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Measurement, reporting and Verification (MRV) of non-CO_2 greenhouse gases

International Best Practices and Suggestions for China

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Executive Summary

Measurement, Reporting, and Verification (MRV) is a systematic approach to tracking and documenting greenhouse gas (GHG) emissions and emission reductions. *Measurement* refers to the tracking and documenting of data and information on GHG emissions or emissions reductions; *reporting* refers to the sharing of measurement information using standardized methods, processes, and formats; *verification* refers to independent assessments of reported GHG emissions and reductions that are typically carried out by a third-party verification body for impartiality (UNFCCC, 2014; WRI, 2016; USAID, 2018; GMI, 2023).

MRV can be used across all sectors and for all GHGs to track emissions patterns, evaluate programs, and promote transparency. While the specifics of MRV vary by context, it is typically done at the national, organizational, or facility level. Benefits of MRV systems for non-CO_2 GHGs include improving emission inventories; facilitating the development of climate change policies and targets; demonstrating progress towards sustainable development; and providing access to external funding sources for economic growth (GMI, 2023).

This paper focuses on issues and international best practices in MRV for non-carbon dioxide (CO_2) GHGs including methane, nitrous oxide (N_2O), and hydrofluorocarbons (HFCs) in specific industry sectors, and suggests a possible path forward for China in developing and implementing a strong MRV system.

Review of International MRV Systems for Non-CO_2 GHGs

Guidelines from the International Panel on Climate Change (IPCC) are commonly employed to compile and report GHG inventories along one of three tiers. Tier 1 involves simplified analysis and estimations when limited data are available and can lead to high levels of uncertainty in emissions estimates. Tier 2 involves more advanced estimation of specific emissions strategies and industry- and country-specific emission factors, while Tier 3, the most advanced, leverages advanced modeling techniques and/or direct measurements.

Measurement

Methane measurements and emission estimates occur along a spectrum of spatial and temporal scales (National Academies of Sciences, Engineering, and Medicine et al., 2018), from large-scale global assessments of annual emissions to small-scale measurements of emissions from individual sources over short (even instantaneous) timescales. There are two types of methane measurement methods, bottom-up and top-down, which are complementary and evolving in definition. *Bottom-up* methods improve understanding of how methane emissions are generated, help build process-based models, and promote the development of mitigation strategies. *Top-down* methods monitor the spatial and temporal trend of methane emissions and enable rigorous comparisons of results from bottom-up methods (National Academies of Sciences, Engineering, and Medicine et al., 2018). Important sources of methane emissions include agriculture, oil and gas development, coal mines (including active, abandoned, and surface mines), and landfills. Advanced and rapid development of remote sensing technologies for measuring methane in recent years are providing higher-resolution measurements in key sectors such as the oil and gas sector.

Nitrous oxide (N_2O) emissions are quantified by models that rely on emission factors derived from experimental data for specific activities; their accuracy depends heavily on the quality of the data on which they are based. Measuring N_2O emissions through experimentation is complex and entails consideration of diverse sources, including agricultural practices, industrial processes, fuel combustion, and waste and wastewater management, while also requiring a comprehensive understanding of intricate soil and environmental dynamics. Factors such as soil type, humidity, temperature, and nutrient management can influence N_2O emissions, and making accurate measurements requires thorough on-site research and sustained monitoring across various scenarios. N_2O sampling methods can be broken into two broad groups, chamber and micrometeorological, while analysis involves chromatographic, optical, and amperometric techniques.

Hydrofluorocarbons (HFCs), a category of fluorinated gases (F-gases), are commonly used as substitutes for ozone-depleting substances in refrigeration systems or as foam-blowing agents. Their high Global Warming Potential (GWP) makes them potent contributors to climate change; since 2019, the Kigali Amendment to the Montreal Protocol has aimed to phase down their production and consumption. Bottom-up and top-down approaches are also used to quantify HFC emissions. The bottom-up method relies on product inventories and chemical sales data to estimate emissions but are susceptible to errors and manipulation (Nisbet and Weiss, 2010). By contrast, the top-down method employs meteorological data (e.g., wind speed and direction) to project how HFCs are transported in the atmosphere. It is often considered more reliable than bottom-up estimates but is more complex. Further, discrepancies between bottom-up and top-down estimates can be quite large, leading to uncertainty about how effectively the Kigali Amendment's phase-down goals are being met.

