose no immediate direct threat to human health when present at moderately elevated levels in the atmosphere. However, because these gases are long-lived, they accumulate in the atmosphere, and even small, but persistent emissions contribute to climate change. Thus, the task of 'monitoring' is not merely one of looking for large exceedances in local concentration, but of determining the underlying rate of emissions driving local concentration variability, in the long-term. This is a much more challenging task. It requires both measurement of concentrations and, for most source types, additional measurement of local meteorology and relatively sophisticated atmospheric transport modelling.

In NSW, methane and other greenhouse gas emissions have traditionally been accounted for using 'bottom-up' inventory approaches, which are subject to considerable uncertainty. There is strong evidence that augmenting bottom-up methods with 'top-down' emissions monitoring approaches (based on direct measurement of atmospheric composition) can improve the accuracy of estimations and help prioritise mitigation action over time, these are discussed in Sections 3.3 and 4.5. As such, both bottom-up and top-down approaches are considered here.

There are a multitude of methods and technologies available to determine methane emissions from facilities, subsectors and sectors. To limit the scope of the review, it is important to define the spatial and temporal scales at which emissions are to be monitored.

The focus of this review is on monitoring methane emissions at key EPA-licensed facilities. To determine the key facilities, we must start at a spatial scale that encompasses the entirety of NSW, and then identify those facilities that are most significant in terms of their emissions, which is similar to the prioritisation outlined in section 3. This requires emissions quantification at spatial scales ranging from the state of NSW, down to regional and facility scales. To estimate facility scale emissions using bottom-up techniques and/or to gain a greater understanding of the processes that emit methane, activity scale monitoring is often also required, for example to estimate methane emissions vented from underground coal facilities. Therefore, this review considers methods that apply to spatial scales ranging from the state of NSW to activity scales, and those in between.

In general, reporting cycles are annual and often linked to the financial year. Therefore, it is important that methane emissions estimates are representative of **annual emissions**. The nature of methane emissions across NSW and throughout the year will exhibit a range of temporal variability, which is relevant for all sectors of interest, including coal mining, waste and agriculture. Temporal variability of methane emissions is significant. Using a Solid Waste Disposal sector landfill facility as an example, temporal variability will almost certainly include the following (as illustrated in Figure 7):

- sporadic or episodic emissions, which could be related to facility management processes such as turning over or extracting waste at a landfill site

- diurnal variability, which can be related to changes in environmental conditions such as temperature, or processes that follow human activity during the day
- weekly variability, which is reflected in a clear shift in human patterns between weekdays and the weekend, such as the delivery of waste to a landfill
- seasonal variability, such as changes in temperature, rainfall and humidity throughout the year, which affect methane production processes.

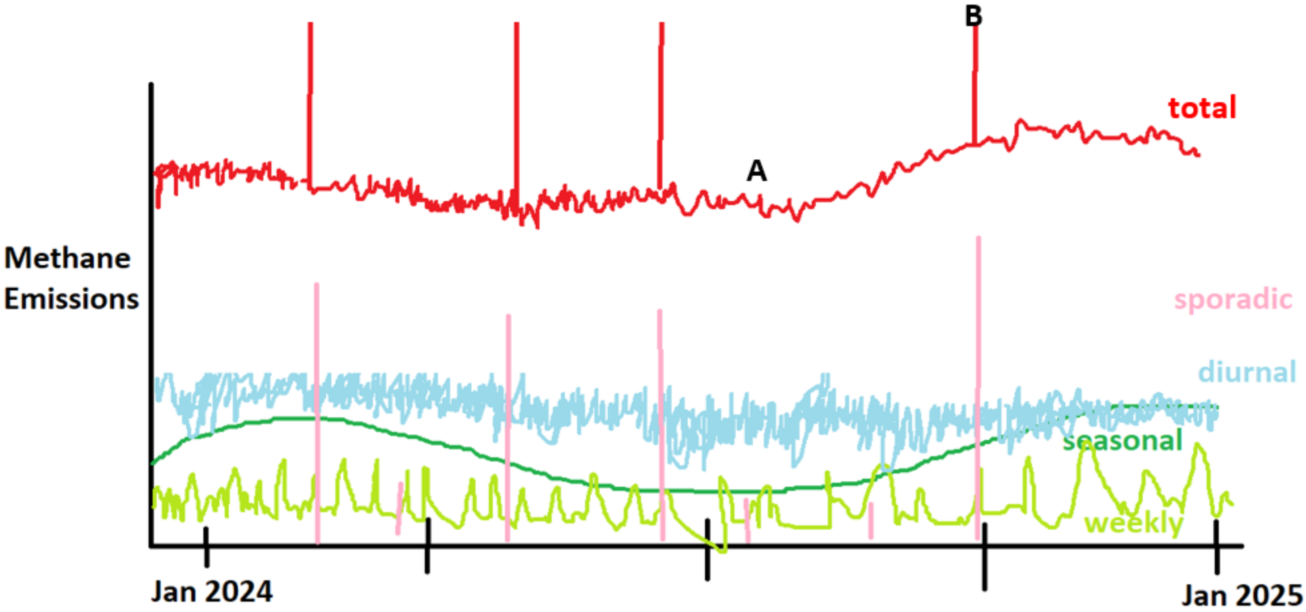

Figure 7 Illustrative example of annual emissions from a facility with various types of temporally varying components. (Source: CSIRO)

Sporadic (pink), diurnal (light blue), weekly (light green) and seasonal (green)) combine to give total methane emissions (red). Samples collected at points A and B would have very different results, illustrating the need for representative sampling.

Each of these sources of temporal variability can be important. It is therefore vital to ensure that sampling occurs frequently enough to capture such variability, where it is significant. This review considers the ability of technologies and methods to capture temporal variability across these timescales.

4.2 Bottom-up

4.2.1 Overview

Bottom-up techniques are commonly applied to estimate methane emissions across facility, state, national and global scales. This includes national greenhouse gas inventories reported to the *United Nations Framework Convention on Climate Change* (UNFCCC) (UN 1992), such as the Australian national inventory reports (NIRs) (e.g. Cth DCCEEW 2024b). The Australian NIRs use a range of bottom-up methods and emission factors, including those prescribed in a variety of IPCC guidelines (IPCC 2006; IPCC 2014; IPCC 2019; IPCC 2024), along with country-specific methods that are outlined in the NIRs. Also, where NGER data are used, the emission factors prescribed in the

National Greenhouse and Energy Reporting (Measurement Determination) 2008[7] are used. See section 4.2.2 for further information on the NGER Measurement Determination.

Bottom-up estimations of greenhouses gases including methane for a facility or sector generally rely on the following process:

- Identify all significant pathways for emissions from a facility or sector.
- For each pathway:
  - Measure the **activity** that is related to these emissions, for example, the number of cattle or amount of coal extracted
  - Multiply this activity by an **emission factor** (activity × emission factor). In their most basic form, emission factors may be a default Intergovernmental Panel on Climate Change (IPCC) factor applied globally. In more sophisticated bottom-up techniques, the emission factors may be tailored and more specific.
- Add up the emissions for all pathways to give the total emissions for the facility or sector.

To demonstrate this process, a simplified illustration of the bottom-up estimation of methane emissions for selected pathways involving coal extraction, gas production and cattle farming are shown in Figure 8.

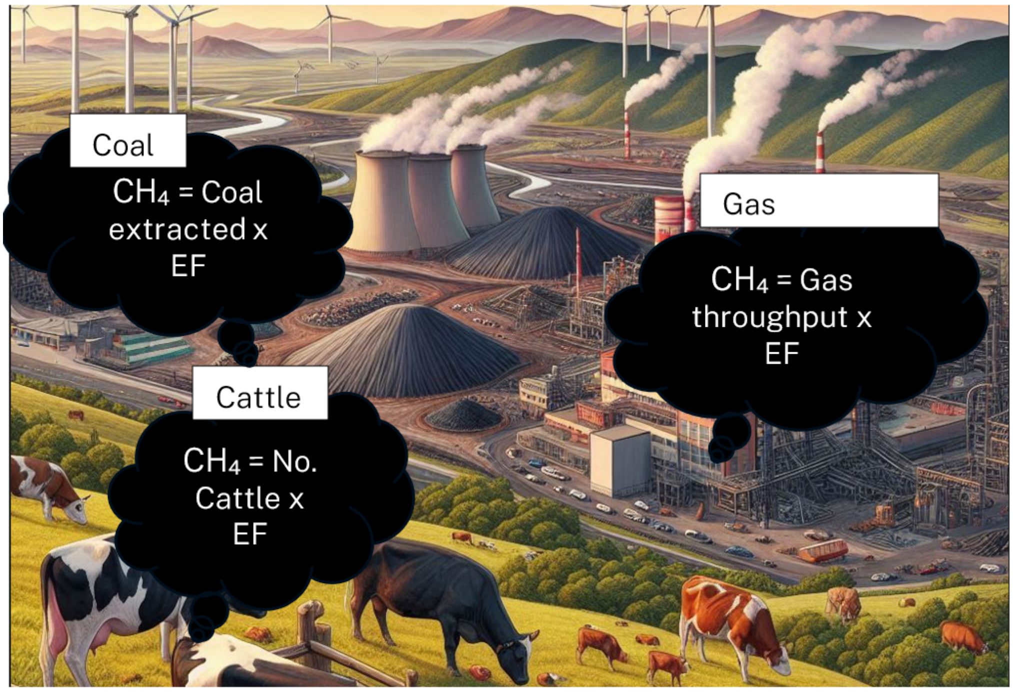

Figure 8 Illustration of bottom-up techniques for estimating methane emissions for various sectors. (Source: CSIRO)

Emissions are generally calculated by multiplying activity data (e.g. number of cattle, amount of coal extracted or gas throughout) by an emission factor (EF).

Activity data may be derived from published or unpublished data, including state or federal government statistical databases and industry surveys. It may also be measured onsite by operators at a facility. Principal sources of activity data for estimating Australia's *National Inventory Report*

[7] https://www.legislation.gov.au/F2008L02309/latest/text

2022 (Cth DCCEEW 2024b) include mandatory reporting data, published and unpublished data, and various data supply agreements.

Emission factors are usually determined by measuring an activity and its related emissions, and then deriving a relationship between these two parameters. In their most generalised form, emission factors may be a default factor that is derived from one or more studies and applied globally, such as those prescribed in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC Guidelines) (IPCC 2006, 2019). In more sophisticated bottom-up techniques, the emission factors may be derived from activity and emissions data more specific to their application, and these may be tailored to a certain country, state, region, season or class of activity. For example, the NIR 2020 has different emission factors for fugitive emissions for different activities associated with natural gas, such as onshore natural gas wells, offshore platforms and gas processing plants (DISER 2022a).

The potential of bottom-up techniques to provide high-resolution methane emission estimates at monthly time resolution and at facility to national scales has been demonstrated internationally (Maasakkers et al. 2023). The US EPA provides a high-resolution inventory of methane emissions that can be used by researchers to better compare the national Inventory of U.S. Greenhouse Gas Emissions and Sinks with emission estimates from more regional and local observations of atmospheric methane.

4.2.2 National Greenhouse and Energy Reporting (Measurement) Determination 2008

At the facility scale, the most commonly applied bottom-up techniques are prescribed in the *National Greenhouse and Energy Reporting (Measurement) Determination 2008*[8] (NGER Measurement Determination). The NGER Measurement Determination is used by entities to determine their greenhouse gas emissions and fulfil their obligations under the *National Greenhouse and Energy Reporting Act 2007* (NGER Act)[9] and associated legislation, including the National Greenhouse and Energy Regulations 2008 (NGER Regulations).[10] The NGER Act and NGER Regulations define the conditions by which entities are captured by the NGER Scheme.

The NGER Measurement Determination provides methods to estimate greenhouse gas emissions from the following sectors:

- energy, including:
  - fuel combustion including solid and gaseous fuels
  - fugitive emissions including coal mining (surface and underground), oil and natural gas
- industrial processes such as mineral products, chemicals and metals (aluminium and steel)
- waste, including solid waste disposal, wastewater handling and incineration.

The emissions estimates produced from the NGER Scheme are a principal data source for the Energy, Industry Processes and Product Use, and Waste sectors in the NIRs (e.g. Cth DCCEEW

[8] https://www.legislation.gov.au/F2008L02309/latest/text

[9] https://www.legislation.gov.au/C2007A00175/latest/text

[10] https://www.legislation.gov.au/F2008L02230/latest/text

2024b). The NGER Measurement Determination does not cover the Agriculture or the LULUCF sectors. These are covered by the NIR methods (Cth DCCEEW 2024b).

The NGER Measurement Determination provides four different orders of methods that can be used to calculate emissions from a source. Generally, as the order of the method increases from Method 1 to Method 4, so does the level of accuracy but also the technical complexity. The reporter is able to choose which method they apply. The methods are:

1. **default method**, where emissions are typically determined simply by multiplying an activity by an emissions factor (Method 1)
2. **industry-based sampling** at a facility to gain more accurate estimates of emissions (Method 2)
3. **industry-based sampling with extra standards** (Method 3)
4. **direct monitoring of emissions** either as continuous emissions monitoring (CEM) or periodic emissions monitoring (PEM) (Method 4). This method is rarely applied except for estimating fugitive emissions from underground coal extraction.

The methods outlined in the NGER Measurement Determination exhibit many of the general advantages and disadvantages of bottom-up techniques, as outlined in the sections below. Many of the issues stem from using emission factors that may not be representative at the facility scale, particularly when lower-order methods such as Method 1 are applied. It is for reasons such as these, that the recent Climate Change Authority *2023 Review of the National Greenhouse and Energy Reporting Legislation* (CCA NGER Review) (CCA 2023) recommended to:

> 'Phase out Method 1 estimation methodologies for fugitive methane emissions, including as a matter of urgency for the extraction of coal in open cut coal mining.' (Recommendation 15, CCA 2023).

It is also worth noting that CCA NGER Review (CCA 2023) highlighted the prevalence of Method 1 application and the inability to trace the methods used by reporters.

The recently released Australia Government response to the 2023 CCA NGER Review (Cth DCCEEW 2024a) has addressed some of the concerns highlighted by the review, including the phasing out of Method 1 for estimating fugitive emissions from the extraction of coal from open-cut mines (Recommendation 15) for Safeguard Mechanism facilities, and the publishing of methods used by Safeguard Mechanism facilities to estimate scope 1 fugitive methane emissions from coal mining, and oil and gas (Recommendation 9).

There are also limitations to data availability in the NGER Scheme that are relevant to data users trying to estimate methane emissions at a facility scale. Firstly, the emissions are reported as CO_2-e emissions, rather than by a specific gas such as methane. Recent changes to the NGER Scheme saw the publication of Safeguard Facility's emissions broken down by carbon dioxide, methane and nitrous oxide for the 2023–24 financial year (CER 2024g). The publication threshold of 100 kt CO_2-e/year for Safeguard Facilities also only captures about the top 50 emitters in NSW.

4.2.2.1 Uncertainty in underground coal mining emissions

As stated in the NGER Measurement Determination, Method 4 is the only method available for determining fugitive methane emissions that result from the extraction of coal from underground coal mines, although for other underground coal mining processes (such as flaring of coal mine waste gas) lower-order methods are available. The methane emissions estimates from underground coal mining are generally considered to contain low uncertainty because they are estimated using Method 4, whereby emissions are monitored directly. However, even within this highest tier method available in the NGER Measurement Determination, there are circumstances in which the application of this method may still lead to emissions estimates with relatively large uncertainties. This is of concern due to the high magnitude of emissions from this subsector (that is, 22% of NSW, and 46% of EPA-covered methane emissions in 2022).

