National Emissions Monitoring Roadmap

The Superpower Institute

Executive Summary

Accurate measurement of greenhouse gas emissions is of critical importance to meeting the internationally agreed climate goals contained in the Paris Agreement. Australia has committed to improving measurement, reporting, and verification of greenhouse gases in a number of international agreements. These include the Global Methane Pledge and the very recently announced International Working Group to develop a Measurement, Monitoring, Reporting, and Verification framework for the gas industry.

Australia has the potential to have world-leading monitoring capability, but lacks core scientific infrastructure required to deliver on its global commitments in the most effective way. This roadmap seeks to remedy this. Relatively minor investments in developing capacity in critical areas will greatly improve Australia's ability to deliver upon those commitments, and allow the nation to once again lead global progress toward credible, transparent and verifiable greenhouse gas emissions reporting.

Technologies to measure greenhouse gas emissions are undergoing a step change, with more growth on the way. Initiatives such as the Oil and Gas Methane Partnership, the Steel Methane Partnership and a number of other industry and international agreements have accelerated development of these important tools. The total estimated cost of this new network capability would be $40 million initially for the establishment of the network and related workforce capacity expansion, and $6 million per year for maintenance and ongoing operational staffing. It is vital that Australia ride this wave, rather than allowing itself to be caught by it.

The National Emissions Monitoring Roadmap lays out a plan for the establishment and strengthening of the National Emissions Monitoring Network, an integrated greenhouse gas monitoring network over Australia utilising a mix of ground-based, in situ, and remote sensing, along with satellite measurements in combination with inverse modelling.

This network should have the following features:

- A minimum of 12 new monitoring sites established around Australia, with each measuring methane, carbon dioxide, and nitrous oxide, and ancillary gases.
- In addition, at least four of the new sites should incorporate vertical column measurements (validated with aircraft-based in situ measurements) to measure the primary greenhouse gases (carbon dioxide, methane, and nitrous oxide) to ensure comparability of in situ and satellite data sets and to enable accurate inverse modelling
- The establishment of a central calibration laboratory to propagate calibration, perform quality control over the network and to anchor its data to global standards
- The suite of gases monitored should be reviewed every two years, taking into account need, available technologies, and global monitoring trends, with provision for equipment upgrades to align with global best practice over time.

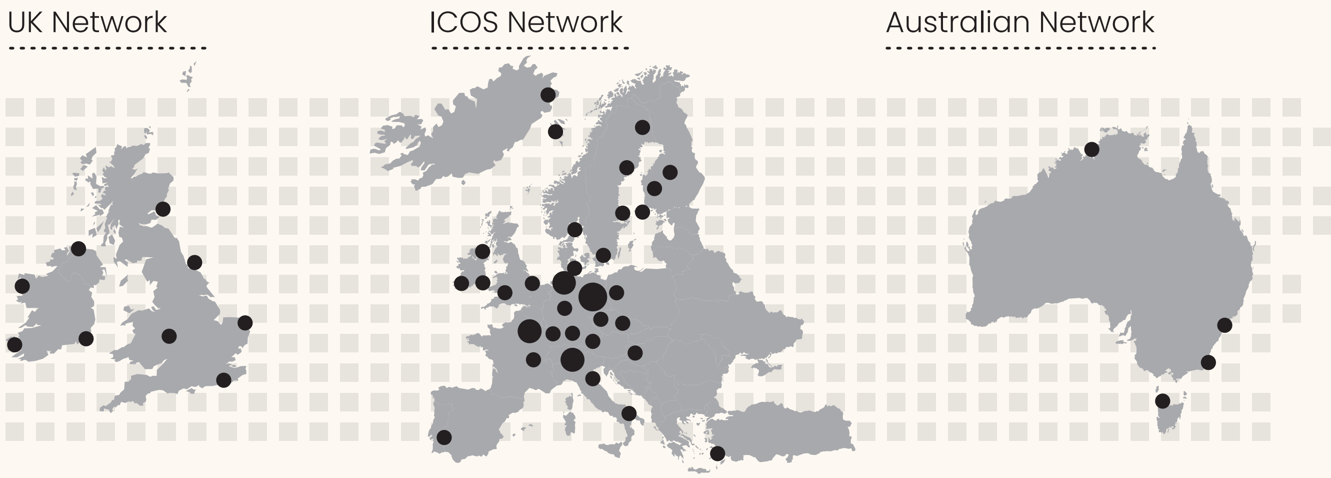
It is essential that Australia's national science agency, CSIRO, play a key role in coordinating the monitoring network and managing the data collected, with maintenance of the network and some elements of the data collection being managed by relevant local partners, including CSIRO, state and territory governments, and the university sector. Data collected through the network should be made freely available both nationally and internationally, and should follow best practices to ensure global comparability.

The proposed monitoring network meets several policy needs:

- **It will increase our ability to verify facility-level monitoring under the National Greenhouse and Energy Reporting Act 2007 (NGER Act)** using regional atmospheric measurements to verify aggregate regional bottom-up reporting. Delivering this roadmap complements the work the Climate Change Authority is currently undertaking on measurement, reporting and verification under that Act.
- **Emissions could more precisely be attributed to their source** sector via measurements of co-emitted tracers. Accompanying targeted mobile and satellite measurements are necessary to evaluate emissions with the granularity required to verify facility-level reporting and identify specific mitigation opportunities. This is immediately relevant for ensuring that the Safeguard Mechanism delivers on its important goals.
- **Australia will better be able to track progress toward its legislated commitments under the Paris Agreement.** Improving the top-down picture of Australia's greenhouse gas emissions would play a vital role in verifying Australia's reported emissions and greenhouse gas inventory.
- **Precise knowledge of Australia's emissions would allow cost-effective mitigation providing a strong return on investment in the network.**
- **Carbon dioxide uptake from offsets would be able to be estimated more reliably,** with implications for evaluating the climate benefits and commercial viability of sequestration projects.

It also **improves Australia's ability to contribute to global climate and greenhouse gas monitoring.** Our existing network currently lags behind comparable greenhouse gas monitoring networks in Europe and the UK.

Greenhouse Gas Monitoring Networks



UK Network
- 9 sites
- 0.24 million km²
- 1 site per 0.03 million km²

ICOS Network
- 40+ sites
- 4 million km²
- 1 site per 0.1 million km²

Australian Network
- 4 sites
- 7.6 million km²
- 1 site per 1.9 million km²

Figure 4; page 18: Greenhouse Gas Monitoring Networks

Improvements are needed to the NGER Act to incorporate empirical measurement data at both source and site level. These measurements should be required of operators, with independent verification run by scientists. The proposed NEMN will allow verification of regional emission totals from key emission areas. For facility specific reporting and verification, more targeted measurement approaches such as airborne and ground-based mobile surveys are required to provide the empirical evidence needed to evaluate compliance with regulations and identify mitigation opportunities.

This proposal builds on Australia's existing strengths in greenhouse gas monitoring, including a dedicated Atmospheric Composition and Chemistry Group within CSIRO Environment, expertise within the Bureau of Meteorology, and world-leading research groups within the University of New South Wales, the University of Wollongong, The University of Melbourne, and Swinburne University. By expanding the existing network of four monitoring sites to a total of at least 16, Australia will have the data needed to robustly measure greenhouse gas concentrations across the continent.

The network will be supported with a state-of-the-art modelling system to transform the concentration measurements into emissions. Australia has been a world leader in this form of modelling for three decades, pioneering the use of satellite data and the continuous in situ measurements made by the network (Rayner & O'Brien, 2001; Law et al., 2002). The same modelling approaches will also guide the optimal placement of stations in the network to maximise information on emission (Ziehn et al., 2016).

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Background

Greenhouse gas measurement and monitoring

Long-term, high-quality atmospheric observations have played a key role in our understanding of large-scale greenhouse gas cycles and the role of these gases in driving climate change. Through atmospheric monitoring we have measured the rise in atmospheric carbon dioxide concentrations and the behaviour of methane concentrations, and through isotopic analysis have unequivocally identified that this increase is due to human activities such as burning fossil fuels (Hmiel et al., 2020). Monitoring has also identified large terrestrial carbon dioxide and methane sinks such as the northern hemisphere forests, and shown that these natural sources and sinks behave differently as a result of large-scale climate patterns such as the El Nino Southern Oscillation, with implications in the future should these patterns change as a result of climate change (Bastos et al., 2018; Dannenberg et al., 2021; Keenan & Williams, 2018).