Reporting and Verification

The United States Environmental Protection Agency (US EPA) characterizes GHG emissions through two complementary programs: the U.S. Inventory of Greenhouse Gas Emissions and Sinks ("the Inventory") and the Greenhouse Gas Reporting Program (GHGRP). The Inventory provides a comprehensive account of total U.S. GHG emissions across all sectors, including fossil fuel burning, industrial processes, and agriculture, as well as sinks such as carbon uptake and storage in forests, plants, and soils. The GHGRP, established in 2008, requires large emitting facilities across the U.S. to report GHG emissions data and additional relevant information, and covers carbon dioxide, methane, nitrous oxide, and various fluorinated gases. The EPA's web-based Applicability Tool helps facilities determine if they need to report annual greenhouse gas emissions, which are submitted via the EPA's e-GGRT system.

The European Union's Regulation on the Governance of the Energy Union and Climate Action dictates the process and required annual reports covering emissions from a range of sectors including energy; industrial processes; land use, land-use change and forestry (LULUCF); waste; and agriculture. The European Environment Agency (EEA) prepares the EU's official GHG inventory, which is submitted to the UNFCCC each spring and covers emissions dating back to 1990, up to two years prior to the current year. To support engagement and transparency, the EU's Emission Monitoring and Reporting website shares information on monitoring regulations, historical GHG inventories, and climate progress reports. Both the U.S. and EU are considering updating its reporting and verification process and requirements to include greater emphasis on direct emission measurements in the coming years.

In the U.S. state of California, the Mandatory Reporting of Greenhouse Gas Emissions (MRR) regulation mandates the annual reporting of GHG emissions from various sectors including electricity generators, industrial facilities, fuel suppliers, and electricity importers. Data collected under the MRR framework, which is made publicly available each year, is integral to initiatives such as the Cap-and-Trade Program and the California Greenhouse Gas Inventory. The California Air Resources Board (CARB) provides a dedicated Mandatory GHG Reporting website where emissions data from 2008 to 2021 can be accessed.

Review of China's MRV System for Non-CO_2 GHGs

China, as a party to the United Nations Framework Convention on Climate Change (UNFCCC), has complied with its obligation to submit national communication reports on climate change. The Ministry of Ecology and Environment (MEE) in China is responsible for organizing the development of the national GHG inventory and submitting the inventory report to the UNFCCC.

China has adopted the "2006 IPCC Guidelines for the Preparation of National Greenhouse Gas Inventories," signaling a robust and internationally aligned approach. The scope of emissions sources includes six key GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and high-global-warming-potential fluorinated gases like hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The inventory has evolved to encompass a broad array of sectors including energy, industrial processes, land use, land use change and forestry (LULUCF), waste, and agriculture.

Currently, no single organization is designated to compile the inventory and prepare compliance reports; instead, these tasks are mainly outsourced to various research institutions (Feng, 2022), This approach has its drawbacks. Areas for improvement include the transparency of China's inventory reports, completeness of emission sources, and consistency in time-series data. Further, some basic data relies on expert collection or estimation through surveys, which can lead to significant challenges in the continuity of work and data reliability (Feng, 2022).

As China progresses in the establishment of its GHG MRV system, several significant barriers remain. These include insufficient legal and institutional support, which makes the enforcement and standardization of protocols difficult. Additionally, technical guidelines and standards are not yet fully developed, compromising the quality and reliability of collected data. Variability in the capabilities of third-party verification agencies adds another layer of complexity, eroding trust in the data generated. Finally, there is a pressing need for capacity building at both the governmental and enterprise levels to effectively implement and manage the MRV system. These barriers impact the efficiency and credibility of China's GHG MRV system.

Suggestions for China’s MRV System for Non-CO_2 GHGs

By implementing a strong, efficient MRV system, China’s government and industries can strengthen their commitment to combat climate change and foster a sustainable and greener future. We provide several recommendations for China to consider as it refines its non-CO_2 GHGs MRV system.