For underground coal mining, the relevant method to determine emissions is outlined in 'Subdivision 3.2.2.2 — Fugitive emissions from extraction of coal' (sections 3.5 to 3.13) of the NGER Measurement Determination. The following sections outline the method for underground coal mining and discuss where certain approaches permissible under the method may lead to uncertainty. Under the NGER Measurement Determination, emissions are calculated according to a specific equation which requires a range of parameters to be measured. The same equation is used for both continuous emissions monitoring (CEM) and periodic emissions monitoring (PEM). The parameters which typically have the largest impact on the estimate are the proportion of gas type in mine-return vented air (Cjct) and flow rate of the gas stream (FRct) (CER 2024b), both of which may be highly variable relative to other measured parameters. However, the measurement of pressure (Pct) and temperature (Tct) are also important. Any uncertainty in the parameters measured will feed directly into the uncertainty of the calculated emissions.

4.2.2.1.1 Measurement standards

The NGER Measurement Determination specifies that flow rates and concentrations measured by CEM must be undertaken in accordance with an appropriate standard. However, for PEM, the measurements may be undertaken in accordance with either an appropriate standard or the applicable state or territory legislation. The NGER Measurement Determination provides examples of appropriate standards, such as *Method 3C – Determination of Carbon Dioxide, Methane, Nitrogen and Oxygen from Stationary Sources* (US EPA 2017). The NGER Measurement Determination does not provide specific performance requirements for the devices used to measure concentration, flow rate, pressure or temperature, which as stated above are key parameters.

For NSW, the safety regulations regarding methane monitoring in underground coal mines are outlined in the Work Health and Safety (Mines and Petroleum Sites) Regulation 2022.[11] This requires that the designs of certain types of flammable gas (including methane) monitors are registered, and it specifies standards for such plant that is required to be registered. *AS/NZS 60079.29.1 :2017 - Explosive atmospheres – Gas detectors – Performance requirements of detectors for flammable gases* outlines the performance requirements for each test. This shows that for a volume fraction up to 5% methane in air, the performance limits are at their most stringent ±0.1% methane or 5% of value (whichever is greatest). The uncertainty, with respect to the accuracy of a reading, may be the combined uncertainty of several of these tests, including the calibration curve, short-term and long-term stability. Therefore, even if the performance of the gas monitor were within ±0.1% methane limits for each of these tests, the combined uncertainty of a reading may be much larger than this.

Work health and safety regulations are mostly concerned with methane concentrations in the percentage (i.e. parts per hundred) range, as the lower explosive limit is about 4% (i.e. 4 parts per hundred or 40,000 parts per million). However, for emissions monitoring, it may be necessary to measure down to a few parts per million, which requires instrumentation that is 10,000 times more

[11] https://legislation.nsw.gov.au/view/html/inforce/current/sl-2022-0509

sensitive, with a much lower detection limit and operating range. As stated in the CER coal mining guideline (CER 2024b):

'Establishing and documenting that the equipment used is appropriate for measuring the full range of the variability in the gas proportion is important. Where measurements frequently fall below or outside the equipment calibration range, the equipment may not be suitable to use for measuring gas proportion in the gas stream for the purpose of NGER reporting.'

4.2.2.1.2 Frequency of measurement

The NGER Measurement Determination allows the direct measurement of emissions released from the extraction of coal from an underground mine during a year to be calculated using either CEM or PEM. This allows the entity to choose either CEM or PEM to determine emissions.

There are distinct differences between CEM and PEM that likely guide entities towards the use of PEM when estimating emissions from underground coal mining. Of the CEM requirements outlined in Part 1.3 of the Determination, some of the distinguishing features include (emphasis added):

- measurements by CEM must be taken frequently enough to **produce data that is representative and unbiased**
- the CEM equipment must **operate for more than 90% of the period** for which it is used to monitor an emission.

These contrast with PEM requirements that, unlike CEM, are specific to underground coal mining and include:

- sampling by PEM must be undertaken during the year for a sufficient duration to **produce representative data** that may be **reliably extrapolated** to provide estimates of emissions across the full range of operating conditions for that year.

Therefore, the sampling frequency can be significantly lower for PEM than CEM, which makes it less technically demanding and lowers the associated costs. The other key difference is that PEM allows measurement of flow rate and concentration to be undertaken either in accordance with applicable state or territory legislation **or** an appropriate standard. However, CEM only allows measurement of flow rate and concentration in accordance with an appropriate standard (i.e. not in accordance with applicable state or territory legislation). This ability to use measurements that are already required under state or territory legislation, which in NSW includes the Work Health and Safety (Mines and Petroleum Sites) Regulation 2022, allows operators to minimise their overall monitoring costs. It is for reasons such as these, that entities are most likely to use PEM rather than CEM to estimate emissions.

It is difficult to quantify the exact proportion of entities that use PEM compared to CEM, because these details on methods used are not published with Safeguard Facility data or are not generally publicly reported. Details of the methods used by underground coal mines to monitor emissions are sometimes publicly available through their respective Air Quality and Greenhouse Gas Management Plans. For example, Appin underground coal mine stated in their Air Quality and Greenhouse Gas Management Plan that they use a PEM system for monitoring methane and carbon dioxide at mine upcast ventilation shafts.

The CER coal mining guidelines states that periodic ventilation surveys must be performed at least monthly, **or** when there is a significant change in mining operations. These surveys are often the most suitable source for the PEM sampling of the measured flow rate. Where emissions are determined by PEM regimes as coarse as one measurement per month, undersampling could result in significant uncertainty of the estimates. The NGER Measurement Determination does include rules on representativeness and accuracy of data.

However, it is difficult to ascertain how an emissions estimate can be judged if it is an over- or underestimate of the true values at a 95% confidence level, unless the true value is known. Such quantities are provided for CEM, whereby CEM equipment must operate for more than 90% of the period for which it is used to monitor an emission (s 1.26(4) of the Determination).

4.2.2.1.3 Summary

In summary, there are potentially significant uncertainties that could arise when calculating emissions from underground coal mining, which relate to the monitoring frequency and the lack of specific or appropriate performance requirements for the devices used to measure methane concentration, flow rate, pressure and temperature.

4.2.3 Advantages of bottom-up techniques

Bottom-up techniques are widely implemented and have a number of advantages compared to top-down techniques, including that they generally have the following characteristics:

- relatively easy to apply, including at scales ranging from facility to national
- low cost
- low equipment requirements
- monitoring in some cases may already be legislated (e.g. for safety) so there may be no additional burden in applying this technique
- in the case of IPCC Guidelines and NIR methods, they are aligned to international standards for reporting to the UNFCCC and thus can be used to meet international obligations
- to a limited extent, data are publicly available; for example, methane emissions are available through Australia's National Greenhouse Accounts for various sectors at the state and national level.

4.2.4 Limitations to bottom-up techniques

There are also a number of limitations to bottom-up techniques, which include:

- high reliance on the accuracy of emission factors and activity data, which is particularly relevant for lower-order (simplified) methods
- limited accuracy when applying emission factors derived at broad scales, such as global or national scale, to smaller scales such as local or facility scale. For example, default emission factors derived from the IPCC Guidelines, which may be considered accurate at the global scale, may not take into account the specific processes or environmental conditions that affect methane emissions at a specific facility, or in a specific region of Australia
- capture only identified emission pathways and therefore may not capture all sources of emissions
- emission factors may be derived from a limited number of studies, or may be outdated
- limited independent verification by top-down methods that have been calibrated against controlled release studies

- limited data availability at scales finer than state-level for specific gases such as methane, and for emissions that are below reporting thresholds such as the NGER Scheme (CER 2024d).

In addition to the limitations outlined above, considerations around the uncertainty of bottom-up techniques are provided in section 3.3. The accuracy of bottom-up techniques is being improved through greater use of top-down methods in inventories, which has been encouraged by the IPCC (IPCC 2019). At least six countries, including Australia, are already using top-down methodologies to inform and improve their inventories (Peters et al. 2023).

4.3 Top-down

4.3.1 Overview

In contrast to the inventory or 'bottom-up' approaches to estimating emissions, a 'top-down' approach measures atmospheric composition at two or more locations and uses modelling tools to infer emissions from both the wind data and the difference in concentration between the measurement locations (i.e. the spatial gradient in concentration). Critical to the top-down approach is the need to robustly measure or represent the concentration of methane present in the air outside the boundary of the area being analysed (i.e. boundary condition). Figure 9 provides a schematic representation of the top-down approach for emissions monitoring. Methane is ubiquitous, but not homogenous in air; this is represented by the variation in orange colour in Figure 9. Methane concentration is measured at the upwind boundary condition on the left of the diagram. As the air is blown across the facility, it is enriched in methane due to the emissions from the facility. The concentration of methane downwind of the facility (represented by the darker orange colouring) can then be used with atmospheric transport models to infer the size of the emissions in the source region (in this instance a single facility).

Techniques for top-down approaches have been developed for a broad range of spatiotemporal scales ranging from annual global scale emissions determinations to minutely or hourly emissions determinations from a single facility or sub-facility. Because the top-down approach measures an integrated signal in the atmosphere, it is particularly useful for quantifying fugitive emissions or detecting emissions from sources or processes that may otherwise be absent from or poorly accounted for in a bottom-up approach.

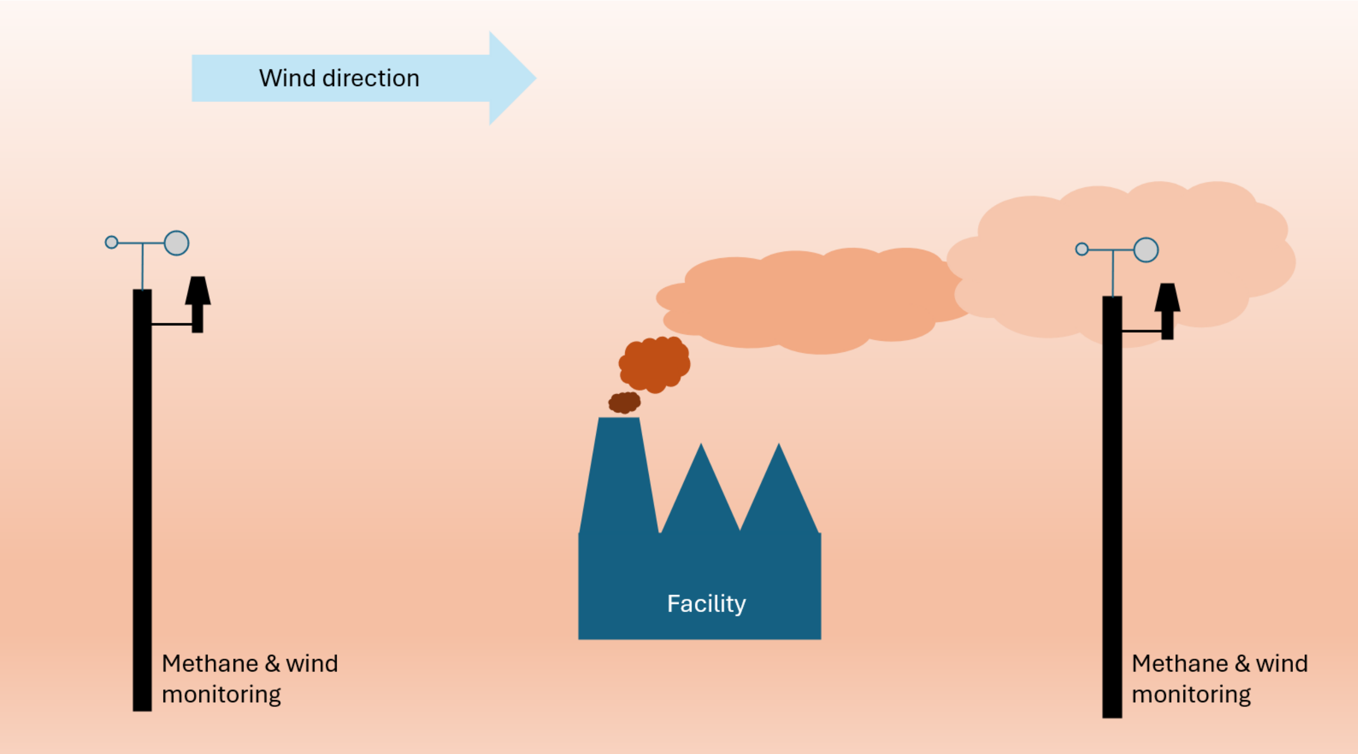

Figure 9 Schematic diagram of the top-down approach for emissions monitoring. (Source: CSIRO)

A significant advantage of deploying top-down methodologies at a facility scale is that they can be evaluated (and potentially calibrated) against controlled release experiments. This capacity to rigorously evaluate the accuracy of top-down methods has cascading value. It provides both a means of verifying bottom-up methods and the information needed to improve those methods. For this reason, bottom-up and top-down approaches are highly complementary and should be integrated to determine more robust, less uncertain estimates of emissions (section 4.5).

The biggest challenges with the top-down approach arise from two areas. Firstly, adequately defining the boundary conditions across the domain is needed to ensure that derived emissions estimates relate to the region or facility of interest. At a facility scale, this is often best achieved by strategically placing monitoring instruments diametrically across a facility based on prevailing meteorology. This allows upwind and downwind measurements be to obtained which can determine emissions due solely to the facility in question. However, mobile surveys or regional scale observing networks may also be used to determine suitable boundary conditions. Secondly, a fit-for-purpose modelling tool for the relevant spatial scale is needed to transform any observed increases in atmospheric gas concentration measured upwind and downwind of a facility, into an 'emission flux'. There are a range of atmospheric transport models and modelling tools which may be appropriate for facility scale fugitive emissions determination (see section 4.3.2).

The cost effectiveness of different analytical instruments to act as the workhorses of a ground-based monitoring network will vary depending on sector or industry, the relative strength and density of fugitive methane sources, and the facility's proximity to other methane emissions. These issues will be discussed in the coming sections as each technology is reviewed.

The following sections outline the array of top-down approaches available for monitoring methane emissions.

4.3.2 Atmospheric inverse approaches

Atmospheric inverse approaches, also known as atmospheric inversions, are particularly useful for verifying emission inventories (or bottom-up approaches), improving our understanding of unknown or uncertain emission sources, and estimating emissions across various spatial and temporal scales.

Atmospheric inversions are used to infer emissions by integrating modelled concentrations (simulated by an atmospheric transport model, see section 4.3.2) with atmospheric observations (ground-based and/or remote sensing). This process refines emissions so that the modelled concentrations optimally match with observed concentrations, producing a 'top-down' emission estimate.

There are inherent challenges in atmospheric inversions that must be acknowledged. Uncertainties can arise from various sources, including inaccuracies in the prior emissions estimate, errors in the meteorological data, and systematic and random errors in the model itself. These uncertainties can propagate through the modelling process, affecting the reliability of the output. Therefore, it is essential to conduct model verification studies and to incorporate comprehensive uncertainty analyses to identify and mitigate these issues.

Moreover, to have an efficient inverse approach, careful design of the observational network is crucial. Measurement stations must be strategically positioned for inferring emissions. If measurement sites are located too close to or too far from emission sources, the data collected may not significantly enhance the information about the source of the emission. Careful consideration of these factors can significantly improve the accuracy of emission estimates and model performance.

An optimal network design involves selecting measurement sites based on a combination of factors, including emission sources, prevailing wind patterns and topographical features. It is crucial to position measurement sites where they can capture the most representative data in order to reduce uncertainties in the emission estimates. This strategic positioning not only enhances the quality of the observational data but also improves the inversion process by ensuring that the model can use these data effectively to refine emissions estimates. Ground-based monitoring networks are comprehensively explained in section 4.3.6.

Inversions are based on different mathematical frameworks, including Bayesian and mass balance approaches, which are discussed in the following sections.

4.3.2.1 Bayesian approach

A Bayesian inversion is a probabilistic approach that incorporates prior knowledge of emissions (often from inventories or bottom-up estimates) and combines it with observed concentration data. The method uses Bayes' theorem to refine the prior emission estimates, accounting for uncertainties in both the emissions and the observations. The result is a posterior distribution that balances the prior estimates with the observed data, providing an improved estimate of emissions.