Monitoring networks should have a broad capability, including mixed-source greenhouse gases such as carbon dioxide, methane, and nitrous oxide, novel synthetic greenhouse gases such as chlorofluorocarbons and their replacements, and air quality particulates. Increasingly, these networks are focusing on anthropogenic emissions, as well as understanding the natural cycles of carbon dioxide and methane.

Until recently, greenhouse gas monitoring consisted only of ground stations. Since around 2010, satellite measurements have also been used to support these monitoring activities and to cover gaps in the ground station networks. As the costs of monitoring equipment have reduced over time, the density of monitoring networks has increased in many parts of the world, supporting monitoring and reporting for UNFCCC processes as well as other domestic climate and air quality policy outcomes. This has also been driven by the diversifying technologies available for atmospheric monitoring, ranging from ground-based to satellite, which each have complementary capabilities. Ground-based remote sensing measurements such as the Total Column Carbon Observing Network (TCCON) provide an essential link between satellite and surface measurements that can ensure that all observations are linked by the same measurement scales and are therefore consistent.

Existing monitoring capability in Australia

Australia's existing greenhouse gas monitoring system comprises four sites ground-based in situ measurement sites, two with accompanying total column measurements. However, there are a range of strong capabilities and expertise that can be called upon to support and complement the development of an expanded greenhouse gas monitoring network. These include a dedicated Atmospheric Composition and Chemistry (ACC) Group within CSIRO, science capability within the Bureau of Meteorology, and air quality monitoring systems through state EPAs. Australia is also host to several world-leading university research groups with relevant expertise, particularly at the University of New South Wales, the University of Wollongong, The University of Melbourne, and Swinburne University.

Existing regulatory environment in Australia

Australia is a party to several agreements and commitments in relation to greenhouse gas emissions. In its updated Nationally Determined Contribution under the Paris Agreement, Australia has committed to reducing its greenhouse gas emissions to 43% below 2005 levels by 2030. This commitment covers all sources and sinks of anthropogenic emissions of carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride and nitrogen trifluoride. The monitoring of emissions of species such as HFCs is also a requirement of the Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer, which Australia has accepted (United Nations, 2016). Furthermore, all the states and territories in Australia have committed to net zero by 2050 or earlier, with interim targets combined amounting to a 37 to 42% reduction on 2005 emissions Australia-wide by 2030 (ClimateWorks Australia, 2021).

Australia is also a signatory to the Global Methane Pledge, which seeks to reduce global methane emissions by at least 2020 levels by 2030. This includes a commitment to work towards continuous improvement in greenhouse gas inventory reporting, including working towards the highest tier of IPCC methodologies (Climate & Clear Air Coalition, n.d.).

As a member state of the World Meteorological Organisation, Australia is also a party to international greenhouse gas monitoring efforts including the Global Atmosphere Watch (GAW) and Global Greenhouse Gas Watch (G3W) programmes. These monitoring programmes also support the implementation of the Paris Agreement by providing top-down input into elements such as the Global Stocktake and Enhanced Transparency Framework.

Emissions inventories

The Paris Agreement and the Montreal Protocol are predominantly based on reported emissions. However, the actual success of these treaties in reducing emissions of greenhouse gases and ozone-depleting substances depends not on what is reported, but on what is actually emitted into the atmosphere. Ensuring that the reported emissions are as close as possible to actual emissions is therefore crucial to support these treaties and the success of measures put in place to comply with them.

Australia's national greenhouse gas inventory for reporting emissions under the Paris Agreement relies heavily upon bottom-up estimation methods, which can be inaccurate depending on the robustness of the data used or models to calculate the relevant emission factors. For instance, more than 99% of carbon dioxide emissions reported through the NGER scheme rely on emission factors and other analysis of inputs at a facility level, with only 0.4% being reported by way of direct monitoring (Department of Climate Change, Energy, the Environment and Water, 2023). Although the percentage of methane emissions captured by direct measurement is considerably higher at 47% (Department of Climate Change, Energy, the Environment and Water, 2023), a recent report from the International Energy Agency estimated that coal mine-related methane emissions could be underreported based on top-down atmospheric readings and satellite monitoring (IEA, 2023), although we note that the Department of Climate Change, Energy, the Environment and Water contests this analysis (Australian Government Department of Industry, Science, Energy and Resources, 2021a).

On their own, top-down methods also face constraints. For example, satellite monitoring can be unreliable under certain geographic and atmospheric conditions, and may not be available at a suitable resolution for facility-level monitoring. As a result, emissions inventories can have significant uncertainties, as demonstrated in Figure 1 which shows changes in Russia's reported emissions of methane from its energy sector (over page, top), and in the US's carbon dioxide emissions from industrial processes (over page, bottom).

Revisions in reported Energy CH_4 emissions: Russia

Official international reports submitted 2006-2022

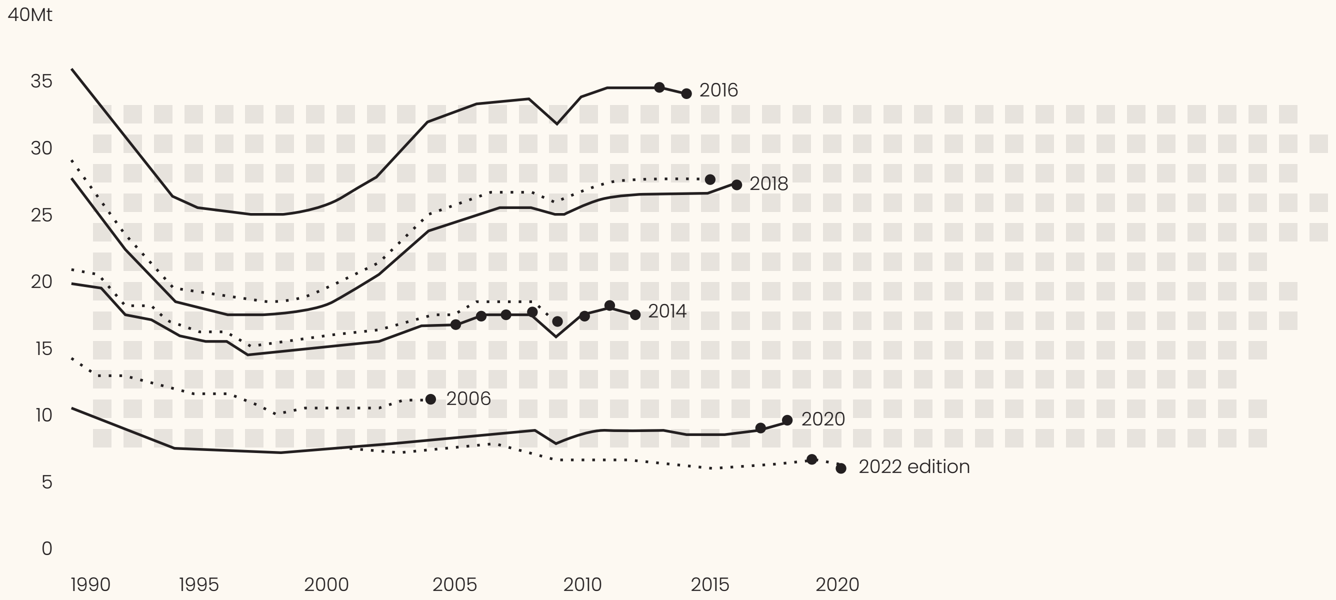


Figure 1.1: Revisions in methane and carbon dioxide emissions (Peters et al., 2023). Data: UNFCCC.