1. **Identify responsible government agencies and provide institutional support.** The government can identify the specific agencies dedicated to non-CO_2 GHGs, which can then coordinate stakeholder relationships and provide technical support, develop technical guidelines, and regulate policies. Over time, the government can increase funding for the monitoring, reporting, and verification of non-CO_2 greenhouse gas emissions to support the work of agencies, enterprises, and third-party institutions, and improve the quality and efficiency of monitoring and verification activities.
2. **Develop relevant policies and regulations,** including mandatory reporting requirements, financial incentives, and penalties for non-compliance.
3. **Improve standards and technical guidelines** to ensure consistency, accuracy, and reliability of emissions data, build trust and credibility in the MRV system, and enable easier comparison of data with other countries. China should develop sector-specific guidelines, incorporate international standards, enhance data quality, promote transparency, and involve stakeholders in the development process. Pilot projects can test and refine the technical guidelines before widespread adoption, while capacity building programs can provide stakeholders with the necessary skills and knowledge.
4. **Enhance research and development (R&D) for detection and quantification technologies**, such as remote sensing technologies for methane measurement**,** in order to improve the accuracy, efficiency, and reliability of monitoring systems and enable more precise data gathering.
5. **Establish demonstration testing sites for sectors with less mature detection technologies.** This could include sectors like abandoned mines and fluorine industries, where environmental monitoring may be less mature or challenging due to sector-specific complexities. Expanding the application of detection technology and fostering collaboration among government agencies, research institutions, and private enterprises will be key to building a robust and integrated environmental monitoring system.
6. **Improve the reporting and data management system.** Currently, GHG emission reports must be submitted via the Ministry of Ecology and Environment’s environmental information platform, which collects and stores emission data. But this system can be improved to store data in a more consistent and organized manner, as well as incorporate data analysis and visualization functions.
7. **Improve the quality of third-party verification.** Third-party verification helps to ensure that data reported by companies and organizations is accurate and reliable; builds trust between stakeholders, including regulators, companies, and the public; and identifies areas for improvement in emissions reporting and measurement.
8. **Provide capacity building and training.** Skilled personnel are needed to accurately measure and report GHG emissions, as well as verify reported data. Capacity building

and training can align MRV systems across organizations and sectors, and promote the adoption of best practices and technologies.

9. **Monitor and evaluate the MRV system** to identify gaps, inconsistencies, and errors in reported data, which can lead to improvements and adjustments to the system. For example, combining top-down and bottom-up approaches for measurements can help improve accuracy of emission estimates and reduce uncertainties. Monitoring and evaluation can also identify areas where additional capacity building and training are needed, and can provide insights into the effectiveness of emissions reduction policies and programs to inform future policy decisions.

1. Overview

Measurement, Reporting, and Verification (or "MRV," as it is commonly known) is a systematic approach to tracking and documenting greenhouse gas (GHG) emissions and emission reductions. The three elements of an effective MRV framework are described as follows (UNFCCC, 2014; WRI, 2016; USAID, 2018; GMI, 2023). *Measurement* refers to the tracking and documenting of data and information on GHG emissions or emissions reductions. *Reporting* refers to the sharing of measurement information using standardized methods, processes, and formats. *Verification* refers to independent assessments of reported GHG emissions and reductions that are typically carried out by a third-party verification body for impartiality.

MRV can be used across all sectors and for all GHGs to track emissions patterns, evaluate programs, and promote transparency. It is typically done at the national, organizational, or facility level. The specifics of MRV vary by context. This paper specifically focuses on MRV for non-carbon dioxide (CO_2) GHGs including methane, nitrous oxide (N_2O), and hydrofluorocarbon (HFC) emissions and reduction efforts in specific sectors.

By providing accurate and reliable data on GHG emissions, an MRV system for non-CO_2 GHGs can be used in several ways: to improve emission inventories; to enhance the setting of targets and development of policies related to climate change; to demonstrate progress towards sustainable development; and to provide access to external funding sources for economic growth (GMI, 2023).

The development of a robust MRV system can improve emission inventories by reducing uncertainties and improving accuracy. The use of Tier 1 methodologies, which are the most basic and rely on default values, can lead to high levels of uncertainty in emissions estimates. However, by incorporating data collected through MRV activities, which are location-specific and based on bottom-up measurements, these emission inventories can be strengthened.