Bayesian methods are particularly useful when there is uncertainty in both the emissions and atmospheric data, as they allow for rigorous quantification of uncertainties. Commonly used Bayesian-based inversion systems include synthesis inversions, four-dimensional variational (4D-Var) data assimilation inversions, and Kalman filtering-based inversions.

4.3.2.2 Mass balance approach

The mass balance approach is a relatively simple inverse method that infers emissions by measuring the difference in pollutant concentrations upwind and downwind of a source. This method works well in situations where the atmospheric conditions are relatively steady, and the source region is well-defined. Mass balance models can be used with data collected from a variety of platforms, including aircraft, drones or fixed towers. The mass balance approach is less computationally demanding than other inverse methods; however, its accuracy depends heavily on the spatial and temporal representativeness of the observations, as well as the quality of meteorological data, which must be sufficiently detailed to capture the transport of pollutants.

4.3.3 Atmospheric transport models

Atmospheric transport models are essential mathematical tools for mapping between emissions and concentrations. These models can normally be run in two modes: forward and backward. Forward models simulate the transport of emissions to atmospheric concentrations based on meteorological data and boundary conditions, such as background concentrations. Backward models produce backward trajectories that trace the movement of air masses back in time to identify potential emission sources. This dual capability allows for a comprehensive understanding of both the dispersion of gases and the identification of emission sources.

Various mathematical frameworks are employed in forward modelling, depending on the modelling objectives. These include Gaussian models for localised dispersion, Lagrangian models for particle tracking, and Eulerian models for grid-based atmospheric transport. These approaches differ in how they mathematically model the dispersion of gases and their movement within the atmosphere.

- Gaussian models use statistical distributions to represent the spread of pollutants from a source, ideal for short-range dispersion.
- Lagrangian models track individual particles or parcels of air, providing detailed paths of pollutants, useful for complex terrain and varied meteorological conditions.
- Eulerian models, on the other hand, use a fixed grid to simulate how gases interact and move over large areas, offering comprehensive insights into regional and global transport.

Running these models requires substantial technical expertise. Due to the complexity of the modelling frameworks and the need for accurate parameterisation, most users rely on skilled modellers or atmospheric scientists to operate them effectively. For instance, understanding input data (such as meteorological fields), selecting the appropriate model type (e.g. Gaussian, Lagrangian, Eulerian), and interpreting results demand advanced knowledge in meteorology, numerical modelling, and often atmospheric chemistry. However, detailed atmospheric chemistry knowledge for methane is less critical, as methane is effectively inert over the timescales relevant for facility scale emissions estimation. Nevertheless, an average licensee would typically need to engage a specialist with experience in atmospheric modelling to achieve reliable results.

The frequency of running atmospheric models depends on their purpose. While operational air quality forecasts may require daily runs, long-term emission studies may involve periodic runs over months or years. Specific objectives, data availability, and resource constraints generally determine how often these models are executed. Moreover, as mentioned above in section 4.3.2, it is essential to conduct model verification studies to validate atmospheric transport models. This involves systematically evaluating the model’s performance and adjusting the network configuration as needed to enhance its robustness. Additionally, sensitivity analysis is a key component in understanding which input variables have the most significant impact on model outputs, guiding efforts to improve data accuracy.

4.3.3.1 Gaussian models

4.3.3.1.1 AERMOD

AERMOD is a steady-state Gaussian plume model developed by the American Meteorological Society and the US EPA's Regulatory Model Improvement Committee. It is currently used for regulatory purposes in Victoria, Australia; the US EPA also recommends it for air quality dispersion modelling (US EPA 2024a). AERMOD has a number of advantages over traditional Gaussian models, such as improved handling of complex urban topography and night-time boundary layers.

AERMOD may have limited accuracy in areas with frequent calm conditions or stagnation events. As a steady-state Gaussian plume model, it relies on consistent wind speeds to model dispersion accurately, making it less reliable under low-wind scenarios. In such cases, non-steady-state models like CALPUFF (a non-steady-state Gaussian puff model), Lagrangian models (which track individual particles or puffs), or Eulerian models may be more suitable. Eulerian models, which use a fixed grid to simulate pollutant dispersion across regions, can handle complex meteorological conditions and are particularly effective when representing slower-moving or stagnant air masses.

4.3.3.1.2 CALPUFF

CALPUFF is a non-steady-state model capable of accounting for meteorological variations along the pollutant trajectory. The NSW EPA uses it for specialised applications where simpler models like AERMOD may be inadequate (NSW EPA 2022a). CALPUFF is approved by the US EPA as an alternative model for regulatory applications. CALPUFF offers advantages over AERMOD in handling complex meteorological conditions, including variable winds, calm conditions, and long-range transport, making it especially useful in areas with challenging terrain or frequent low-wind events.

4.3.3.2 Lagrangian

4.3.3.2.1 WindTrax

WindTrax is a Lagrangian model that simulates particle dispersion and is often used for tracking pollutant plumes. WindTrax is usually used for simulating short-range atmospheric dispersion, particularly effective for distances within about 1 km of the emission source. Employing Lagrangian stochastic particle approach, WindTrax assesses turbulent transport on the micro-meteorological scale. It features an intuitive graphical interface, making it accessible to non-specialists, and allows users to simulate both point and area sources as well as various types of concentration sensors. WindTrax operates in both forward and backward modes, calculating emission rates and downwind concentrations, and supports mixed source and sensor types, providing significant flexibility for experimental design.

4.3.3.2.2 HYSPLIT

The hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model, developed by US National Oceanic and Atmospheric Administration (NOAA), is a modelling tool widely used in atmospheric transport and dispersion studies. As a forward model, HYSPLIT simulates the dispersion and trajectory of pollutants, providing valuable insights into how emissions spread across local to global scales. This capability is particularly useful for tracking and forecasting the movement of wildfire smoke, volcanic ash, and other airborne pollutants and greenhouse gases. One of the key benefits of HYSPLIT is its ability to incorporate both puff and particle dispersion methods, allowing for detailed simulations of pollutant behaviour. However, like any model, it has its limitations, including the need for accurate meteorological data and the potential for errors in complex terrain or rapidly changing atmospheric conditions.

In addition to its forward modelling capabilities, HYSPLIT can also be used for backward modelling through back-trajectory analysis. This involves tracing the path of air masses backward in time to identify their origins and establish source-receptor relationships. By combining forward model outputs with atmospheric observations, HYSPLIT can refine emissions estimates, providing a more accurate picture of emission sources. This dual functionality makes HYSPLIT a powerful tool for both simulating pollutant dispersion and identifying emission sources.

4.3.3.2.3 STILT

The stochastic time-inverted Lagrangian transport (STILT) model, an open-source particle dispersion model, extends NOAA's HYSPLIT model to improve simulation accuracy and simplify atmospheric modelling workflows. STILT is particularly effective for simulating the transport of pollutants and greenhouse gases through the atmosphere. By using meteorological data to transport an ensemble of air parcels backward in time, STILT calculates influence footprints that define the upstream area influencing a given location. This method is invaluable for mapping pollution, fine-tuning emissions inventories, and tracking changes in emissions over time.

The STILT model offers several advantages over the HYSPLIT model, including enhanced boundary layer and vertical mixing estimates through improved parametrisations, the ability to efficiently manage and run numerous simulations simultaneously using high-performance computing resources, and more precise gridded footprints using Gaussian weighted methods. STILT does appear to be better suited for simulating methane and chemically inert tracers, whereas HYSPLIT offers better capabilities for resolving detailed atmospheric chemistry. However, STILT also has some disadvantages compared to HYSPLIT, for example, it may run slower per simulation depending on the set-up.

4.3.3.3 Eulerian

4.3.3.3.1 Community Multiscale Air Quality (CMAQ)

The community multiscale air quality (CMAQ) model is a widely used model for gridded atmospheric transport and air quality simulations. It can be run across a range of spatial scales, from high-resolution regional modelling (e.g. urban environment) to coarser global scale simulations. To perform these simulations, CMAQ needs to be coupled with a meteorological model to provide the necessary atmospheric inputs (e.g. wind fields, temperature, humidity). The weather research and forecasting (WRF) model is commonly used for this purpose, as it provides high-resolution meteorological data compatible with CMAQ's requirements. Together, the WRF-CMAQ system allows for robust and detailed atmospheric transport simulations under varying meteorological conditions.

4.3.3.3.2 WRF-Chem

The weather research and forecasting model coupled with chemistry (WRF-Chem) is a powerful tool designed to simulate the interactions between atmospheric chemistry and meteorology. WRF-Chem integrates complex chemical processes with weather forecasting to provide detailed insights into air quality and atmospheric composition. This model is widely used for simulating the transport and transformation of pollutants and greenhouse gases. The model's flexibility allows it to be applied to various regional and global scales. However, WRF-Chem, unlike CMAQ, does not have the ability to be run in backward mode and provide back-trajectory information. Moreover, WRF-Chem's online coupling requires significant computational resources and can be more complex to set up and run compared to WRF-CMAQ's offline approach.

4.3.4 Tracer release

An alternative way of accounting for atmospheric transport without sophisticated modelling is to conduct a tracer release experiment. This involves releasing a stable atmospheric tracer from the source region or facility of interest at a known rate. Downwind observations of both methane and the tracer can then be used to infer the methane emission (Bai et al. 2021; Feitz et al. 2018).

When selecting and releasing a tracer, the following parameters are important:

- the tracer gas should be different from any gases that are normally emitted from the source or facility
- the tracer must be released in sufficient quantity so that the appropriate signal to noise ratio is achieved by the relevant gas analyser
- ideally, the tracer should have a low global warming potential and not be an atmospheric pollutant.

Commonly used tracers included acetylene (C_2H_2; Feitz et al. 2018), nitrous oxide (N_2O) (Bai et al. 2021) and sulfur hexafluoride (SF_6) (Moate et al. 2021). The tracer release technique has been shown to give quite accurate results when estimating methane release rates during controlled methane release experiments (e.g. Feitz et al. 2018). However, while informative are unlikely to be used operationally due to site accessibility constraints and safety concerns with the release of some potential tracers (e.g. acetylene).

4.3.5 Ground-based monitoring networks

Ground-based monitoring networks typically consist of two or more stationary monitoring sites, that rely on wind to bring signal (i.e. concentration enhancements of methane, or any other gas being monitored) from the source area to the sensors over time. A ground-based network can be optimised by analysing the local meteorology (e.g. using wind roses) to determine where best to site each monitoring station. Determination of each station's 'footprint' ensures the source area is adequately sampled. The station's footprint depends on both its height above ground (or the height from which the air is sampled) and the precision of the sensor. The monitoring stations must be located to provide both the upwind boundary condition (a reasonable proportion of the time), and for one or more stations in the network to sample air that has passed over the source area (a reasonable proportion of the time).

There are now a wide range of analytical instruments or sensors available to be deployed to monitor methane emissions (see section 4.3.5.2).

The choice of instrument to improve emissions estimates at a facility-level depends very strongly on a number of factors. One key factor to consider is the strength of the source and the distance from the source that the sensors are located. Well-defined source areas with relatively high emissions may be adequately monitored with an array of small footprint, low-cost sensors deployed close to the source. However, for a more diffuse areal emission or a collection of pseudo-point source emissions associated with a facility, higher (medium to high) precision analysers located further from the source, providing a broader footprint, may be required to provide reliable and accurate emissions determination.

The density of a monitoring network (i.e. the number of ground-based stations per unit area in the network) will depend upon the number and expected strength of the sources in a region, and on the meteorology. In Luhar et al. 2020, the authors used just two ground-based stations to infer fugitive emissions from coal seam gas operations in the Surat Basin over an 18-month period. This work made careful use of the geometry of the coal seam gas industry corridor in combination with the prevailing meteorology, and used carbon monoxide measurements as a tracer of biomass burning to exclude methane emissions from a different source category. This work also harnessed data from CSIRO's Global Atmospheric Sampling Laboratory to provide a suitable boundary condition for the model.

The investment in the density of a network requires careful consideration. Multiple high-precision, robust instruments that are housed well (in sheltered, temperature-controlled environments) are relatively expensive to purchase and deploy. However, they tend to be stable over many years and have minimal labour overheads in both hardware troubleshooting and data quality control. Investment in a denser network of observations (that are well inter-calibrated) will always improve the model's ability to accurately infer emissions. However, it follows a law of diminishing returns, with each additional station contributing less information to improve the estimate (assuming all monitoring sites are well located).

In addition to the number and spatial distribution of monitoring locations, the height of sensors (or their intakes) is an important consideration. The higher the intake height, the more representative monitoring will be of a wider area. Intake height needs to be relative to the height of the source. For near homogeneous ground level emissions (e.g. wastewater treatment plant ponds) ground-based monitoring from masts (e.g. 5–20 m) is suitable. But for emissions from a stack with high ejection velocity, ground-based monitoring close to the site and at low height may not see the emissions plume at all. In these circumstances, measurements from towers ranging in height from 100 to 300 m, at a location further downwind of the source to allow for atmospheric mixing, may be more suitable.

Where tall masts are employed in a ground-based network, multiple inlets at a range of heights can be used to determine a vertical concentration gradient. This can provide useful information to improve a model's ability to infer the strength of emissions.

4.3.5.1 Pros and cons of ground-based monitoring networks

The advantages of ground-based monitoring networks are as follows:

- Ground-based networks have a strong advantage for long-term improvement of emissions estimates, and to track emissions reductions over multi-year timescales.
- Because they operate continuously, they are able to provide genuinely representative sampling, unlike campaign surveys or even emissions derived from satellite data which only have periodic overpasses.
- Ground-based networks are suited to incorporation of co-emitted tracers and/or methane isotopes as a means of source discrimination. This can be important given the methane is emitted from such a large number of natural and anthropogenic sources.

The disadvantages of ground-based monitoring networks are:

- Adding additional measurements to discriminate between sources adds capital costs, a modest additional operating overhead, and additional analysis time.

- Survey campaigns that can dynamically isolate individual facilities can more directly attribute emissions to individual facilities.

4.3.5.2 Types of instruments and sensors

4.3.5.2.1 High-grade methane analysers

High-grade, continuous methane analysers form the backbone of many ground-based networks globally. For example, CSIRO operates several such instruments in Australia and across Australia's Antarctic Territories, including a network of Picarro CRDS analysers across Greater Melbourne to improve quantification of urban methane emissions and to help prioritise and track mitigation actions.

The value of these instruments is their high precision, linearity and stability over long periods. These characteristics make it possible to maintain robust, hierarchical calibration regimes over decades and to define the compatibility between individual analysers and between networks. This capability ensures that emissions estimates derived from such networks are not biased due to calibration errors or instrument drift. Also, in extensive networks, robust boundary conditions are always available for the domain in question. The longevity of these instruments deployed in this way lends itself to long-term tracking of emissions reductions trends.

These instruments have very low detection limits and provide data that can be used to detect and quantify emissions from 10s to 100s of kilometres away. As such, they are well-suited to estimating regional to national scale emissions, which are aligned to inventory goals. While expensive, these instruments are equally suited to smaller domain or facility scale monitoring.

4.3.5.2.2 Mid-grade methane analysers

There are now a range of somewhat less expensive methane analysers available, such as the LiCOR LI-7810 and the Asea Brown Boveri Ltd's Ultraportable gas analysers. This allows trading off some precision and, potentially, reliability for a greater density of observations or a lower capital cost across a network. With suitable cross-calibration protocols, data from mid-grade methane analysers can be combined with data from a high-precision regional to national scale network to provide robust boundary conditions to the modelling tool(s).