Revisions in reported IPPU CO_2 emissions: USA

Official international reports submitted 2003-2022

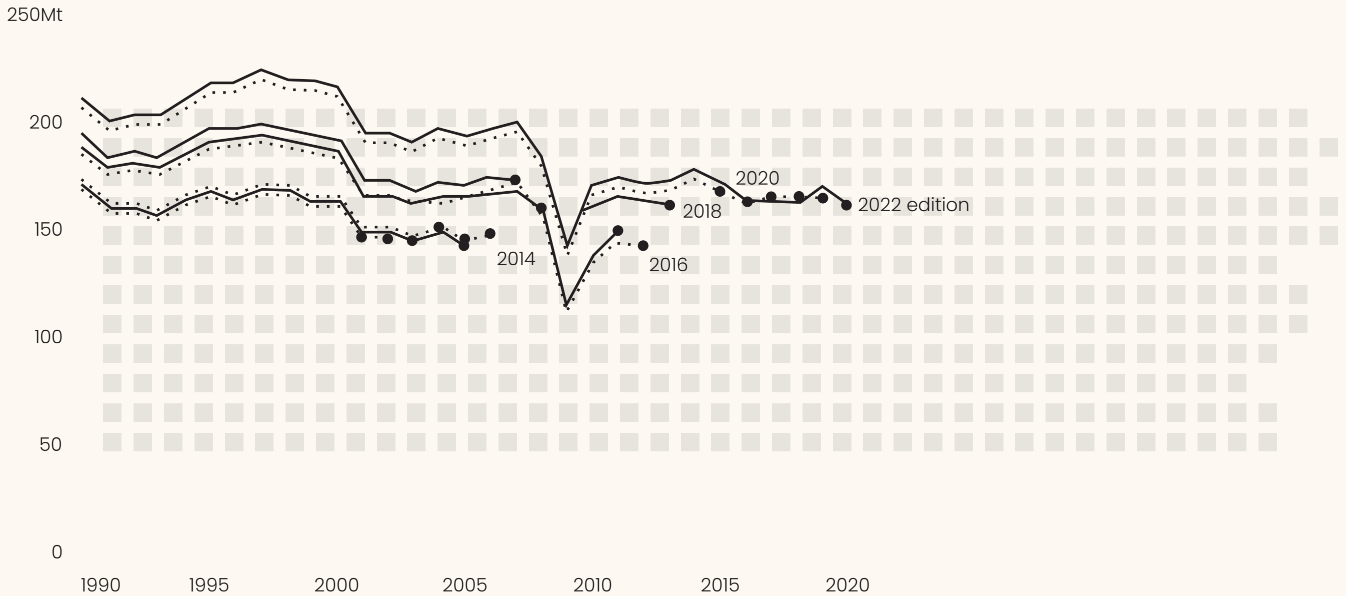


Figure 1.2: Revisions in methane and carbon dioxide emissions (Peters et al., 2023). Data: UNFCCC.

A consistent approach using multiple complementary data sources for comparison and integration is therefore essential to ensure that Australia's national emissions data are robust. This also serves a valuable role in supporting verification of facility-level emissions reporting under national programs such as NGERS and the Safeguard Mechanism.

Verification

Monitoring atmospheric concentrations of greenhouse gases is important to provide an independent estimate of emissions. Depending on the type and scale of measurement platform or network, atmospheric monitoring can be used to assess large-scale emissions such as the accuracy of the national inventory and impact of national and international policies (Henne et al., 2016; Lunt et al., 2021), down to smaller scale monitoring that can be used to evaluate the accuracy of individual asset-level reporting and the compliance with regulations (Pühl et al., 2023).

National-level verification depends on long-term near-continuous monitoring from ground-based networks and/or satellites that can detect emissions from broad regions over a number of years. Since these measurements are sensitive to measurements across a wide area, they 'see' the sum of all sources, and can be used to determine total emissions of each gas for comparison with the national inventory. For example, using data from a network of measurements on telecommunications towers, the UK provides an annex to their annual UNFCCC submission that presents a verification of their reported emissions for all principle greenhouse gases (Brown et al., 2023). Australia currently performs a similar verification for F-gases (synthetic greenhouse gases such as chlorofluorocarbons (CFCs) and their replacements), albeit with relatively high uncertainty due to sparse measurement coverage (Dunse et al., 2022). Additional examples from Australian and internationally are summarised in Table 1 (over page).

Table 1: International examples of the use of atmospheric measurements in national-level emissions verification (adapted from Peters et al., 2023)

Country	Gases	Notes
Australia	HFCs, sulphur hexafluoride	HFCs and sulphur hexafluoride estimates done by CSIRO based on observations at the Cape Grim Baseline Air Pollution Station in Tasmania
	Methane (one year, one region) .	In 2019, the CSIRO undertook analysis of methane plumes in the Surat Basin, Queensland, using two flux towers to obtain a 'top-down' estimate of methane emissions, and the regional estimate was within 10% of the top-down estimate
Germany	Carbon dioxide, methane, nitrous oxide	Verified with the help of the data sets recommended by the 2019 IPCC Refinements: EDGAR inventory, ECMWF's CAMS inverse-modelling data, Pollution Release and Transfer Register (PRTR), EU's ETS.
New Zealand	Methane (regional)	Inverse modelling was tested on regional and national emission estimates for 2011 to 2013 and 2018 using two observing stations. For the South Island results were reasonable, but more observations & research is required. The North Island results are not as robust.
Switzerland	HFCs, sulphur hexafluoride	Selected observations from Jungfraujoch are used with a simple formula to estimate emissions, with a discussion of divergences for each species.
	Methane, nitrous oxide	Inverse modelling used to validate total Swiss methane and nitrous oxide emissions, particularly the spatial extent, using Swiss observations. Due to variability and uncertainty, it is not possible to validate the reported emissions.
UK	Carbon dioxide, methane, nitrous oxide, HFCs, PFCs, sulphur hexafluoride, nitrogen trifluoride	Inversions are based around observations at Mace Head and supplemented with additional observations since 2012. A dispersion model is used with data from different sites for each species. Results for each species is discussed. Methods for verifying carbon dioxide estimates are being improved.
USA	HFCs	Additional quality control is performed by comparing the emission estimates derived from atmospheric measurements to the bottom-up emission estimates. Given the magnitude of the uncertainties relative to the size of any apparent emission changes, and the limited time-period of the analysis, overall trends in most of the gases are hard to discern with confidence except in the case of HFC-32.

Whilst these large-scale atmospheric monitoring approaches may identify discrepancies in the reported total of national greenhouse gas emissions, they cannot necessarily explain the underlying reason for any differences. Approaches to verify emissions from individual sectors at the national scale are not straightforward. Methods commonly rely on assumptions about the spatial distribution of emissions within a country (Pison et al., 2018) or exploit some inherent tracer (such as the $\delta^{13}CH_4$ isotopologue for methane) which has a different emissions ratio from different source sectors. The development of these methods remains an active area of research.

Measurements that focus on specific regions or source sectors are another approach to verify emissions from specific source sectors. These measurements may be from ground-based, aerial or satellite platforms, and need to be of sufficient detail or resolution to be able to attribute emissions to a specific source, or source sector. Where these cover a statistically representative sample, they have the potential to be used for comparisons at national levels. For example, regional level studies, such as those conducted in the Surat basin, allow broader conclusions on the larger-scale reporting of emissions from sectors such as coal seam gas to be inferred (Luhar et al., 2020; Neininger et al., 2021). This case study is discussed further at the Appendix.

Recent top-down estimates of greenhouse gas emissions in Australia prompted the Department to review the inventory methods for open-cut coal mines in Queensland (Australian Government Department of Industry, Science, Energy and Resources, 2022; Deng et al., 2022; Sadavarte et al., 2021). In particular, the results from Sadavarte et al. (2021) showed that their satellite-based estimates of methane emissions from Queensland coal mines were significantly higher than those reported to the Australian government for two of their three study locations, especially at the open cut (surface) coal mine. In response to these studies, the Department stated (Australian Government Department of Industry, Science, Energy and Resources, 2022):

> *“The Department believes that the new satellite data is valuable and opens up new possibilities to test and improve the emission estimates reported in national greenhouse gas inventories.”*

The review of inventory methods led to the development of an “improved” method (Australian Government Department of Industry, Science, Energy and Resources, 2022). This improved method includes a 38% increase in the methane emission factor for open cut coal mines in Queensland (increased from 1.20 to 1.65 CH4 m3/ tonne of coal produced). Overall, the improved method led to an average annual increase of 44% (1.6 Mt CO2-e per year) in methane emission estimates from Queensland open-cut coal mines over the 1990 and 2021 time period, which was equivalent to 0.3% of Australia’s total national greenhouse gas emissions (Figure 2).