A strong MRV system can facilitate the setting of ambitious yet feasible emission reduction targets and goals, as well as the development of supporting climate change mitigation policies and programs. MRV has been crucial in helping countries set national GHG emissions reduction targets, evaluate performance, and implement policies related to their Nationally Determined Contributions (NDCs) under the Paris Agreement (Grue + Hornstrup A/S et al., 2018). Although many countries have not yet included specific non-CO_2 reduction targets in their NDCs, these emissions are significant and can greatly contribute to overall emissions reduction goals. A robust MRV system can help countries identify key sources of non-CO_2 GHG emissions and areas of greatest reduction potential, as well as demonstrate their progress towards climate goals.

MRV systems for non-CO_2 GHGs can also support their capture and utilization (e.g., methane), which provides significant economic and social benefits beyond climate. These advantages align with the United Nations' Sustainable Development Goals, such as those for accessible and clean energy (Goal 7) and sustainable cities and communities (Goal 11). MRV systems can provide information to monitor progress towards sustainable development goals.

MRV can also facilitate and increase access to capital to fund mitigation actions for non-CO_2 emissions. Specifically, MRV methods allow for the quantification of reductions, making it easier for developers to demonstrate projects' potential and actual mitigation benefits to potential financiers and funders. MRV is also essential for obtaining funding through carbon markets, whether mandatory or voluntary.

GMI has outlined general principles and best practices for MRV of methane emissions in the biogas sector (GMI, 2023). These can be applied more broadly to support the fundamental requirements of any emissions accounting framework; by utilizing these principles, government agencies can create MRV systems and plans that are specifically tailored to their needs. GMI's principles are summarized below.

1. **Measurement**

   From a bottom-up perspective, the measurement of data is the most critical aspect of MRV, as it forms the foundation for ascertaining emissions reductions from implemented actions. Best practices include:

   - **Developing a measurement plan** that provides facility personnel with a blueprint of key steps, including defining what data and information need to be collected, how the data and information need to be collected, how data are checked for accuracy, and how to aggregate and summarize data to determine the GHG reductions achieved.

   - **Choosing a method for quantifying emissions reductions** to be used at least once per year. The method used for calculation, either ex-ante or ex-post, can vary depending on the reporting program's specific needs and requirements.

     - Ex-ante quantification models and forecasts potential emissions or emissions reductions prior to the project's implementation. These estimates are typically based on assumptions and may have a large degree of uncertainty.
     - Ex-post quantification relies on data collected from the project site and is often necessary for formal emissions reductions reports.

   - **Using established methodologies and tools**, such as those based on IPCC Guidelines for National Greenhouse Gas Inventories or the various tools and resources provided by GMI, for calculating emissions and emissions reductions.

   - **Keeping accurate records and project documentation**, including but not limited to:

     - Emissions reductions data
     - Techniques employed to measure decreases in emissions
     - Types of GHGs covered by the project
     - Activity data and how they are measured
     - Baseline and any underlying assumptions

    - Potential sources of uncertainty
    - Data sources
    - Any missing data associated with the period for which mitigation efforts are quantified.

- **Resolving data gaps and identifying accurate data substitutes** during unexpected interruptions or failures during MRV monitoring. This can be addressed by following program-specific guidelines on how to substitute missing data. When no specific guidance is provided, it is best to use methods that are reasonable, supported by other data from the measurement period, and are conservative in nature. The aforementioned IPCC GHG inventory guidelines offer methods for resolving data gaps by using techniques such as overlap, surrogate data, interpolation, and trend extrapolation. Similarly, for some GHGs such as methane in specific sectors such as the oil and gas sector, following existing international frameworks such as the Oil & Gas Methane Partnership 2.0 (OGMP 2.0) can also resolve data gaps (see section 2.1.1).

2. Reporting

The purpose of reporting is to gather and maintain records of GHG data and share it with relevant parties. Such reports may need to be submitted to national government bodies, local governments, and/or voluntary initiatives and groups. Best practices include:

- **Ensuring that correct project data will be reported** by developing a program to determine the specific type and level of information to be reported. This can include details such as the name and contact information of the project proponent, project location, time frame for emissions reductions, baseline emissions and reductions achieved, and any proposed improvement plans that may be required.