4.3.5.2.3 Low-grade methane analysers

Low-grade methane analysers provide yet another increment in trading precision for a higher density of observations and/or a lower capital outlay. However, these analyser types are not readily calibrated in the same way that mid- and high-grade analysers are, and they are known to be prone to drift with a range of environmental parameters (e.g. temperature, pressure, humidity). This approach, if adopted, would require more resourcing in data handling and quality control, and potentially significantly more maintenance of individual units. At this stage, we are not aware of off-the-shelf low-cost sensors that are sufficiently robust, precise and accurate enough to be used for ambient methane monitoring at a facility scale.

4.3.5.2.4 Open-path techniques

Open-path techniques have a significant strength, particularly for emissions from diffuse areal sources. By measuring the concentration enhancement across 10s to 100s of metres, these measurements are able to capture a more representative portion of emission plumes more frequently than a point measurement site.

However, open-path measurements tend to be more technically demanding to make; and some available instrumentation remains research-grade (e.g. Fourier transform infrared spectroscopy). Even off-the-shelf solutions (e.g. Boreal's laser-based gas detection systems) are pragmatically more difficult to deploy, relying on perpetually clear line-of-sight between the laser and its retroreflector, which could make them difficult to permanently deploy in an operational facility. There is a strong body of literature deploying open-path techniques to quantify methane emissions from agricultural sources (e.g. Bai et al. 2021; Naylor et al. 2016; Deutscher et al. 2021).

4.3.5.2.5 Total column

Ground-based total column observations provide a vertically integrated (column average) measurement of methane enhancement in the atmosphere. They are similar to satellites in that they rely on the sun as the light source. Their strength is their ability to provide vertical information and detect plumes high above the ground, and they are critical to satellite validation.

The Total Carbon Column Observing Network (TCCON) is the gold standard by which satellite observations are validated (Wunch et al. 2011). However, these are expensive research-grade instruments requiring a laboratory to operate them. A more portable and robust option is use of the EM27/SUN photometers used by the Collaborative Carbon Column Observing Network's (Alberti et al. 2022). However, these are still relatively expensive instruments which can be technically demanding.

4.3.5.2.6 Isotopes and co-emitted tracers

As methane is emitted from a wide range of natural and anthropogenic sources, a significant difficulty with quantification of emissions is in attribution of enhancements to a particular source. One means of differentiating sources is by operating a very dense spatial network of measurements, to better map spatial variability between sources. Isotopes and other co-emitted tracers offer a different means to distinguish between sources.

Where there are strongly dissimilar methane source types, isotopes may be used to great effect (e.g. Lu et al. 2021; Kelly et al. 2022). It is increasingly possible to make measurements of $\delta^{13}C\text{-}CH_4$, although calibration standards remain difficult to source. However, measuring variations in the hydrogen isotopes remains a task for specialised laboratory isotope ratio mass spectrometry, so would be very difficult to implement operationally.

Other tracers offer more straightforward means of identifying source types. For instance, ethane is present in fugitive emissions from natural gas; carbon monoxide is a strong tracer of methane from biomass burning or other combustion processes; nitrous oxide is co-emitted with methane from wastewater treatment facilities; and landfills typically act as slowly leaking banks of synthetic greenhouse gases.

In some instances, tracers may be deliberately released at a known rate to accurately infer fluxes (e.g. Feitz et al. 2018) without the need for a plume dispersion model. Again however, these experiments, while informative, are unlikely to be used operationally due to site accessibility constraints and safety concerns with the release of some potential tracers (e.g. acetylene).

4.3.6 Mobile ground laboratories

Mobile ground laboratories usually consist of at least one gas analyser, a GPS and a mobile platform. A basic set-up such as this will enable users to map gas concentrations in two-dimensions, over time, for a wide spatial range that can vary from fine scale (metres) up to very broad scale (100s of kilometres). Such a set-up could be used to qualitatively infer emissions at subregional or facility scale, where it is possible to isolate (i.e. conduct measurements around) sources and thereby determine atmospheric gas concentrations enhancements due to emissions from these sources. This technique was applied by Kelly et al. (2023) who were commissioned by the EPA to conduct two mobile surveys of carbon dioxide, methane and carbon monoxide concentrations around several fugitive methane sources in Western Sydney. These surveys were able to qualitatively assess emissions from facilities, such as landfills and a piggery, and provide recommendations on enhanced emissions monitoring strategies for these facilities.

To quantitatively determine emissions, however, an atmospheric transport model is required to convert gas concentration measurements into emissions, unless the tracer release technique is applied (sections 4.3.3 and 4.3.4; Feitz et al. 2018).

To model atmospheric transport, especially at facility scale, it is highly important to accurately measure the local scale meteorology. The ideal solution is to deploy at least one three-dimensional (3-D) sonic anemometer in a location and height that is most representative of the local scale meteorology where the emissions estimates will be made. Otherwise, deploying 2-D sonic anemometers at multiple heights, or using local meteorological data may also be an option. Gaussian plume models are a relatively simple and commonly applied atmospheric transport model used to convert concentration measurements into emissions estimates (Kumar et al. 2021; Kumar et al. 2022; Kumar et al. 2024).

The mobile platform is usually a road-based vehicle (Kumar et al. 2024; Vogel et al. 2024) but it could also be light rail (Mitchell et al. 2018), a train (Deutscher et al. 2010; Fraser et al. 2011), or a ship (Bukosa et al. 2019). Each of these options has its own benefits and limitations, which generally relate to restrictions in movement either on road, rail or to a lesser extent, at sea. Opportunistic deployment on moving platforms is advantageous in that labour is not required to move the platform, but this is balanced against any introduced travel or accessibility restrictions.

Expanding the suite of gases analysed can have multiple benefits including the analysis of isotopes and co-emitted tracers, to better identify sources of enhancements (section 4.2.5.2.6). However, the selection of gas analysis that are suited to mobile platforms is more limited than for ground-based networks.

4.3.6.1 Pros and cons of mobile ground laboratories

The advantages of mobile ground laboratories over other techniques are as follows:

- They can quantify emissions over large spatial ranges from sub-facility to regional scales.
- It is relatively easy to isolate emissions from particular facilities, where measurements are able to be obtained around a facility (upwind/downwind).
- It is simple to map concentrations, though there are still complexities involved in order to determine emissions.

The limitations of mobile ground laboratories include the following:

- There is limited temporal coverage if mobile laboratories are deployed in campaign mode.
- Mobile laboratories provide only a snapshot of emissions per survey.
- It can be laborious if you have to drive your own vehicle between locations. However, this labour can be reduced if there are other forms of transport available, such as trains.
- Mobile laboratories can only go where there are roads, rail or other forms of access.

Mobile ground laboratories are a commonly applied technique to determine methane emissions from facilities and have been deployed in Australia (Day et al. 2015; Day et al. 2016; Maher et al. 2014; Iverach et al. 2015) and overseas (Kumar et al. 2024; Vogel et al. 2024). The accuracy of this technique when estimating methane emissions at the facility scale has been evaluated through controlled methane release experiments (Kumar et al. 2021; Kumar et al. 2022). For release rates ranging from 0.0005 to 0.1 t CH_4 h^{-1}, conducted over periods of 25 to 75 minutes, the combination of a mobile ground laboratory and Gaussian plume dispersion model was able to estimate the release rates on average to within ±20 to 30% (Kumar et al. 2022) (Figure 10).

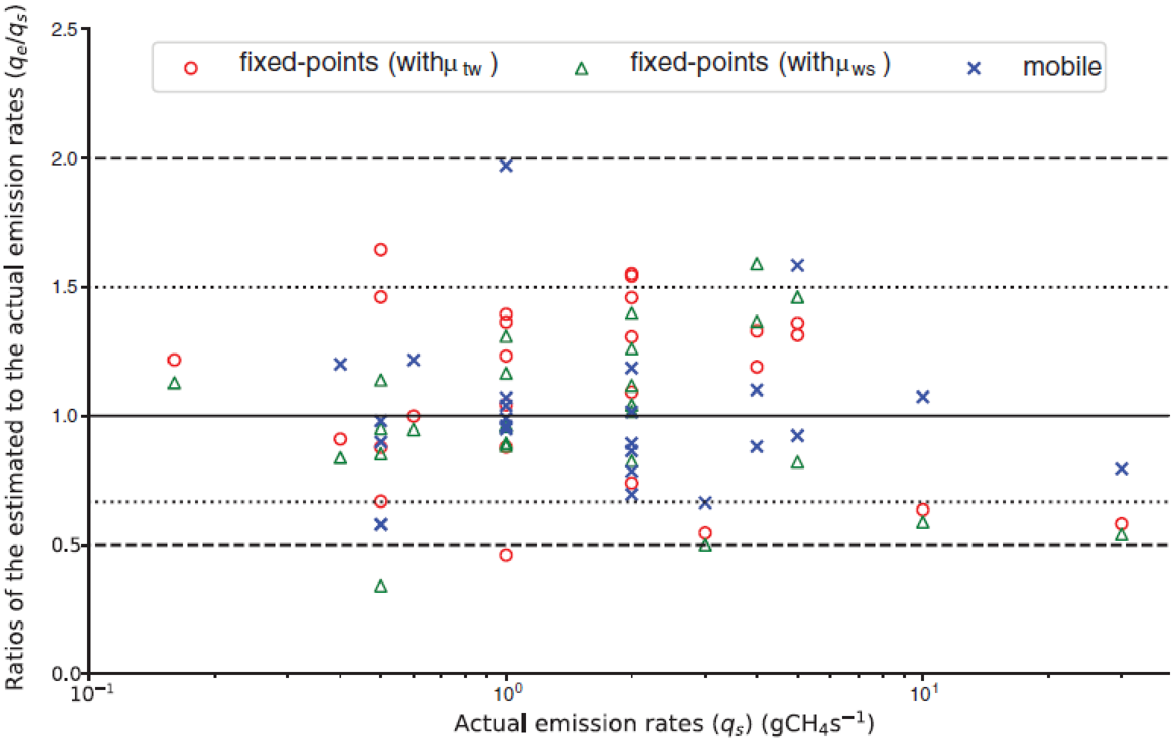

Figure 10 Ratios of estimated to actual release rates for estimates derived from mobile ground laboratory (blue cross) and ground-based network (i.e. fixed point; red circle, green triangle) measurements. (Source: Kumar et al. 2022)

4.3.7 Uncrewed aerial vehicles

There have been major advances in uncrewed aerial vehicle (UAV) technology within the last decade. This has enabled the development of UAV techniques to measure atmospheric methane and to determine methane emissions (Schuyler & Guzman 2017; Shaw et al. 2021; Shah et al. 2020; Allen et al. 2019; Total Energies 2024). UAVs can be used to measure methane in three ways:

- as a platform to take discrete air samples for later methane analysis
- to carry a sampling line tethered to a ground-based methane analyser
- as a platform where an in-situ methane analyser is mounted (Shaw et al. 2021).

The mounting of an in-situ methane analyser on board a UAV offers a greater sampling frequency than discrete measurements but without the flight limitations associated with a tethered sampling line. However, this places limitations on the type of gas analyser that can be used, depending on the payload that can be accommodated by the chosen UAV.

There are many different types of UAVs that are commercially available and well-suited for trace gas and methane monitoring (Schuyler & Guzman 2017; Shaw et al. 2021). This includes fixed-wing

UAVs which can generally cover larger distances and hold larger payloads, and rotary-wing UAVs that are more manoeuvrable and can take off and land vertically (Shaw et al. 2021).

There are a number of methane analysers that are suitable for mounting on board a UAV, including techniques based on laser absorption spectroscopy in the mid- and near-infrared. Shaw et al. (2021) provide a recent review of methods for quantifying methane emissions using UAVs, including a review of methane analysis techniques.

Meteorology (wind velocity) may be measured on UAV although it can be difficult to obtain accurate wind velocities unaffected by the UAV, particularly for rotary-wing UAVs. Meteorology can also be measured at the ground though this can impart an error into emissions estimates if it is distant to where methane is measured and is not sufficiently representative of the meteorology that is dispersing the methane plume. Emissions are typically quantified using mass balance approaches or Gaussian plume modelling (Shah et al. 2020; Shaw et al. 2021).

4.3.7.1 Pros and cons of UAVs

The advantages of UAVs are as follows:

- Ability to obtain vertical methane profiles, including down to ground level (e.g. Figure 11)
- High manoeuvrability, portability
- Sampling not limited by roads or other ground-based infrastructure.

The disadvantages of UAVs are as follows:

- Limited range of suitable methane analysers due to payload restrictions
- Limited flight time and thus temporal coverage
- Limited spatial coverage
- Regulations and flight restrictions including limited to daylight hours, maintaining visual line-of-sight and maximum height
- Risk of equipment damage.

The accuracy of UAV techniques in determining methane emissions has been assessed through controlled methane release experiments (Shah et al. 2020; Shaw et al. 2021). For example, Shah et al. (2020) found that for 22 surveys of a controlled methane release, they were able to quantity emissions within 17 to 227%.

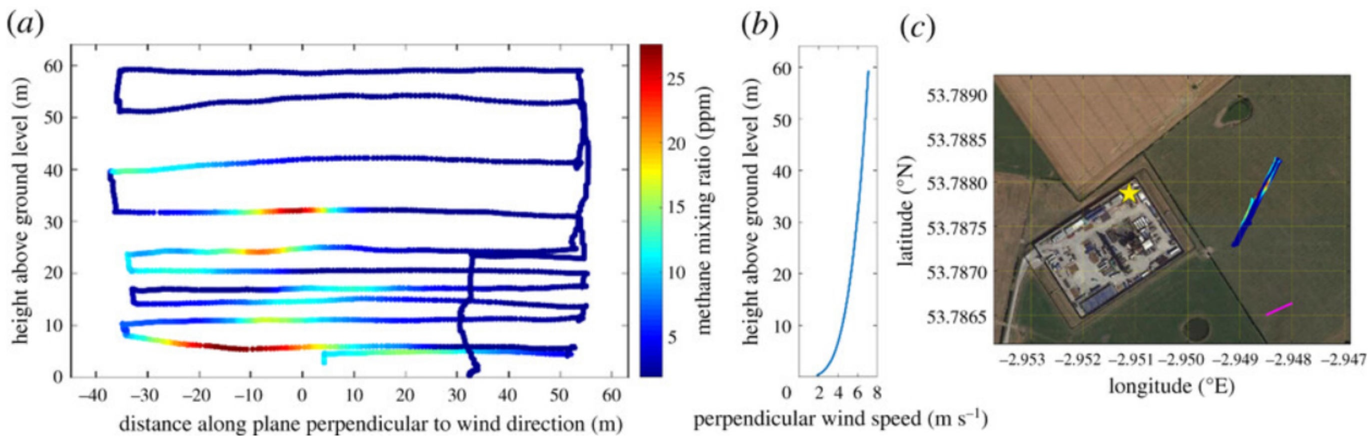

Figure 11 (a) UAV methane measurements (colour) taken downwind of a hydraulic fracturing facility shown in (c); (b) wind speed measured on board the UAV. (Source: Shaw et al. 2021 and references therein)

4.3.8 Aircraft

Aircraft have been used as a platform to rapidly measure atmospheric methane and quantify methane emissions across broad spatial areas in Australia (Neininger et al. 2021; Kelly et al. 2022) and internationally (Chen et al. 2022; Duren et al. 2019; Cusworth et al. 2021, Cusworth et al. 2024). Methane analysis techniques deployed on aircraft include imaging spectrometers (e.g. Duren et al. 2019; Cusworth et al. 2024) and in-situ methane analysers (e.g. Neininger et al. 2021; Conley et al. 2017). This may be complemented by the measurement of other trace gases and isotopes on board the aircraft, or in air samples taken on the aircraft and analysed later in a laboratory (Kelly et al. 2022).