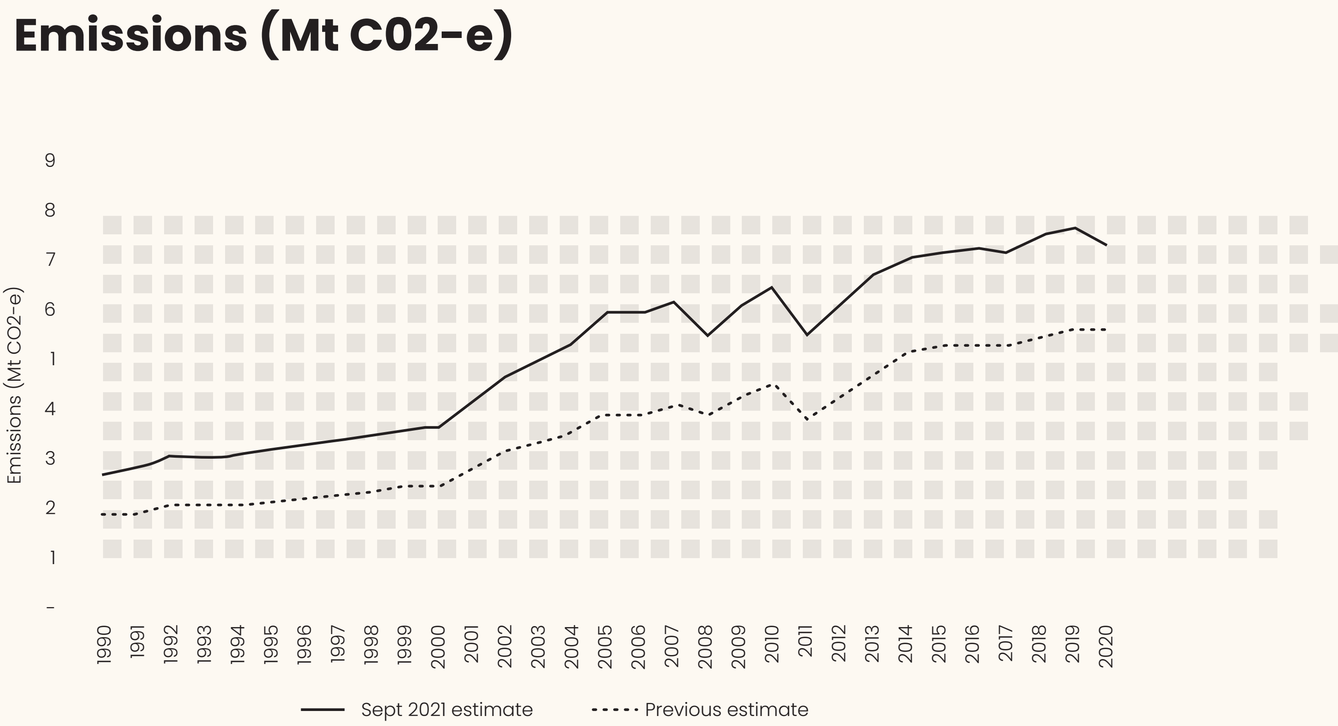


Figure 2: Estimates of Queensland open cut mine emissions (Mt CO2-e) as reported in the National Greenhouse Accounts using a revised (September 2021) method (blue line) and previous method (orange line) (Figure ST2, Australian Government Department of Industry, Science, Energy and Resources, 2022). The revision of the method by the Department was driven by the emergence of satellite methane measurements and associated ‘top-down’ estimates of methane emissions in Australia (Deng et al., 2022; Sadavarte et al., 2021)

A multi-scale observing system, incorporating surface network, ground and satellite based remote sensing, and targeted aerial measurements, has the potential to not only verify emissions on regional and national scales, but crucially to identify the cause of any discrepancies for individual source sectors.

Both measurement-based approaches and inventory compilation rely on models of varying degrees of complexity to predict emissions. Inventory approaches may use process models or a predetermined set of equations to convert operational data to an emission estimate. Atmospheric approaches require a model of atmospheric transport to relate observed concentrations to emissions. In both cases, these models introduce uncertainties that should be considered when attempting to reconcile divergent estimates. Improvements in greenhouse gas emission estimates will be maximised using both.

NGER Act review

While this proposal is principally concerned with verification of Australia's methane emissions, it is important to note that in Australia there is currently considerable movement taking place with regard to its corollaries: measurement and reporting. The Climate Change Authority is currently undertaking a legislated review of the National Greenhouse and Energy Reporting Act 2007 (Cth). In light of Australia's commitments under the Global Methane Pledge, and a number of other international developments, the Minister instructed the Authority to pay particular attention to the issue of measurement and reporting of fossil methane under the Act. This review is scheduled and must be concluded by the end of 2023 under the Act.

The Superpower Institute and CSIRO – along with non-government partners at Ember and the Environmental Defense Fund – engaged deeply with the Authority through this review in an effort to ensure that measurement and reporting of methane under the Act is improved. It is important to summarise some aspects of this work here. The full list of recommendations provided to the Authority is available on request.

In order to improve the measurement, reporting and verification of fossil methane in Australia, we consider it necessary to:

- **Urgently increase the availability and use of operator-led source-level measurement.** Technologies to measure emissions from infrastructure are rapidly developing, yet Australia's emissions reporting system is still largely factor-based, with high levels of uncertainty. There is an urgent need to move from factor-based methods toward direct, and ongoing, measurement of sources.
- **Require operator-led site-level reconciliation measurement.** Operators should be required to reconcile the aggregate of their source-level measurements with site-level measurement in order to ensure that all sources are being appropriately incorporated.
- **Remove general prohibitions on the publication of data provided to the Clean Energy Regulator and dramatically increase the amount of data that is routinely provided from annual reports.** At present, a general prohibition on the publication of emissions data provided to the Regulator prevents independent verification of this information by third parties, with only the highest-level information being available. This restriction is inappropriate, and goes far further than comparable regimes around financial disclosures. It should be lifted.
- **Improve federal-state coordination to align research, policy, funding and law across scales.** The Federal Government should invest to establish this coordination capacity in a central agency along with methane policy coordination to ensure scientific methane emission pathways are reflected in law. The overall goal is to align funding, policy, and coordination to ensure accurate methane measurement, emissions limits, and mitigation across the country.
- **Develop an independent verification program for coal, oil and gas facilities, as well as other sources of methane emissions in Australia.** Alongside the contents of this proposal, the government should require the Clean Energy Regulator to undertake or fund independent verification campaigns, such as those run by scientists from the United Nations' International Methane Emissions Observatory (IMEO).

Improving Measurement

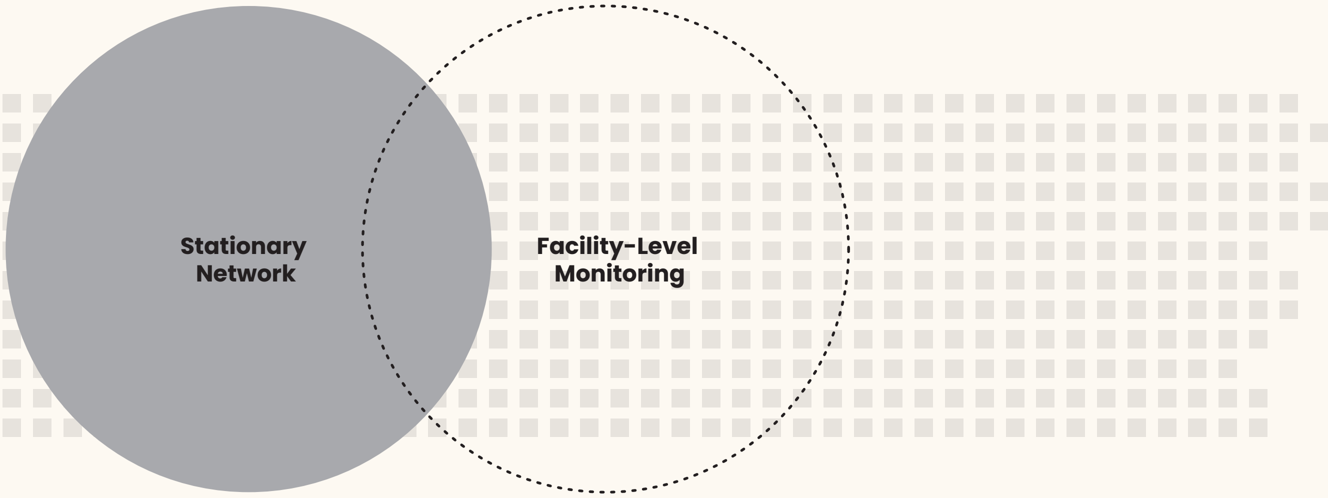


Figure B: Improving Measurement

It is important to note that the development of a stationary network does not reduce the need for facility-level monitoring, but rather complements it. Indeed, the use of independent, top-down methods provides an important assessment of the accuracy of the national inventory methods. This can provide insights to improve the inventory, including, but not limited to atmospheric methods being sensitive to emissions that are missing from the inventory. Australia's capacity to reduce its emissions will be determined by its ability to monitor emissions. The scaling up of the scientific infrastructure and expertise required to routinely complement the national inventory will help steer a path towards cost-effective and defensible greenhouse gas emissions mitigation.