In Australia, Neininger et al. (2021) used in-situ methane, carbon dioxide and meteorological measurements on an aircraft (ARA-Airborne Research Australia) to estimate methane and carbon dioxide emissions from the coal seam gas (CSG) industry in the Surat Basin, Queensland.[12] Their results indicated that CSG sources emit about 0.4% of the produced gas, which was two to three times greater than existing inventories for the region (Neininger et al. 2021). According to the authors, this was the first study in the world to quantify methane emissions from a producing CSG field using airborne measurement techniques (Neininger et al. 2021). A related study by Kelly et al. (2022) used air samples taken from aircraft to analyse methane isotopes and identify inventory knowledge gaps in the Surat Basin. Airborne Research Australia has also been engaged in recent campaigns to measure methane and carbon dioxide emissions from liquefied natural gas across Australia, as well as surface and underground mines in the Bowen Basin, Queensland (Airborne Research Australia[13, 14]; Figure 12).

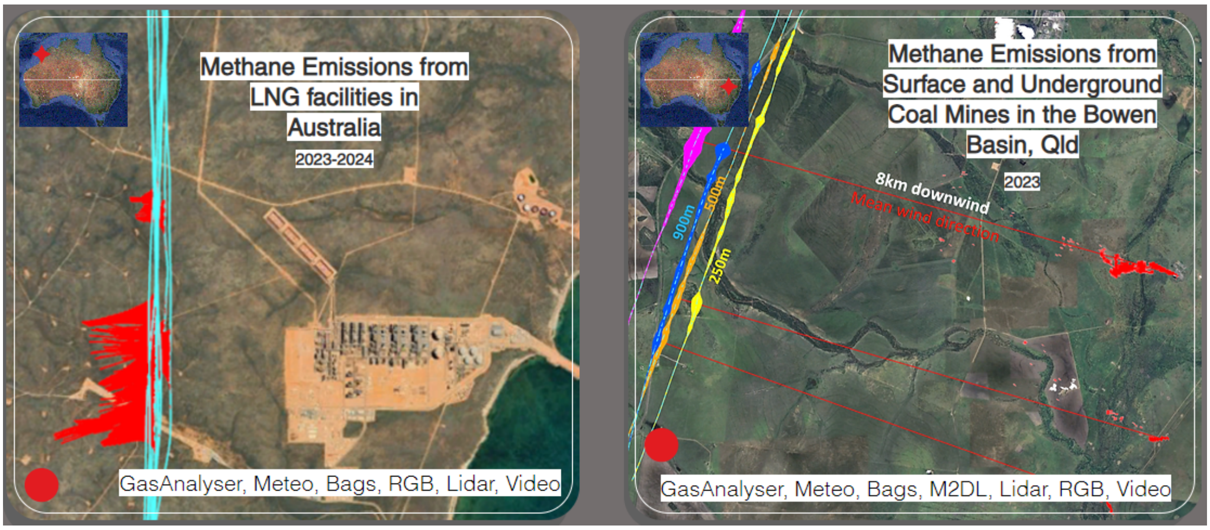

Figure 12 Recent campaigns to estimate methane emissions involving Airborne Research Australia. (Source: Airborne Research Australia 2024)

Aircraft-based imaging spectrometers are generally passive and rely on infrared radiation being emitted from the Earth's surface. This infrared radiation is absorbed by atmospheric methane and the absorption characteristics are used to quantify methane concentrations. Imaging spectrometers

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[12] This work was undertaken during a joint project between ARA (Hacker), MetAir (Neininger) and UNSW (Kelly), funded by UNEP.

[13] https://www.airborneresearch.org.au/

[14] in collaboration with the University of Bremen, Germany, during extensive field campaigns funded by UNEP's IMEO.

are particularly good at scanning point sources over large areas. Cusworth et al. (2024) used the Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) and equivalent imaging spectrometers to survey 20% of landfills in the United States, including hundreds of large landfills, between 2016 and 2022. They found significant point source emissions at most (52%) of the sites, and that their aerial emission rates averaged over all landfills were a factor of 2.7 higher than the US EPA Greenhouse Gas Reporting Program (Cusworth et al. 2024). Cusworth et al. 2024 also compared their emission rate estimates to an independent technique based on aircraft in-situ measurements (Scientific Aviation; Conley et al. 2017) and found good agreement.

4.3.8.1 Pros and cons of aircraft

The general advantages of aircraft techniques include:

- being able to rapidly scan emissions over large spatial ranges (facility to regional)
- being able to obtain vertical methane profiles, including down to near ground level
- not being constrained by ground-based infrastructure (roads, facilities etc.).

The limitations of aircraft techniques include:

- limited temporal coverage
- potentially high operating cost (flight time)
- they are labour-intensive
- passive imaging spectrometers require adequate radiation from ground (albedo, clouds etc.).

The accuracy of aircraft techniques for estimating methane emissions has been evaluated by several controlled release experiments (Sherwin et al. 2021; Chulakadabba et al. 2023; El Abbadi et al. 2024). A recent study by El Abbadi et al. (2024) evaluated the accuracy of five different aircraft techniques (Carbon Mapper, GHGSat-AV, Insight M, MethaneAIR, and Scientific Aviation) through controlled methane releases ranging from 1 to over 1,500 kg CH_4/hour with over 700 single-blind measurements obtained across the five techniques (Figure 13). Their comparison of estimated against reference methane emissions gave slopes ranging from 0.5 to 1.13 (where a perfect agreement would have a slope of 1), with reasonable to very good correlations (R^2 values of 0.61 to 0.93) (Figure 13; El Abbadi et al. 2024).

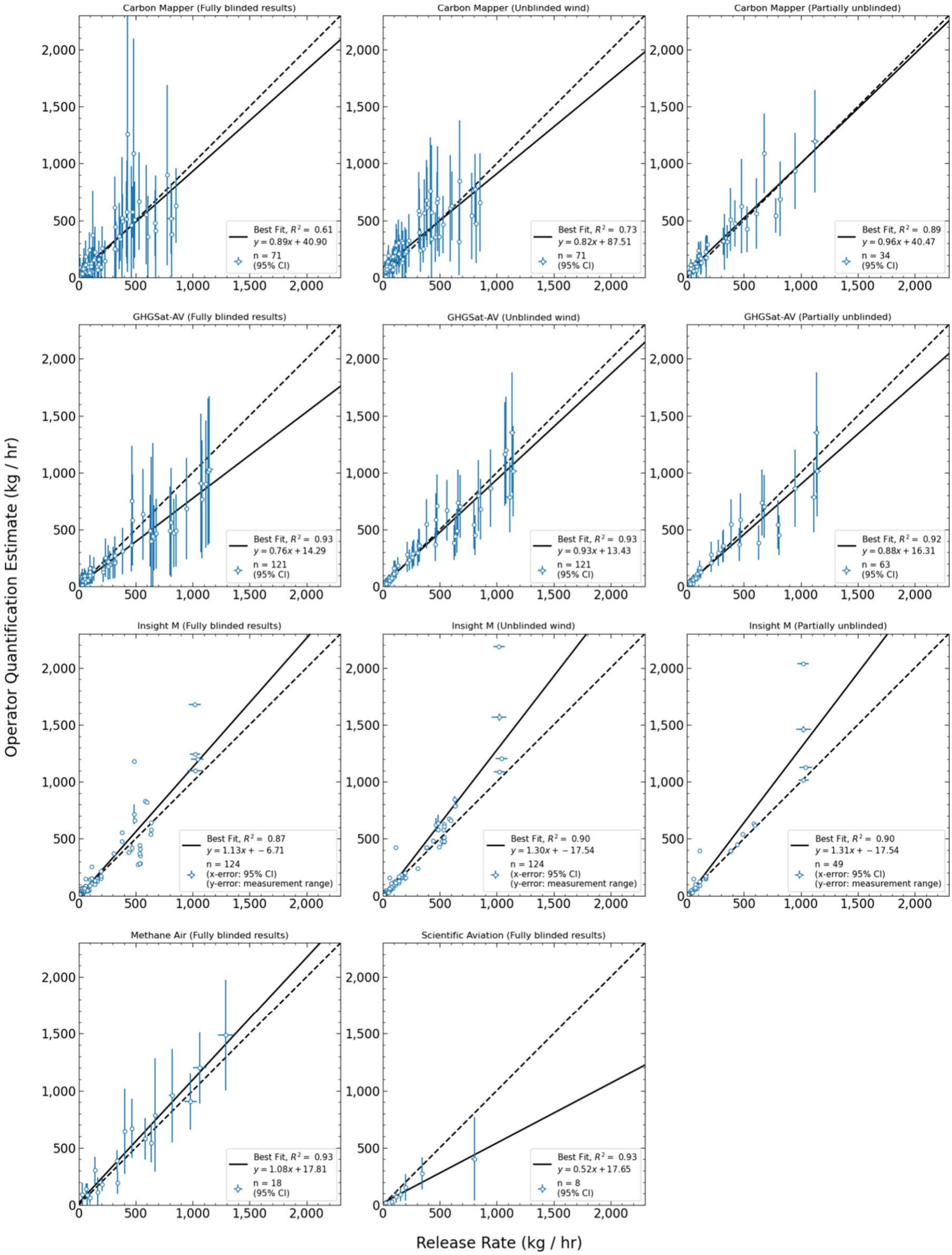

Figure 13 Comparison of estimates to true release rates for five different aircraft-based techniques. (Source: El Abbadi et al. 2024)

4.3.9 Satellites

The development and deployment of methane-measuring satellites has advanced very rapidly over the past few years and this will continue into the future (CEOS 2024). Satellites generally use spectroscopy to quantify methane and other gases in the atmosphere. They detect solar radiation reemitted from the Earth's surface, after it has passed through the Earth's atmosphere (Figure 14). The concentration of methane in the atmosphere is then determined based on the amount of radiation that is absorbed by methane in specific regions of a spectrum.

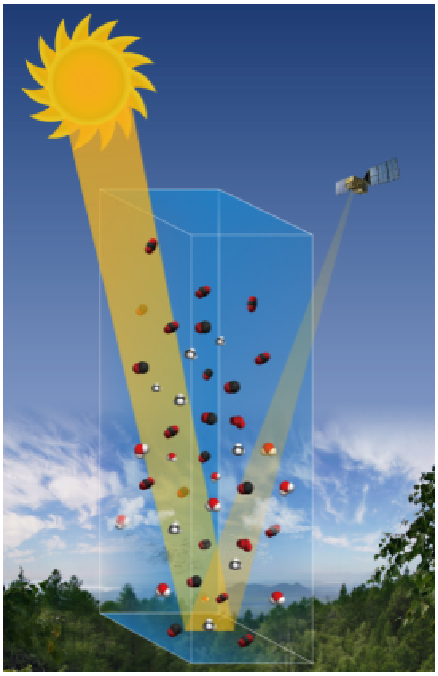

Figure 14 Schematic representation showing radiation emitted from the sun, hitting the Earth's surface and being re-radiated back into space where it is detected by satellite. Satellites quantify the amount of greenhouse gases in the atmosphere by measuring the amount of radiation they absorb in specific regions of a spectrum. (Source: NIES 2014)

Methane satellites are designed for different purposes, with some being more suited to global mapping (very large swath, low resolution) of methane, and others more targeted to facility scale (high resolution). The Committee on Earth Observation Satellites (CEOS) defines facility scale satellites as those with a spatial resolution of less than or equal to 1 km^2 (CEOS 2024). See CEOS (2024) for greenhouse gas (including methane) satellite missions currently in operation and planned for the future. See IEA (2024) for a summary of capabilities for selected satellites that can detect methane in the atmosphere.

The Sentinel-5p (TROPOMI) satellite was used in a recent study by Sadavarte et al. (2021) to quantify super-emitting coal mines in Queensland (see section 3.3). The Netherlands Institute for Space Research (SRON) and Kayrros both use Sentinel-5p (TROPOMI) to provide routinely updated and freely available methane plume maps and methane emission quantification, globally, including Australia and NSW (Kayrros 2024; SRON 2024). The methodology used to determine emissions by SRON (Schuit et al. 2023) and Kayrros (Lauvaux et al. 2022; Sherwin et al. 2023; Sherwin et al. 2024) have been published in peer-reviewed scientific literature.

Another methane satellite that has been very active in Australia is NASA's Earth Surface Mineral Dust Source Investigation (EMIT) imaging spectrometer that has been mounted on the International Space Station since July 2022 (NASA 2024). It has detected over 40 coal mining–related methane plumes in Australia and this information has been used to quantify methane emissions. Data such as this, and other satellite-detected plumes and emissions quantification, are freely available on the

International Methane Emissions Observatory (IMEO) Data Portal.[15] The IMEO Data Portal shows 71 satellite detection methane plumes where emissions rates have been determined in Australia, including 43 plumes in NSW.

The recent launch of MethaneSat and the Tanager-1 satellites promises to provide a major advance in the detection of methane by satellite due to their low detection limits, high resolution and freely available data.

The first results from MethaneSat were published in November 2024 and demonstrate the ability of the satellite to be used to derive methane emission estimates at high resolution over large spatial areas (Figure 15; MethaneSat 2024b). A comparison of MethaneSat (top-down) and inventory (bottom-up) methane emissions estimates showed that those derived from MethaneSat were significantly higher than the inventory (Figure 16; MethaneSat 2024b). The methodology used to determine emissions is published in peer-reviewed scientific literature (Chan Miller et al. 2024). Data is currently available on the MethaneSat data portal, with MethaneSat expected to provide data at full capacity by early 2025 (MethaneSat 2024a).

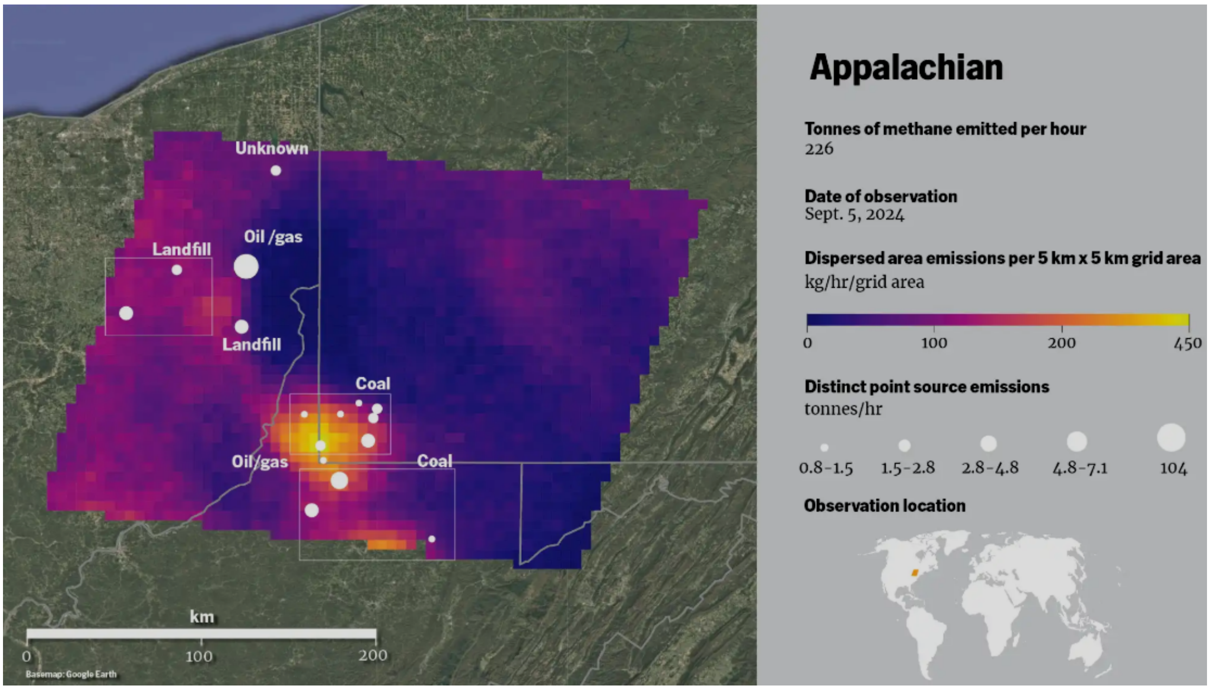

Figure 15 MethaneSat derived methane emissions estimated at 5 km x 5 km resolution over a broad region (c.a. 300 km x 300 km) in the USA Appalachian oil and gas basin. (Source: MethaneSat 2024b)