Similarly, in its submission to the Climate Change Authority's consultation on setting, tracking, and achieving Australia's emissions reduction targets, the CSIRO Environment's ACC Group notes:

> *"The combination of 'bottom-up' and 'top-down' methods provides the most accurate and robust emission estimates, and therefore the best possible information to assess and inform climate change policies and investment. This approach is being increasingly used by the international community to verify and improve the accuracy of national greenhouse gas inventories..." (Langenfelds & Caldow, 2023b)*

The ACC Group similarly called for an expanded monitoring network in its submission to the National Science Priorities Refresh (Langenfelds & Caldow, 2023a).

Uncertainties and impacts on policy and science

The climate mitigation challenge is to limit then reduce the net fluxes of greenhouse gases to the atmosphere, with a focus in the short term on more potent greenhouse gases such as methane given the high level of uncertainty (as discussed below). This involves either reducing sources or enhancing sinks. For the major greenhouse gases there are significant uncertainties in key policy-relevant fluxes. A single network using multiple measurement tools can address the critical uncertainties for the two major greenhouse gases, carbon dioxide and methane.

For carbon dioxide the major source is combustion of fossil fuels. In economies with good commercial and national statistical infrastructure the source strength can be derived from shipment, extraction or purchase of fossil fuel. There is a weaker source due to land use change which is highly uncertain. (Intergovernmental Panel On Climate Change, 2023; Friedlingstein et al., 2022). The natural sink is large (about half the anthropogenic source) but diffuse. It is also highly uncertain in space and time, as is its response to climate change. Assessment of such feedbacks remains one of the greatest uncertainties in climate projections, and monitoring it locally is hence a critical contribution to adaptation planning.

Mitigating carbon dioxide emissions is also addressed by interventions which enhance the natural sink into aquatic or terrestrial systems. Mitigation by enhancing sinks suffers the same uncertainty as quantifying the natural sink. This adds considerable uncertainty to markets established to promote sink enhancement and risks the efficiency of sink enhancement as a mitigation approach. Improvement requires quantifying the change in carbon stock at policy-relevant scales and correctly attributing it to an intervention. The change in carbon stock is the time-integrated change in net flux. Our measurement task is therefore to detect changes in net flux which are small and diffuse with enough detail to attribute them to processes. This has implications for the correct determination of the success or otherwise of deliberate interventions (such as through carbon offsetting projects), as well as processes such as bushfires.

For methane the policy-relevant uncertainties relate to sources. Unlike carbon dioxide in which anthropogenic emissions are usually the result of deliberate processes, fossil fuel methane emissions are frequently uncontrolled ('fugitive') and hence poorly quantified by inventory methods. These fugitive emissions dominate fossil fuel emissions (Department of Climate Change, Energy, the Environment and Water, 2023). Such emissions are strongly associated with facilities for extracting and processing methane. A monitoring strategy for facility-level emissions is outlined above under the 'NGER Act review' section. These facility-level observations require support from the national backbone network described here for three reasons.

1. Identification of local sources requires characterisation of the background concentration; that is, the local concentration unperturbed by the local source. This is achieved by measuring the large-scale but locally "clean" concentration, the exact aim of the backbone observations.
2. While the strongest emissions will be associated with facilities, other anthropogenic emissions are much more diffuse but equally uncertain. These include percolation through groundwater after underground operations and leaks from pipelines. Only a large-scale network such as the national backbone can capture these emissions.
3. Since emissions calculated from different facilities must be comparable, the facility-level measurements must be properly calibrated. Maintenance of a calibration hierarchy is one task of the national backbone.

The cost of uncertainty and methane leaks

> *"Compared to the values at risk, the investments and running costs needed for a global greenhouse gas monitoring and analysis network are marginal and would easily provide return due to the improved effectiveness of the science-guided mitigation strategies." (Integrated Carbon Observation System (ICOS) Research Infrastructure, 2022).*

The comparison of top-down and bottom-up (national inventory) emissions estimates in the Surat and Bowen Basins, as discussed in the Verification section above, led to revision and improvement of the national inventory methods. The resulting change in emissions estimates provides an indication of the uncertainty of these estimates.

For the Bowen Basin, the improved method led to an average annual increase of 44% (1.6 Mt CO2-e per year) in methane emission estimates from Queensland open-cut coal mines over the 1990 to 2021 time period, which was equivalent to 0.3% of Australia's total national greenhouse gas emissions (Australian Government Department of Industry, Science, Energy and Resources, 2022). This suggests that prior to the revision of the method, these emissions may have been underestimated by 44% or 1.6 Mt CO2-e per year. As the atmosphere would see the true emissions, this impacts the effectiveness of climate mitigation strategies that may regulate these emissions. Furthermore, if we consider that the cost of undertaking climate mitigation is less than the cost of climate change impacts if mitigations were avoided, then there is also a financial cost (Garnaut, 2009; Stern & Great Britain, 2007).

If for example, these emissions had been overestimated, there is a risk that an unnecessary financial cost may be imposed on the emitters. This is particularly relevant for industries that are covered by the Safeguard Mechanism, or those industries who have set voluntary emissions reduction targets. In these circumstances, such industries may pay to offset their emissions by purchasing Australian Carbon Credit Units (ACCUs) through the Australian Government's Emissions Reduction Fund, which each represent 1 tonne of CO2-e. The current spot price for an ACCU is about $30 (Jarden Australia Pty Ltd, 2023). Therefore, if it were the case that Queensland open-cut coal mines were overestimated by 1.6 Mt CO2-e per year and they were required to offset these emissions, the unnecessary cost imposed on this industry would equal about $48 million per year. These costs over a ten-year period equate to approximately $498 million, which is many multiples of the amount required to setup and operate a National Emissions Monitoring Network for this period.

Initiative	**Price** (million $AUD)
National Emissions Monitoring Network for 10 years	100
Australian Government – Emissions Reduction Fund	4,500
Australian Government – Net Zero	20,000
US Inflation Reduction Act – clean energy	555,000
European Green Deal – first net-zero continent (by 2050)	c.a. 1,600,000
Global investment required to reach net zero	>100,000,000

Table 2: The cost of establishing a National Emissions Monitoring Network relative to other climate change related investment. The effectiveness of this investment would be enhanced by Australian and international greenhouse gas observing networks.

The White House recently released a fact sheet that stated “Methane leaks amount to billions of dollars’ of wasted natural gas every year” and that “proposed leak-reducing actions will create 10,000 net direct and indirect jobs each year” (The White House, 2023). In Australia, fugitive emissions from fuels resulted in 1.1894 million tonnes of methane emissions in 2021 (Department of Climate Change, Energy, the Environment and Water, 2023). If we consider that one tonne of methane is equivalent to 55 Gigajoules (GJ) (US EPA, 2015), and that the wholesale price of gas per GJ is currently about $15 AUD (Australian Energy Regulator, 2023), then these fugitive methane emissions equates to about $1 billion worth of gas per year. If for example, even just 1% of these emissions were able to be reduced this would equate to a saving of $100 million over ten years, equivalent to the amount required to set up and operate the National Emissions Monitoring Network. This is without even considering the other benefits that it would produce for other sectors, and other gases such as carbon dioxide.

Broadening coverage of gases

We now know we are perturbing greenhouse gas concentrations in the atmosphere causing significant climate impacts. There was a sixty-year delay between the first clear statement of the likely perturbation and measurements to demonstrate it. There was a forty-year delay between the production of CFCs and our ability to measure their increase in the atmosphere. One promising mitigation pathway is increased use of hydrogen as a fuel or reductant, substituting for carbon in both cases. Hydrogen may also perturb the atmosphere. It is an indirect greenhouse gas since it increases the atmospheric lifetime of methane and therefore its Global Warming Potential. It may also contribute to ozone reduction in the stratosphere.

To avoid the same kind of delay it is important that hydrogen is monitored in the atmosphere before an increase in production. More generally, any monitoring strategy should be adaptable to potential new monitoring tasks. The value of this is exemplified by the Cape Grim Air Archive where, as new target species are identified, their history can be deduced by re-sampling air collected at regular intervals since 1978.