[15] https://methanedata.unep.org/

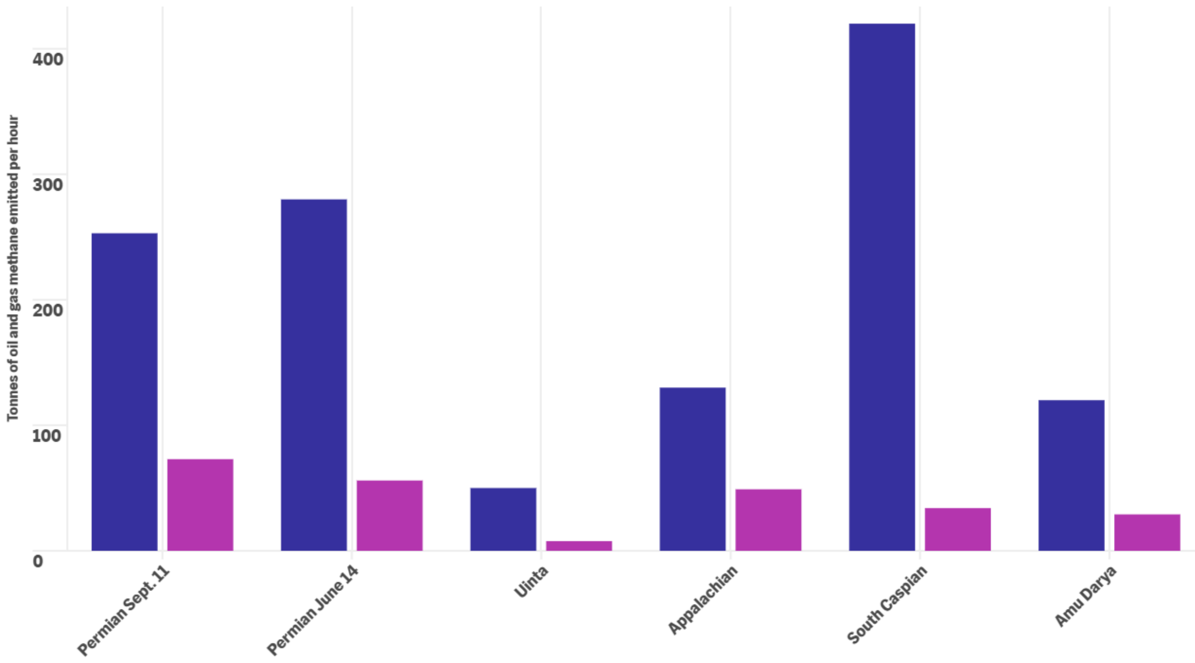

Figure 16 Comparison of methane emission estimates derived from MethaneSat (top-down, blue) and bottom-up (pink) inventory estimates for the USA (US EPA 2024b) and Turkmenistan (Emissions Database for Global Atmospheric Research (EDGAR)). (Source: MethaneSat 2024b)

For the Tanager-1 satellite, the first methane and carbon dioxide emissions estimates containing 300 initial detections were released in November 2024, just three months after the satellite went into orbit (Carbon Mapper 2024c). This includes four methane plume detections and emission estimates from Australia, with three of these related to underground coal mines in NSW (Carbon Mapper 2024b). Tanager-1 emission estimates have already been compared to simultaneous aircraft-based estimates and these initial results have shown good agreement (Carbon Mapper 2024c). Furthermore, Tanager-1 has driven methane mitigation in the Permian Basin through satellite emissions detection, notification of authorities, operator action, and satellite verification, which mitigated a 7 t CH_4/hour leak (Carbon Mapper 2024a; Figure 17).

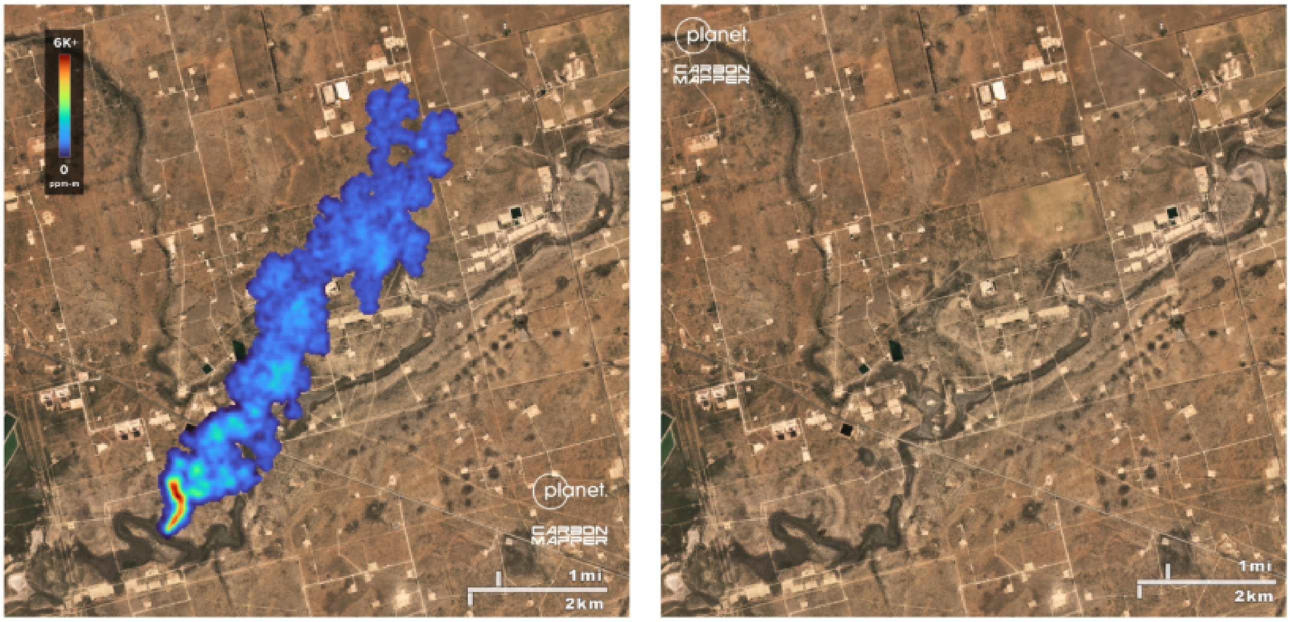

Figure 17 Tanager-1 methane measurements in the Permian Basin showing the presence and absence of a 7 t CH_4/hour leak before (left) and after (right) notification of authorities and operator action which led to methane mitigation. (Source: Carbon Mapper 2024a)

4.3.9.1 Pros and cons of satellite technology

The general advantages of satellite techniques include:

- data are usually freely available, and increasingly this includes methane emissions estimates
- wide spatial coverage (facility to global)
- ability to obtain repeated measurements over time, globally.

The general disadvantages include:

- high detection limits, although satellite technology is rapidly advancing and the detection limits are decreasing over time
- limited temporal coverage
  - snapshot in time corresponding to overpasses with good measurement conditions
  - time to revisit an area varies by satellite in line with its mission and spatial resolution (see IEA 2024)
  - generally require sunlight (daytime) for measurements
- affected by surface albedo, cloud cover and water, which ultimately affects the amount of solar radiation and thus signal that is detected by the satellites.

The accuracy of satellites at estimating methane emissions has been assessed by controlled methane release experiments (Sherwin et al. 2023; Sherwin et al. 2024). Sherwin et al. (2023) conducted what they claim to be the first single-blind controlled methane release testing for satellites. They found that emissions were observed by satellites in the range of 0.2 to 7.2 t CH_4/hour and that 75% of estimates were within 50% of the metered (reference) methane release. Sherwin et al. (2024) tested nine methane-sensing satellites and found that, overall, 55% of mean emission estimates were within ±50% of the metered (reference) release rate, which was similar to the performance of aircraft-based methane monitoring capabilities.

4.4 Emerging technologies and other techniques

There are a range of other technologies that are deployable for determining methane emissions. Some of them are well-tested, while others are emerging technologies that show promise. These are briefly described here, but caution is needed when making recommendations for operational facilities using technologies that have not been rigorously tested in the field. They include:

- **Tunable diode laser absorption spectroscopy** meters are available with relatively high accuracy and appropriate lower detection limits for permanent (10–15 years) installation in pipelines, making them an appropriate option for monitoring of some elements of some subsectors.
- **Chambers** are frequently used at a sub-facility scale to determine emission rates from natural gas infrastructure, or within wastewater treatment facilities. These are simple to use at a small scale but are very difficult to upscale and ensure representative sampling both in space and time. They are also potentially subject to access difficulties in some facilities.
- **Eddy covariance** is a well-tested technique to determine fluxes over relatively small footprints around the measurement site. High temporal resolution (10 Hz) concentration measurements are paired with 10 Hz three-dimensional wind data to infer emissions.

- A range of **multispectral or hyperspectral instruments** known as 'quantitative optical gas imaging' are becoming available, developed to quantify methane emissions. These show promise but are currently prone to significant quantification errors based on controlled release studies, except under conditions of very high flux rate. Further work is likely needed to improve and standardise the deployment of such instruments for quantification purposes.
- **Differential absorption LiDAR (light detection and ranging)** is a remote sensing technique which transmits tuneable wavelength light over a measurement region and relies on aerosol and particulate backscatter to return light to a sensitive detector. The technique can be tuned to measure methane over complex terrain or in hazardous environments.

4.5 Integrated greenhouse gas observing systems (bottom-up and top-down)

Each bottom-up and top-down method for methane monitoring has its own benefits and limitations (summarised in Table 4 and Table 5 in section 5.1). Using a combination of bottom-up and top-down approaches facilitates comparisons of emission estimates and evaluations of uncertainties, and leads to the improvement of both methods and more accurate emissions estimates (Figure 18). Furthermore, top-down methods can be verified and somewhat calibrated using controlled methane release studies, then applied at different scales alongside bottom-up methods to assess their accuracy and to refine these methods. Such refined bottom-up methods can then be applied at scale, to estimate emissions from a subsector or sector in a more accurate way than if bottom-up only methods were applied.

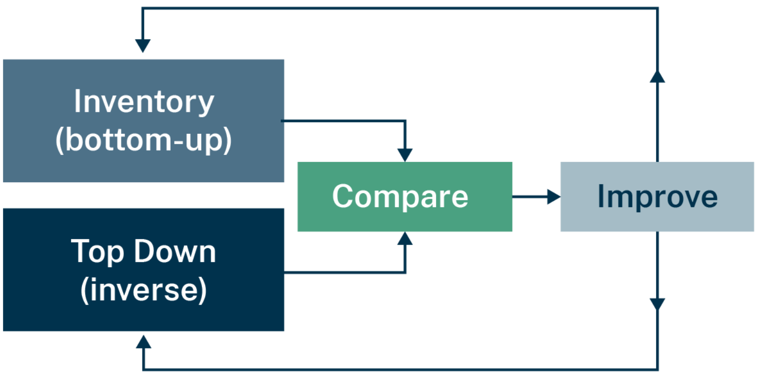

Figure 18 A simplified diagram showing how the combination of bottom-up and top-down methods facilitates comparison of emission estimates, leading to the improvement of both methods and thus more accurate results. (Source: adapted from a figure by Dr Ann Stavert and used with her permission.)

There is not one single method that will provide the best option for all applications. The suitability of certain methods for different applications will depend on important method features such as their spatial and temporal coverage, and their detection limit, which can vary by orders of magnitude between methods (Table 4 and Table 5; Figure 19; Figure 20). The best solution to cover all applications is an integrated methane observing system that combines multiple bottom-up and top-down methods to harness the advantages of each technique and overcome the limitations of individual methods.

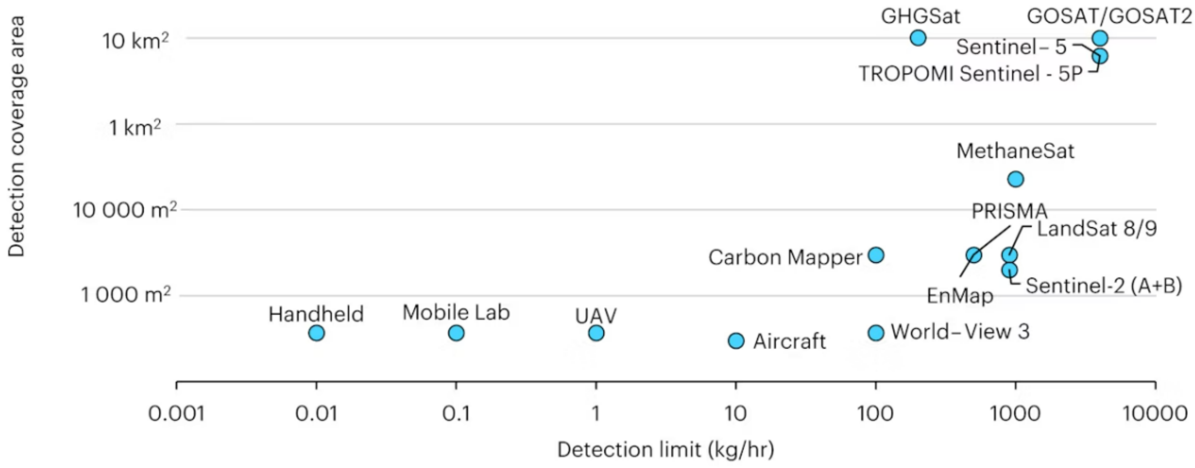

Figure 19 Summary of detection coverage areas and detection limits for a range of methane measurement techniques including handheld devices, mobile laboratories, uncrewed aerial vehicles (UAVs), aircraft and a variety of satellites. (Source: IEA 2024)

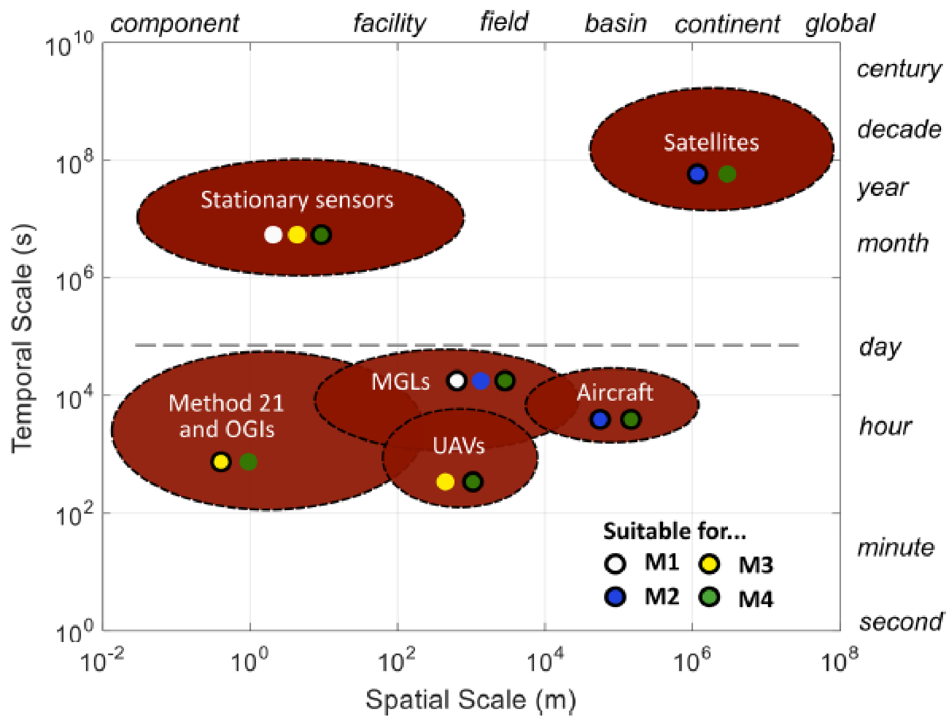

Figure 20 Summary of temporal (seconds on left axis; context on right axis) and spatial scales (metres on bottom axis; context on top axis) covered by a variety of techniques used for mitigating fugitive methane emissions. (Source: Fox et al. 2019)

These include concentration detectors associated with the US EPA's Method 21 (Determination of Volatile Organic Compound Leaks), optical gas imaging cameras (OGIs), stationary sensors, mobile ground laboratories (MGLs), uncrewed aerial vehicles (UAVs), aircraft and satellites. These techniques are suitable for M1: Develop and refine emissions factors to improve inventories, M2: Estimate top-down emissions from a region with multiple sources, M3: Conventional, close-range LDAR using handheld instruments, and M4: Rapid screening for anomalous emissions

There are now many examples where the comparison of top-down and bottom-up emissions estimates has led to method reviews, method revision and an overall improvement in the accuracy of emissions estimates (e.g. Luhar et al. 2020; DISER 2021; Sadavarte et al. 2021; DISER 2022b; Dunse et al. 2022; Cth DCCEEW 2024c; Chan et al. 2024). In Australia, satellite-based estimates of greenhouse gas emissions, including the Sadavarte et al. (2021) study, prompted the Australian Government to review inventory methods for open-cut coal mines in Queensland (DISER 2022b). This led to a 'significant improvement in the method' which resulted in a 44% increase (1.6 Mt CO_2-e/year i.e. 57 kt CH_4/year (IPCC AR5, 100-y GWP)) in methane emission estimates from Queensland open-cut coal mines (Figure 5; DISER 2022b).