The most cost-effective path to a flexible monitoring strategy is to strengthen the existing flask sampling programme. This programme affords broad spatial sampling while using only one central state-of-the-art laboratory for potential novel and expensive measurements. If the need arises, continuous in situ sampling can be rolled out as it becomes possible. This approach has been very successful for carbon dioxide and methane.

International networks

The strategy of combining top-down and bottom-up methods has been implemented and expanded by other nations and regions as part of their greenhouse gas accounting systems (as described for example in Deng et al., 2022 and Peters et al., 2023).

As a leading example, Europe’s Integrated Carbon Observation System (ICOS), developed over the last 15 years, now operates 46 long-term, continuous atmospheric greenhouse gas monitoring sites across 14 nations, as well as various mobile monitoring platforms, and the required supporting infrastructure such as central calibration laboratories, and inverse modelling systems targeted to national and regional greenhouse gas emissions determination. It is supported by wide inter-governmental, institutional and industry collaboration and investment, and continues to expand rapidly.

This support has stimulated significant scientific and socio-economic benefits as shown below in Figure 3, including:

1. Delivery of high quality, standardised, freely available greenhouse gas data at increasingly high spatiotemporal scales, across atmosphere, ecosystem and ocean domains (Integrated Carbon Observation System, 2023). This includes half a million datasets downloaded yearly from the ICOS Carbon Portal and 15,000 publications citing ICOS data.
2. Increasing international collaboration across science, government, industry, and policy domains.
3. Community engagement through the development of freely available tools, procedures, webinars, and the organisation of ICOS scientific conferences.
4. Informing policy makers to enable effective science-based climate solutions, including with ICOS being accepted as an official Observer to the UNFCCC in 2019.

Increase in Citations & Publications in Media

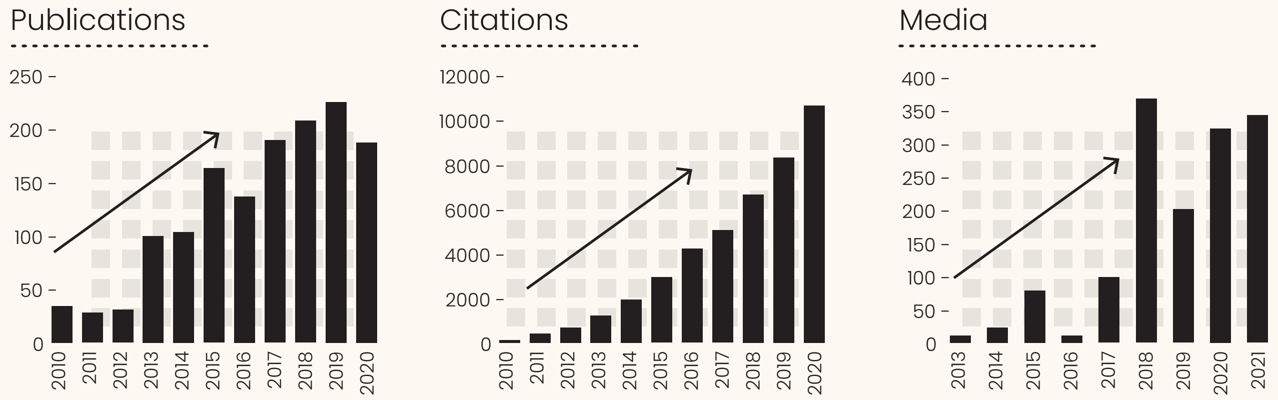


Figure 3: Increase in ICOS-related publications, citations, and mentions in the media from 2010 to 2021.

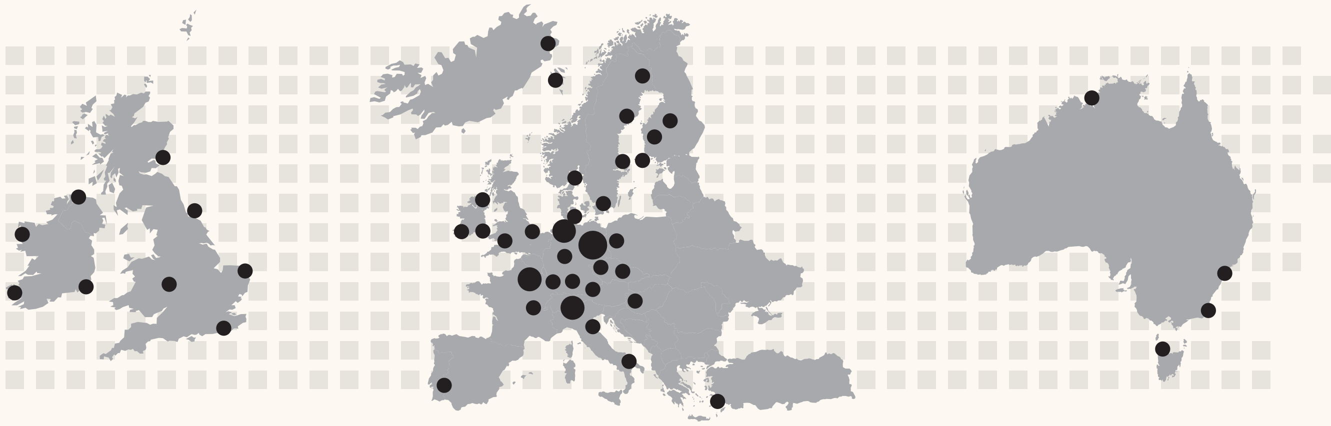
Other examples of nations with substantial greenhouse gas monitoring networks include:

1. The UK which operates 6 sites within the larger ICOS program,
2. The USA with greenhouse gas monitoring conducted using various techniques by multiple federal and state-based agencies; the National Oceanic and Atmospheric Administration (NOAA) alone operates 11 sites with ground-based continuous monitoring, 25 with discrete surface air sampling and 11 with regular aircraft-based vertical profiling (see NOAA Observation Sites website),
3. New Zealand, which is currently adding to its established long-term monitoring program to develop a national network of 17 continuously monitoring sites (Carbon Watch NZ).

The number of sites in ICOS and other international networks dwarfs that in Australia, which has only 4 comparable sites covering a landmass area that is similar to either Europe or the USA (and 29 times larger than NZ). In fact, the European (ICOS) and UK networks are 22x and 47x denser in sites (per unit area) than the Australian network (Figure 4)

Greenhouse Gas Monitoring Networks

UK Network | ICOS Network | Australian Network



UK Network
- 9 sites
- 0.24 million km^2
- 1 site per 0.03 million km^2

ICOS Network
- 40+ sites
- 4 million km^2
- 1 site per 0.1 million km^2

Australian Network
- 4 sites
- 7.6 million km^2
- 1 site per 1.9 million km^2

Figure 4: Greenhouse Gas Monitoring Networks

During 2023 the Nineteenth World Meteorological Congress adopted Resolution 5 (Cg-19) – Global Greenhouse Gas Watch (G3W). The G3W is an ambitious and urgent initiative to significantly strengthen the scientific basis to guide mitigation actions taken by the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. As a Member State to the World Meteorological Organization (WMO), and a Party to the UNFCCC and Paris Agreement, Australia has an obligation to contribute to this initiative, noting "the need to substantially improve geographic coverage of greenhouse gas observations in under sampled regions" (WMO, 2023, pg. 67). With only two current in situ Global Atmosphere Watch (GAW) observatories across the continent at Kennaook/ Cape Grim and Gunn Point, Australia classifies as a significantly under-sampled continent.

The roadmap presents a path for Australia both to address its sovereign need to harness a sound scientific evidence basis for mitigation action and verification, and to contribute significantly to the global enterprise of developing an integrated, sustained, and operational global greenhouse gas monitoring system through G3W. While G3W encompasses ocean carbon cycle observations and direct greenhouse flux measurements (at local scales), the development of ground-based observations is considered the highest priority to deliver the scientific basis for mitigation action. This is closely followed by the need to develop remote sensing and vertically resolved observations of greenhouse gases (WMO, 2023).

Technical requirements

Existing tools and technologies

CSIRO operates a world-class **central calibration laboratory** that has maintained atmospheric measurements of all greenhouse gases on internationally recognised mole fraction (concentration) scales for more than three decades, with strong links to other research institutions globally. This is the cornerstone upon which this network would be built.

Surface-based in situ observations are high precision, continuous observations of concentration, able to be rigorously calibrated across domestic and international networks to ensure cross-compatibility.

Flask sampling is an excellent tool for extending the breadth of observed trace gases, when analysed at a central laboratory on a range of instrumentation (high-precision, well calibrated). Flasks may be filled either routinely (e.g., fortnightly at 2pm on a Wednesday) or when particular criteria for sampling are met. Sampling conditions are often meteorological, but may also be triggered under elevated concentrations to seek covariances with other trace gases to allow source attribution.

Surface based remote sensing provides total or partial column amounts (during the daytime) and are integral to understanding the vertical structure of emitted plumes. Ground based remote sensing measurements provide the ability to validate observations from satellites, and can themselves be validated with well-calibrated in situ measurements using aircraft.

Satellite remote sensing provides broad spatial coverage of total column amounts albeit with reduced precision relative to surface-based observations. In general, satellites are limited to clear sky hours near local noon during each overpass (typically every few days to daily), but can provide measurement coverage in inaccessible or poorly observed regions. A further set of satellite platforms provide high spatial resolution imagery for point-source emissions detection, but have limited swath widths and relatively high detection limits restricting their detections to only the largest point-source emissions.

Mobile observing platforms

- Ground based vehicles equipped with analysers can be useful to survey facilities to regional scales identifying and quantifying emissions hot spots.
- UAVs provide vertical profile information that can be used to quantify emissions at a facility or sub-facility level.
- Aircraft provide wide spatial coverage and vertical profiles and can be used to quantify emissions at facility and regional scales.

From these characteristics, it is clear each of the existing tools can have a role to play for determining emissions. The in situ surface and surface/satellite remote sensing platforms are key to verify emissions across regional, state, and national scales, particularly for the major greenhouse gases. Flask sampling will allow additional constraints on a broader basket of gases as well as isotope constraints for improved sector determination for gases such as methane.

Whilst not part of a core measurement network considered here, mobile observation platforms not only provide a cross-validation dataset but provide additional granularity that addresses specific source sectors and can be used for targeting mitigation. For example, airborne platforms provide better distinction between neighbouring sources that cannot be resolved from broad area observations. Vehicle-based mobile measurements can be used to directly identify urban leaks of methane, and notifications sent to utility companies of leak locations for repairs to be conducted.

Therefore, an optimal observing network that addresses both verification and mitigation would harness all sets of observations.

Technical and infrastructure gaps

While the principal criterion for the siting of new observatories should be determined by optimising the spatial areas of high fluxes (anthropogenic or natural), a key consideration will be available physical infrastructure. Making use of telecommunications tower infrastructure to co-locate atmospheric observations (such as is common in Europe and the USA) provides the benefits of improved sampling height, power and communications.

While Australia has an excellent scientific capacity in atmospheric monitoring, skill gaps to successfully grow a monitoring network on the scale proposed in this roadmap include:

- Technicians to assemble the supporting infrastructure, including production of calibration gases needed.
- Measurement scientists to maintain quality control in observations
- Atmospheric modelling scientists to transform concentrations and column average amounts into flux estimates.

It is important to note that the timescale of this work extends beyond the global 'net zero' target in 2050. Beyond 2050, the necessary 'negative emissions' needed to correct the temperature overshoot will need to be monitored, as will the trends in natural fluxes under a perturbed climate. As such, this roadmap represents a long-term investment in Australia's monitoring capability over a multi-decadal timescale and through multiple phases of the greenhouse gas mitigation challenge.

Network design concepts and roadmap options

Design of a proposed ground-based national observing network is guided by previous network optimisation modelling studies. Ziehn et al. (2016) identified five optimal areas for new in situ measurement sites to supplement the existing non-urban sites useful to regional scale greenhouse gas emissions monitoring applications (Kennaook/Cape Grim, Tasmania [CGO] and Gunn Point, Northern Territory [GPA]). The modelling exercise was performed separately for each of the main anthropogenic greenhouse gases in carbon dioxide, methane, and nitrous oxide. It assessed possible measurement sites on their capacity to reduce uncertainty in prescribed (anthropogenic and natural) flux fields. No consideration was given to monitoring for presently unknown fluxes, or focusing on specific regions or source categories. The pool of potential new monitoring sites was limited to Bureau of Meteorology weather watch radar stations.

Key takeaways from that study are:

1. Additional sites would be most valuable near regions of biologically productive land along the eastern and northern seaboards; this spatial distribution is similar to that of population-based anthropogenic greenhouse gas emissions on the eastern seaboard.
2. Highest ranked prospective areas on the eastern seaboard were inland rather than on the coast.
3. The optimal distribution of sites is similar for the three greenhouse gases. Thus to first order, a single 'combined' network could form the backbone of a national, ground-based monitoring system for all major greenhouse gases.

Key features

The proposed network would use the basic structure determined by Ziehn et al., combined with additional design elements as described below. The selection of specific site locations is informed by transport model analysis of seasonal/annual footprints; that is, showing the frequency at which airmasses pass over neighbouring regions before reaching the site. It is envisaged that sites could be coordinated with existing telecommunications towers (so that air can be sampled from above ground level) and their associated infrastructure (power, logistical access, housing for instrumentation).

A basic network consisting of 4 existing (CGO, GPA and urban sites at Aspendale and Wollongong) and approximately 12 additional sites as displayed in Figure 5 would have the following features:

- National coverage such that sustained fluxes anywhere on the mainland, Tasmania and some smaller islands and offshore industrial facilities will at some times be observed at one or more measurement sites; this would capture signals from presently known fluxes/regions and any sufficiently large contributions not recognised in existing inventories, and would track changes in those fluxes into the future,
- Site density weighted to regions of higher population and biologically productive land,
- A subset of sites located in proximity to major urban areas (ideally approx. 200 km separation for optimal flux estimation by inverse models) to provide frequent observations of what are known to be significant anthropogenic greenhouse gas emission sources in Australia; these sites would also provide opportunity for discrete sampling of time-integrated urban plumes, enabling analyses of trace gas species that are less amenable to in situ measurement but are valuable for apportioning fluxes to different source/sink processes (e.g. 14CH4, some non-methane hydrocarbons, and synthetic gases),
- A subset of sites located to observe outflow from regions with large and/or contested anthropogenic methane emissions, such as coal and gas fields in Queensland and New South Wales,

- Locations of other sites coordinated to satisfy national/regional coverage objectives and to provide boundary conditions for smaller scale targeted emissions measurement campaigns, such as at a facility level.

Proposed Network

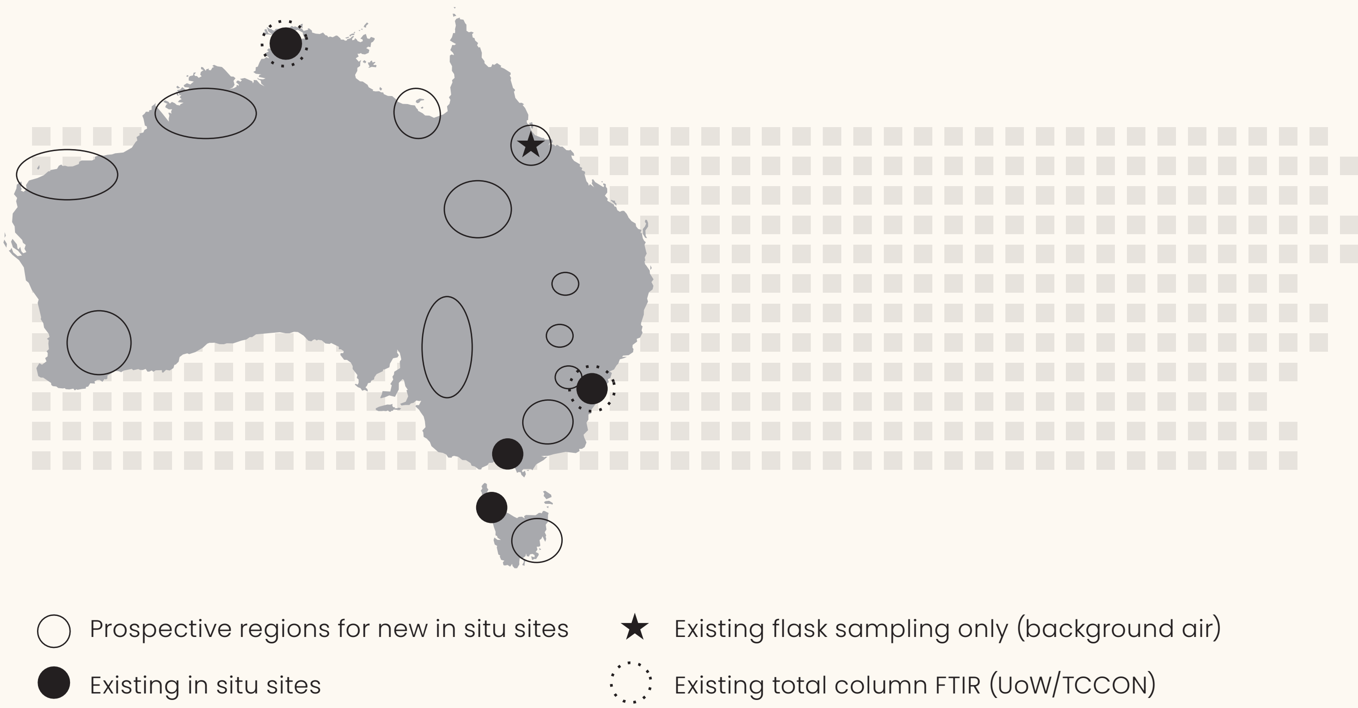


Figure 5: A proposed basic network of ground-based observing sites to provide national/regional coverage of Australia's methane (and other greenhouse gas) emissions.