Another example is the Luhar et al. (2020) (CSIRO) study of methane emissions in the Surat Basin, which provided top-down emissions estimates using an inverse modelling approach that incorporated in-situ atmospheric monitoring of methane at two locations between 2015 and 2016. These results were used by the Australian Government in their Quarterly Update of Australia's National Greenhouse Gas Inventory: September 2020 (DISER 2021) and compared against their bottom-up inventory estimates for the Surat Basin, and its subdomain that was dominated by coal seam gas (CSG) emissions. The comparison indicated good agreement between the bottom-up and top-down (Luhar et al. 2020) methods. The Luhar et al. (2020) study and the comparison it enabled was cited in DISER (2021) as being 'especially valuable'. However, the good agreement was a result of changes to the inventory methods that occurred since 2015, which increased methane emissions from CSG operations in the Surat Basin by a factor of 2.8 (DISER 2021).

For synthetic greenhouse gases, CSIRO has provided the Australian Government with emissions estimates derived from atmospheric observations and top-down methods for many years (e.g. Dunse et al. 2022; Cth DCCEEW 2024b). These have provided invaluable independent assessment of the accuracy of emissions estimates and methodologies included in the national inventory reports, as well as insights that can be used to improve the bottom-up inventory methods (e.g. Cth DCCEEW 2024b). As a result, they have also been cited by the Australian Government as being 'especially valuable' (DISER 2022a).

The 2019 Refinement to the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) encourages greater use of top-down methods in inventories and details the value of being able to compare bottom-up and top-down emissions estimates (see chapter 6, IPCC 2019). There are at least six countries that currently use top-down methods in their national greenhouse gas inventories reported to the UNFCCC, including Australia, Germany, New Zealand, Switzerland, United Kingdom and the United States of America (Peters et al. 2023). This is being expanded through projects such as the Process Attribution of Regional Emissions project (PARIS 2024).

Integrated greenhouse gas observing systems, covering methane and other major greenhouse gases such as carbon dioxide and nitrous oxide, are expanding and being further developed globally. This is being driven by the need for urgent climate change mitigation, and through various initiatives such as:

- the World Meteorological Organisation's (WMO) Global Atmospheric Watch programme (GAW) (WMO 2024a)
- the Integrated Global Greenhouse Gas Information System (IG3IS) (IG3IS 2022) hosted by WMO
- the WMO Global Greenhouse Gas Watch (G3W) (WMO 2024b)
- prominent examples where integrated greenhouse gas observing systems are being developed and implemented include programs in the US (GHG IWG 2023), the European Union (CAMS 2024; ICOS RI 2024).

Ground-based in-situ greenhouse gas measurement networks generally form the foundation of integrated greenhouse gas observing systems around the world. These networks are fundamental as they are able to provide long-term, continuous observations of multiple greenhouse gases, isotopes and tracers, with high precision and accuracy (section 4.3.5; Table 4 and Table 5 in section 5.1). They also have the ability to provide high spatial coverage as long as there is a sufficient number of stations within a network. Example networks from around the world, including Australia, New Zealand and Europe are shown in Figure 21, including:

- Integrated Carbon Observing System (ICOS RI 2024)
- United Kingdom Greenhouse Gas Observations network (UK Met Office 2023)
- New Zealand’s CarbonWatchNZ in-situ greenhouse gas measurement network (GNS Science 2024)
- Australian Greenhouse Gas Observing Network (CSIRO 2024a).

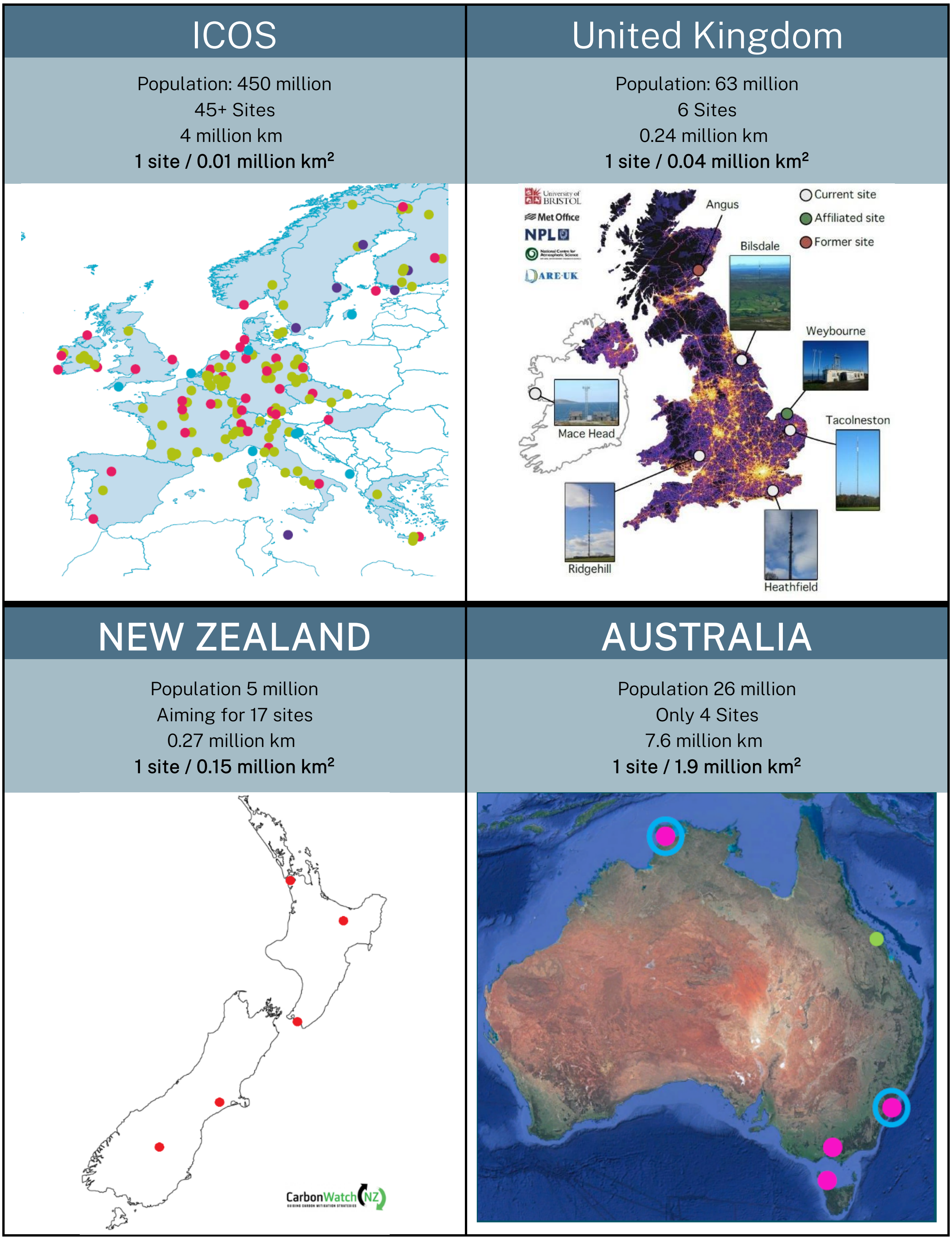

Figure 21 Examples of ground-based atmospheric greenhouse gas networks including station density relative to area

From top left to bottom right this includes the Integrated Carbon Observing System (red dots = atmosphere stations (not all shown); ICOS RI 2024), the United Kingdom Greenhouse Gas Observations network (UK Met Office 2023), New Zealand's CarbonWatchNZ in-situ greenhouse gas measurement network (not all sites shown, aiming for 17 sites; GNS Science 2024), the Australian Greenhouse Gas Observing Network with four sites (pink circles) and two of these with total column instruments (blue circles; CSIRO 2024a). The Australian network is operated by CSIRO and the University of Wollongong and has a site density that is orders of magnitude less than that of the other networks.

The long-term observation sites within the Australian Greenhouse Gas Observing Network (CSIRO 2024a) are operated by CSIRO and the University of Wollongong. The network consists of four sites which all maintain in-situ measurements of atmospheric greenhouse gases and a selection of other gases, and in some cases, greenhouse gas isotopes. Two of these sites also have total column instruments maintained by the University of Wollongong as part of the international Total Carbon Column Observing Network (TCCON) and Network for the Detection of Atmospheric Composition Change. Australia currently has a site density that is orders of magnitude less than the other networks such as New Zealand and Europe, which limits the ability to accurately estimate greenhouse gas sources and sinks at national scale (Figure 21; Haverd et al. 2013; Villalobos et al. 2023). Expansion of the Australian network has been in planning for over 20 years (Law et al. 2004; Ziehn et al. 2014; Ziehn et al. 2016). In line with recent efforts by the WMO and other agencies to expand greenhouse gas observations around the world, there has been recently renewed efforts to expand the Australian network (e.g. Langenfelds & Caldow 2023; Rayner et al. 2023).

5

Suitability of methods for sectors

5.1 Method summary

Table 4 and Table 5 provide a summary of the available approaches to estimating methane emissions. Section 5.2 considers a range of factors that facilities will need to consider in determining the suitability of these techniques to their situation.

Table 4 Summary and comparison of methane emissions monitoring technologies. The different configuration options for ground-based networks are further summarised and compared in Table 5

Approach	Bottom-up	Top-down				
Technique	NGER/ANGA/IPCC	Ground-based networks	Mobile (vehicle)	UAVs	Aircraft	Satellite
Pros	Aligned with UNFCCC Freely available	High spatial, temporal coverage Low labour*	Wide spatial range Easy to isolate facilities	Vertical profile (3D) Portability	Wide spatial coverage Vertical profile (3D)	Free data Rapidly evolving Spatial coverage
Cons	Limited independent verification Temporal resolution Data availability at facility scale	Network density constraints	Laborious Temporal coverage Road limited	Limited flight time Flight restrictions Limited sensors Laborious	Temporal coverage Cost (flight) Laborious	Detection limits Limited temporal coverage (albedo, clouds)
Temporal	Yearly	Hours to years	Minutes to days	Minutes to days	Hours to days	Days to years
Spatial	Facility to global	Sub-facility to global	Sub-facility to regional	Sub-facility to facility	Facility to regional	Facility to global
Uncertainty	Varied	Low to medium	Low to medium	Low to medium	Low to medium	Medium to high
Cost	Low	Low to High (density, analyser)	Low to medium	Medium	Medium to high	Data user = Low

Table notes:

This table presents only approximate values. These estimates will vary depending on the exact configuration and application of each method.

* If high-grade analysers are used (see Table 5 for further information).

Table 5 Top-down: technologies for ground-based networks

Technique	High-grade analyser	Medium-grade analyser	Low-grade analyser	Open-path	Total column	Isotopes and tracers
Pros	Robust, low labour, high precision	Medium density at mid cost	Low cost, higher density possible	Integrated measurement over long distance	Vertically integrated measurement	Assists source discrimination
Cons	Higher capital cost compared to medium and low-grade analysers	Limited tested options on the market	Poor precision, difficult to rigorously calibrate, prone to drift, high labour cost	Requires clear line-of-sight at all times. Some instruments research-grade	Daylight, clear sky measurements only. Instruments research-grade	Isotopes technically demanding
Temporal	Continuous	Continuous	Continuous	Continuous	Daytime	Continuous and/or discrete
Spatial	Scalable at cost	Scalable	Readily scalable	Scalable (limited; environment-dependant)	Scalable at cost	Scalable at cost (analyte dependant)
Uncertainty	Low	Medium	High	Low to medium	Low to medium	Low to medium
Cost	High initial capital cost. Low labour cost.	Moderate capital and labour cost.	Low capital outlay. Labour for data QA/QC costs may be high	Capital plus labour costs relatively high for long-term use.	Capital and labour costs relatively high.	Additional mid to high cost to add capability to the network. Labour cost high for Isotopes.

5.2 Factors to consider

5.2.1 Best-practice emissions estimation from continental to facility scale

Increasing knowledge of the spatiotemporal pattern of methane (and other greenhouse gas) emissions is a critical precursor to developing effective mitigation action. This is true at all scales, from the global to the facility scale. There is a large volume of scientific evidence that now points to significant uncertainties in the inventory approaches to emissions accounting (e.g. section 3.3). The 2019 refinement of the 2006 IPCC guidelines advocates for integrating atmospheric measurements to improve national greenhouse gas inventories (IPCC 2019). In many cases incorporating top-down learning has led to systematic improvements to inventories (e.g. Luhar et al. 2020; Chan et al. 2024).

Because of the need to provide well-calibrated and robust boundary conditions in a top-down approach to emissions estimation, **there is a critical role for a backbone network of regional scale monitoring** with high-precision analysers. This infrastructure would help meet Australia's obligations to the World Meteorological Organisation and Global Greenhouse Gas Watch (G3W). Furthermore, such a network would provide high-quality boundary conditions for facility scale emissions estimates linked to the relevant international mole fraction scale, for not only methane, but also other trace gases (carbon dioxide, nitrous oxide, carbon monoxide, $\delta^{13}C\text{-}CH_4$). This may be useful for discriminating between different sources of methane emissions (or for sources which require their own improvements to emissions reporting). This background monitoring network could be used to estimate regional and continental scale greenhouse gas emissions, providing a top-down verification on total emissions reporting at a regional and national level.

Satellite data (if available at the resolution required) would be used to provide broad surveillance of significant sources or source regions, but these need to be ground-truthed by the in-situ monitoring network and other ground-based observations (Finman 2024).

Best-practice top-down emissions estimates at the facility-level would be characterised by a higher density of (potentially lower precision) measurements while maintaining rigorous comparability between facilities. To ensure this, there needs to be standardised calibration protocols between facilities and compatibility between the cascading spatial scales, that is, facility-level calibration must be linked to the higher-level calibration scale. While facility scale monitoring (close to the source) would not necessarily require the same analytic precision as the background network, all data streams must be calibrated to the same scale to infer real emissions from measurement data within a modelling framework. Calibration biases between measurements can lead to the inference of false emissions.

While there is value in a diversity of approaches, to better understand a problem, from the pragmatic perspective of implementing guidelines across industries, a unified modelling approach to infer emissions from measurement data should be adopted, to maximise comparability of facility scale results within and between sectors.