The network of field sites would be supported by an adequate stock of spare instruments that could variously be used for:

- Prompt replacement of faulty equipment at field sites to minimise data loss,
- Mobile QA/QC of field site operations through temporary deployment alongside working instruments, as is routinely done in the European Integrated Carbon Observing System (ICOS) program (ICOS, n.d.),
- Short term testing of new/ alternate sampling sites,
- Short term atmospheric monitoring near flux regions of interest

Measured gases

Each measurement site would be equipped with a high-precision in situ methane analyser. Deployment of similar instruments for measurement of other gases would be assessed on a cost-benefit basis for individual sites. It is noted here that once site infrastructure is established for methane, there is reduced incremental cost in deploying and concurrently operating other instruments. Indeed, most of the commercially available instruments that are fit-for-purpose for methane monitoring also measure carbon dioxide. There would be value in measuring other gases at most or all these sites. This could include other greenhouse gases that are important in their own right for emissions accounting purposes (nitrous oxide and the synthetic greenhouse gases like CFCs and their replacements), and other gas species that provide extra information to help interpret methane data and attribute fluxes to spatial regions and source/sink processes. Such species include gases that are co-emitted with methane (such as non-methane hydrocarbons, carbon monoxide, and hydrogen) and isotopologues of methane. For example, methane emitted by bacterial (agriculture) and thermogenic (fossil fuel) sources have different isotopic signatures making methane isotopes especially valuable tracers.

In situ measurements would be complemented by vertical column measurements at selected sites, using ground-based remote sensing instruments that measure methane, carbon dioxide, nitrous oxide, and other species of interest. These data would help constrain vertical transport, which is important for flux estimation by inverse methods, and provide ground-truthing of satellite measurements. Total column measurements made from the ground (and validated with aircraft-based in situ measurements) are crucial to ensure the comparability of in situ and satellite data sets and enable accurate inverse modelling. Access to tall towers would provide further quantification of vertical mixing rates through ability to routinely sample air from different above-ground altitude levels.

Costs

There are two broad costs components to the National Emissions Monitoring Network: establishment costs and ongoing maintenance and operations. Based on the costs of establishing and running similar networks internationally, as well as the maintenance of the existing Australian monitoring sites, the estimates costs are as set out in Table 3.

Item	**Cost** (AUD, 2023 figures)
Establishment (Including equipment costs, freight, and technical labour force)	$40 million
Annualised maintenance and operations (Including calibration, instrument upgrades as required, and the maintenance of an appropriately qualified technical labour force)	$6 million
Estimated total cost over the forward estimates	$60 million

Table 3: Estimated cost of establishing and maintaining the National Emissions Monitoring Network.

Recommendations

Recommendation 1: Development and maintenance of a core background greenhouse gas monitoring network

Australia should construct a backbone network of in situ and ground-based column measurements of key greenhouse and related gases to monitor local and national mitigation strategies, which should be planned to be in place throughout the nation's transition to net zero emissions.

This network should include the following elements:

- A minimum of 12 new monitoring sites established around Australia as proposed at the 'Network design concepts and roadmap options' section, with each site capable of monitoring methane, carbon dioxide, and nitrous oxide (and co-emitted gases such as non-methane hydrocarbons, carbon monoxide, hydrogen, and synthetics), together with isotopes.
- Total column measurements made from the ground (and validated with aircraft-based in situ measurements) for methane, carbon dioxide, and nitrous oxide at least four of the sites to ensure comparability of in situ and satellite data sets and to enable accurate inverse modelling.
- The establishment of a central calibration laboratory to anchor its data to global standards and to perform quality control over the network.

The suite of gases monitored should be reviewed every two years, taking into account need, available technologies, and global monitoring trends.

Recommendation 2: Data collection and availability

Data collected through the network should be made freely available both nationally and internationally, and should follow best practices to ensure global comparability.

Recommendation 3: Network coordination and upkeep

It is essential that CSIRO plays a key role in coordinating the monitoring network, ensuring rigorous calibration across the network and managing the data collected. Maintenance of the network infrastructure and data collection should be managed by relevant local partners, which includes CSIRO, universities, and existing state-based air quality monitoring networks

Appendix – Surat Basin case study

The top-down estimates of methane emissions in the Surat Basin provided by Luhar et al. (2020) enabled the Department of Industry, Science, Energy and Resources (the Department) to conduct a comparative analysis between bottom-up (national inventory) and top-down methods (Australian Government Department of Industry, Science, Energy and Resources, 2021b). The Department's analysis showed that the methane emissions determined using national inventory (bottom-up) methods were 17.7% and 7.7 % higher than those determined by the top-down methods, for the subdomain covering the coal seam gas (CSG) development areas in the Surat Basin, and the greater Surat Basin study domain, respectively.

In their analysis, the Department noted that the Luhar et al. (2020) study was "especially valuable" and that by comparing bottom-up and top-down emissions estimates, that the "set of methods used to estimate methane emissions in the Australian Government's National Inventory Report 2021 (forthcoming) are well-supported by independent analysis undertaken by the CSIRO and reported in Luhar et al 2020" (Australian Government Department of Industry, Science, Energy and Resources, 2021b). It is important to recognise that the relatively good agreement between the two methods is due in part to the updates to national inventory methods used to estimate methane emissions from CSG, which occurred between 2015 and 2021 (per Table 3 below). This is reflected in the following statement by the Department in their analysis (Australian Government Department of Industry, Science, Energy and Resources, 2021b):

> *"The good fit is partly the result of recent improvements in estimation methods for CSG production in the national inventory, which have led to a more than doubling of estimates of emissions from this source in the Surat Basin since 2016."*

This provides a clear indication of the uncertainty involved with these methods, and the importance of utilising independent top-down down methods to assess and improve the national inventory methods.

Bottom-up method	Methane emissions (x106 kg CH4 yr-1) from CSG operations
(1) – National inventory 2021 methods	46.8
(2) - Katestone inventory in Luhar et al. (2020) (analogous to national inventory 2015 methods for CSG)	16.5
Difference (1) – (2) %	+183.2%
Ratio (1) / (2)	2.84

Table 4: Bottom-up methane emission estimate for CSG operations in the Surat Basin for 2016 (adapted from Table ST2, Australian Government Department of Industry, Science, Energy and Resources, 2021b). These bottom-up emissions estimates were calculated using national inventory methods (April 2021) and Katestone 'bottom-up' methods (Luhar et al. 2020). For CSG, the Katestone bottom-up analysis utilised estimation methods from the National Greenhouse and Energy Reporting (Measurement) Determination 2008.

Glossary of acronyms

ACC Group	Atmospheric Composition and Chemistry Group, CSIRO
ACCU	Australian Carbon Credit Unit
CFCs	Chlorofluorocarbons
CSG	Coal seam gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EPA	Environmental Protection Authority
G3W	Global Greenhouse Gas Watch
GAW	Global Atmosphere Watch
GJ	Gigajoule
HFCs	Hydrofluorocarbons
IMEO	International Methane Emissions Observatory
IPCC	Intergovernmental Panel on Climate Change
Mt CO2-e	Million tonnes of carbon dioxide equivalent
NGER Act	National Greenhouse and Energy Reporting Act 2007
PFCs	Perfluorocarbons
TCCON	Total Column Carbon Observing Network
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organization

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