A cascading approach to emissions monitoring would be bolstered by a mobile capability to use in campaign mode to validate operational emissions estimates or investigate regions of anomalously high emissions revealed by the broader in-situ network and or satellite monitoring. Mobile capability might consist of an instrumented vehicle, short-term deployments of open-path technologies and/or drone capabilities to map plumes in 3D.

Although outside the strict scope of this report for licensed facilities, the development of a regional scale monitoring network should be considered a priority. It would help build capability and capacity in the workforce to tackle top-down methane emissions estimation and would provide the foundation for delivering consistency between emissions estimates from facilities and across sectors.

5.2.2 Capital costs

The capital outlay necessary to implement robust facility scale monitoring of methane emissions depends on factors that will vary by sector, depending on the spatiotemporal characteristics of the emissions. Table 6 provides approximate costs of components of a top-down approach to fugitive methane monitoring.

Table 6 Approximate capital costs of components of a top-down approach to fugitive methane monitoring, with detail about the expected lifetime of each capital component

Capital item	Approximate cost	Expected lifetime (years)
Calibration span gases	$10,000	10–15

Capital item	Approximate cost	Expected lifetime (years)
Reference standard	$5,000	2
Picarro CRDS	$150,000	7–8
LiCOR methane analyser	$80,000	5–7
Boreal open-path laser	$75,000	10
Tuneable diode laser absorption spectroscopy (in pipeline)	$50,000	10–15
EM27 SUN	$200,000	7–8
Meteorological station	$5,000	10
Tower, instrument housing, peripherals (e.g. pressure regulators, flushing pumps)	$20,000	20

A critical component in establishing a monitoring operation will be investment in calibration standards, that will link data within and across facilities, and at broader regional and national levels to ensure inferred emissions are real. To ensure this, operators must procure calibration standards that have been assigned on a well-defined and maintained mole fraction scale. A mole fraction scale is a standardised method for measuring concentration of gases, such as the WMO X2004A mole fraction scale for methane.

A guiding principle, especially for sectors with diffuse emissions, is that the capital investment in several analysers (at least two, preferably three or more) will significantly improve the robustness of emissions estimates that are able to be made compared with a single piece of monitoring kit. Greater spatial information will improve understanding of the source area, and allow emissions to be determined more precisely. However, both the capital outlay and operating overheads for running an extensive network of analysers will need to be weighed against improvements in data and emissions estimation.

For all ground level areal or semi-areal sources, measurement of the local wind speed and wind direction will be necessary to interpret concentration enhancements (above the background levels present in the air mass first impinging on the site) and model the emissions causing the observed enhancements.

Modelling costs may include a licence fee for software, along with labour costs to run the model. Undertaking modelling to infer emissions from the concentration data requires considerable specialised technical skills, which are more difficult to codify than running analytical concentration measurements. The workforce required to undertake the modelling may best sit outside facility operators. This will be discussed further in the section below.

5.2.3 Labour costs and technical feasibility

5.2.3.1 Labour costs

For the purposes of implementing concentration monitoring, some indicative figures regarding labour costs are provided here. Installing instrumentation could be expected to need two weeks' labour from one person. This step, in particular, may be outsourced. Ongoing operation of instrumentation to maintain data quality control would then require about one hour per week. Factoring in repair and maintenance would likely consume another two weeks' labour per year. Altogether, this would probably impose a labour cost of 0.1–0.2 full-time equivalent per facility to implement concentration monitoring, depending on the number of measurement locations and the technical experience of the staff. Alternatively, these ongoing tasks may also be outsourced.

5.2.3.2 Technical feasibility

Given that some EPA-licensed premises will necessarily employ staff with technical skills, the ongoing operation of many of the measurement techniques that are fit-for-purpose would likely be able to be conducted by existing staff employed by those facilities, with development of standard operating procedures. Though undoubtedly this will place a greater demand on technical staff, it is unlikely that these operators would need to hire staff with specific new skills to deliver reliable concentration measurements. However, in order to establish consistency across facilities, further work developing technical guidelines for suitable analysers will be needed.

For many of the top-down approaches recommended, local meteorological data will also be required to be measured. However, in many cases, these observations are already in place, or there exists precedent for requiring operators to implement this. For industries where air quality concerns may be an issue, recording of weather data is already mandatory (refer to the EPA *Approved Methods for Sampling and Analysis of Air Pollutants in NSW* [NSW EPA 2022a]).

Moving from concentration monitoring to emissions monitoring involves an additional level of technical expertise to undertake modelling of emissions. These skills are unlikely to currently exist within the workforce of licensed facilities. To address this skills gap, a range of approaches could be considered:

- Large facilities may invest in capability within the business, to establish routine top-down emissions estimation. This may aid the licensee in identifying appropriate mitigation measures, help demonstrate the success of mitigation actions over time and improve the transparency of emissions reporting.
- In regions of clustered licensed premises, licensees may contribute to a central, shared modelling capability, to make best use of all data streams from the area. This could be cost-effective, but also have the advantage of being able to leverage data streams from a region (improve boundary conditions between facilities) to inform emissions estimates at individual facilities.
- The EPA or other NSW Government agency could develop modelling capability, funded through operators. This approach has the advantages of improving transparency and credibility, allowing for greater capability development, and optimising the consistency and cross-checking between and across sectors.
- States and territories could leverage and invest in modelling capability at a federal level, through government departments or agencies, provided it were in line with their strategic direction.
- If the data required to model emissions were publicly available, then the broader scientific community might be able to conduct such modelling.

Due to the technical complexity of emissions modelling, it will not be feasible to deliver emissions estimates for all facilities initially. However, the retention of concentration and weather data for facilities would allow retrospective analysis of emissions when necessary.

Finally, establishment of a mobile monitoring capability would have great benefit for progressively enhancing fugitive methane emissions estimates. A mobile facility would be able to validate emissions estimates, or to investigate facilities where there may be red flags (e.g. through satellite data or other means). The main advantages of this approach include its ability to cover large spatial ranges (<1 km^2 to 1000's km^2), to isolate facilities (by driving around the facility), to identify opportunities for leak detection and repair, all at relatively low capital expense.

5.2.4 Suitability and feasibility of methods for sectors or subsectors

For the underground mining sector (identified as a priority sector, see section 3.2), the majority of fugitive methane emissions occur as point source emissions from return ventilation shafts which are already monitored for work health and safety needs. Improving the sensitivity of analytic instrumentation in this sector is readily feasible.

The other priority sectors in EPA's remit, surface coal mining and solid waste (landfills), which can be broadly characterised as areal or near areal surface sources, are similarly amenable to top-down emissions determination techniques. The wastewater treatment and agriculture sectors (both around 5–6% of EPA's remit) are also amenable to these techniques. The permanent installation of equipment to obtain the best possible temporal coverage and monitor long-term trends is the best option available. There are many suitable technologies that are essentially turnkey devices that could be deployed by facility operators for concentration monitoring.

For some facilities, there might be significant benefits in employing open-path techniques to undertake a mass balance approach to estimating emissions. However, for many facilities (especially those located in regions with more variable wind regimes), placing single point analysers (with intakes at 10+ metres above ground level) at a number of locations and allowing the wind to bring concentration enhancements to different analysers over time is likely to be the most appropriate and straightforward way to optimise emissions monitoring.

While ground-based total column measurements of methane enhancements can be very valuable, at this stage, the technical demands of operating them means that they remain in the domain of research equipment and are not yet suitable for widespread deployment at facilities.

The use of a mobile facility, such as a vehicle or drone, instrumented with a methane analyser and anemometer would be feasible to deploy around facilities to provide snapshots of emissions or validate concentration measurements from permanent installations.

6

Future regulatory policy considerations

This section outlines how the EPA will consider CSIRO recommendations on facility-level fugitive methane monitoring.

CSIRO made recommendations on facility-level fugitive methane monitoring for EPA's consideration. The recommendations are based on the best scientific methods. The capability to undertake all the steps, particularly for EPA's licensees, may not be currently available, and training and development may be required. A summary of the key recommendations made by CSIRO include developing:

- **regional greenhouse gas monitoring networks** to establish background methane concentrations
- **a tiered approach to prioritise large emitters** to help focus monitoring efforts
- **facility-level greenhouse gas monitoring** at two or more locations to determine the fugitive methane concentrations from the facility. It may not be scientifically possible or necessary to do facility-level monitoring at all individual facilities. A tiered approach prioritising high emitters will be considered by the EPA
- **top-down modelling** to work out the methane emissions from an individual source or facility based on the concentration measured at a monitoring station. Inverse modelling is complex and requires technical expertise and the right inputs, assumptions and methods. Developing the methodology to get robust emissions will require input from experts and industry.

In addition, CSIRO made recommendations on transparency with reporting and independent verification. Where possible, standardised methods for the measurement, modelling and reporting of fugitive methane emissions are recommended to be developed. The recommendations and how the EPA will consider the recommendations are discussed in more detail in the following sections.

6.1 Regional greenhouse gas monitoring networks

A top priority is to establish regional greenhouse gas monitoring networks. The regional greenhouse gas monitoring network would provide data on background concentrations. This information will be the first step in helping separate emissions from licensed facilities and other sources from beyond the facility's boundary (also referred to as boundary conditions). Regional networks can also help detect the greenhouse gases in a region and will provide long-term broadscale information on greenhouse gas levels. This can help identify emission hotspots.

The NSW Government will be establishing regional greenhouse gas monitoring networks to independently monitor and verify greenhouse gas emissions. The initial networks will be in the Hunter region, where there are large sources of fugitive methane emissions and there are existing air quality monitoring networks that can be used. Once a network has been established, the NSW Government will work with experts to establish methodologies to do inverse modelling and emissions verification.

The NSW Government considers that the regional networks need to collect a few years of data prior to the implementation of facility-level monitoring. This will ensure that there is sufficient background information and established inverse modelling methodologies to support robust estimation of emissions at individual facilities.

6.2 Tiered approach to prioritise large emitters

Establishing greenhouse gas monitoring and emissions estimation capabilities will require time. A tiered approach, starting with large emitters, will help focus efforts. The tiered approach may consider:

- The amount of methane emitted. For example, Tier 1 may focus on large emitters that emit methane equivalent to 100,000 t CO_2-e/year.[16] Tier 2 may consist of facilities that emit between 50,000 and 100,000 t CO_2-e/year.
- Locations where there are clusters (within 5-km radius) of fugitive methane emitting facilities that collectively emit above the Tier 1 methane threshold.

A tiered approach is consistent with the EPA requirements for the planning process and current considerations for decarbonisation actions. The EPA will consider the recommended thresholds and approach in context with other climate change work to ensure consistency.

6.3 Facility-level fugitive methane measurement

Out of the sectors licensed by the EPA, methane emissions from underground coal mines represent about 46% of EPA licensees' methane emissions.[17] The other 54% are mainly from landfills, open-cut coal mines, wastewater treatment plants and agriculture facilities licensed by the EPA (see Table 3).

6.3.1 Underground coal mines

Fugitive methane emissions from underground coal mines are mainly from ventilation air exhausted from ventilation shafts. As the emissions largely occur at discrete point sources, this subsector has relatively easy, cost-effective improvements to measuring methane concentrations to make more robust, and accurate direct observations of emissions. Most underground coal mines in NSW report to NGERs, which requires use of direct monitoring (Method 4) to report fugitive methane emissions. As discussed in the report, direct monitoring can be either continuous emissions monitoring (CEM) or periodic emissions monitoring (PEM). CEM is more likely to capture variability across the year, and thus would yield more accurate results (see section 4.2.2.1). CEM with a fit-for-purpose methane analyser that can detect low levels of methane, coupled with temperature, pressure and flow rate measurement at the ventilation shaft is recommended. These measurements should comply with a set of measurement standards that are appropriately tailored to estimating methane emissions from underground coal mining.

The EPA will consider and consult on this recommendation with the broader climate change requirements and the mitigation guide for coal mines. The considerations will take into account current requirements of the NGER Measurement Determination and any relevant mine safety regulation.

[16] 100,000 t CO_2-e/year is the threshold for the Commonwealth's Safeguard Mechanism scheme.

[17] https://greenhouseaccounts.climatechange.gov.au/

6.3.2 Other sectors

For sectors with fugitive methane not coming out of a discharge point, it is recommended that two to three methane monitors and meteorological stations are installed at suitable locations, on masts at least 10 metres in height but tailored to capture emissions from a facility. The placement of monitors should be optimised based on local meteorology to maximise the opportunity for the monitors to capture emissions from a facility. Suitable locations are often on two opposite sides of a facility, based on prevailing meteorology, to obtain upwind and downwind measurements.

Some facilities may have site-specific factors that make it difficult to do monitoring and estimate fugitive emissions. This may include limited suitable locations to place monitors, proximity to other methane sources, and local terrain and meteorology.

Facility-level monitoring and associated emissions estimation will be considered by the EPA once regional monitoring networks have been established and operational.

6.4 Top-down modelling

Top-down (inverse) modelling is a widely used method to infer emissions and their spatial distribution based on atmospheric observations. It is used to compute the atmospheric transport of emissions from the source to a monitoring station. Top-down modelling combines measured greenhouse gas concentrations with known meteorological and chemical transformation models, to estimate the sources and rates of emissions from an activity or process. These modelled results can then be compared with NGER inventories, and any facility-reported emissions to help verify greenhouse gas estimates.

Ideally, atmospheric modelling should be conducted annually to estimate emissions. Inputs to the model will be from measured methane concentrations and meteorological parameters from the facility-level monitors and regional networks. Due to the complexity of using fit-for-purpose models and accurate parameterisation, most facilities will not have the skills in-house and will need to rely on skilled modellers or atmospheric scientists.

The NSW Government will be working with experts to further develop methodologies for inverse, top-down, modelling.

6.5 Other considerations

The other considerations for facility-level fugitive methane monitoring and emissions estimation are:

- **Transparency in reporting**: measured data and emissions estimates should be made public. Data transparency is critical for quality assurance and quality control, and it enables targeted emissions reduction.
- **Independent verification**: reported emissions are independently verified. This may be targeted to a portion of facilities, for example the top 10% highest emitting facilities. Independent verification enhances accuracy, robustness and defensibility of emissions estimates.
- **Mobile monitoring:** develop mobile monitoring capability to enable verification campaigns and scans of target areas to identify major fugitive methane emission sources.

The EPA is working with experts to explore monitoring techniques such as mobile monitoring. The 2023 study in Western Sydney is an example of mobile monitoring across an area with EPA-licensed facilities, unlicensed facilities, and the potential for natural sources of methane emissions.

7

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8

Abbreviations

Table of Abbreviations

Abbreviation	Meaning
ANGA	Australia's National Greenhouse Accounts
AERMOD	AMS/EPA Regulatory Model
CEM	Continuous emissions monitoring
CER	Clean Energy Regulator
CEOS	Committee on Earth Observation Satellites
CMAQ	Community multiscale air quality
CRDS	Cavity ring-down spectroscopy
CSG	Coal seam gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCCEEW	Department of Climate Change, Energy, the Environment and Water
EF	Emission factor
EPA	Environment Protection Authority
EMIT	Earth surface mineral dust source investigation
GNS	Gas measurement network
HYSPLIT	Hybrid single-particle Lagrangian integrated trajectory
IEA	International Energy Agency
IMEO	International Methane Emissions Observatory
IPCC	Intergovernmental Panel on Climate Change
LDAR	Leak detection and repair
LiDAR	Light detection and ranging
LULUCF	Land use, land-use change and forestry
NGER	National Greenhouse and Energy Reporting
NIR	National Inventory Report
NOAA	National Oceanic and Atmospheric Administration
NSW	New South Wales
PEM	Periodic emissions monitoring
STILT	Stochastic time-inverted Lagrangian transport
SRON	Space Research Organisation Netherlands
TCCON	Total Carbon Column Observing Network
TROPOMI	TROPOspheric Monitoring Instrument
UAV	Uncrewed aerial vehicle
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organisation
WRF	Weather Research and Forecasting

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