- **Reporting data regularly and consistently** by setting specific reporting requirements. Most programs require reporting of GHG emissions and reductions on an annual basis, in accordance with the standard practice of measuring emissions reductions each year. Some programs may have stricter reporting requirements and may require monitoring data to be submitted more frequently.

3. Verification

The purpose of verification is to ensure the accuracy of the techniques used to measure mitigation efforts and the validity of reported data. It can also help project operators identify areas for improvement. Best practices include:

- **Following the requisite steps and processes**, which generally include:
    - Obtaining initial information and documentation on GHG emissions
    - Conducting strategic analysis

  - Evaluating potential risks
  - Designing a plan for verifying and sampling data based on those risks
  - Reviewing GHG data and documentation
  - Conducting on-site visits
  - Making any necessary clarifications or corrective actions
  - Obtaining additional information and documentation as necessary
  - Issuing a verification statement.

  The amount of work necessary for verification is primarily determined by project-specific factors, how data is handled, and the demands of specific reporting program(s).

- **Ensuring data is verified by a third party and meets existing verification standards**. Having a third-party verification body assess GHG data is recommended to promote impartiality, minimize risks, and enhance the trustworthiness of both the data and any emissions reductions resulting from mitigation actions. Verifications should adhere to a verification standard and established guidelines. The standard can either be the International Organization for Standardization 14064-3:2019 Greenhouse Gases – Part 3: Specification with Guidance for the Verification and Validation of Greenhouse Gas Statements, or a different standard developed specifically for the reporting program or country.

- **Adhering to verification content, frequency, and site visit expectations.** The verification process should include evaluations of the project's boundaries, documentation, on-site inspections, measurement and metering methods, data collection and management systems, and an independent calculation of emissions reductions. Reporting should be done annually, but the frequency of verification can vary, with an initial verification done early in the project's lifespan. Almost all programs require a physical visit during the initial verification period, with the frequency of subsequent visits varying among programs.

2. Review of International MRV Systems for Non-CO_2 GHGs

2.1 Measurement

2.1.1 Methane Measurement

Measurement is key to developing a methane emission inventory. Methane measurements and emission estimates occur along a spectrum of spatial and temporal scales (National Academies of Sciences, Engineering, and Medicine et al., 2018), from large-scale global assessments of annual emissions to small-scale measurements of emissions from individual sources over short (even instantaneous) timescales.

In general, there are two types of measurement/monitoring methods: bottom-up methods and top-down methods. These two methodologies are complementary. Bottom-up methods improve understanding of how methane emissions are generated, help build process-based models, and promote the development of mitigation strategies. Historically, bottom-up methods have relied on efforts to scale-up a limited number of component-level or facility-level measurements to estimate emissions at a larger (e.g., regional or national level) scale (Rutherford et al., 2021). Top-down methods monitor the spatial and temporal trend of methane emissions and enable rigorous comparisons of results from bottom-up methods (National Academies of Sciences, Engineering, and Medicine et al., 2018). These top-down methods help estimate aggregated emissions on a regional scale without resolving individual point-sources (Vaughn et al. 2018). Figure 1 illustrates examples of methane measurement platforms operating across a variety of spatial and temporal scales.

Bottom-up methods include point-source measurements, enclosure (chamber) techniques, micrometeorological techniques, perimeter facility line measurements, external tracers, inverse dispersion modeling, and facility-scale *in situ* aircraft measurements. Top-down methods include remote observatories, towers, aircraft mass balance measurements, aircraft remote sensing measurements, and satellites (National Academies of Sciences, Engineering, and Medicine et al., 2018). For aircraft and satellites, they are often referred to as “top-down” as they conduct measurements by looking down from above, despite being more closely aligned with the historical definition of “bottom-up” methods.

Table 1 and Table 2 summarize these methane emission measurement and monitoring methods, along with their advantages and disadvantages. For a more detailed discussion, consult Chapters 3 and 4 of *Improving Characterization of Anthropogenic Methane Emissions in the United States* (National Academies of Sciences, Engineering, and Medicine et al., 2018).

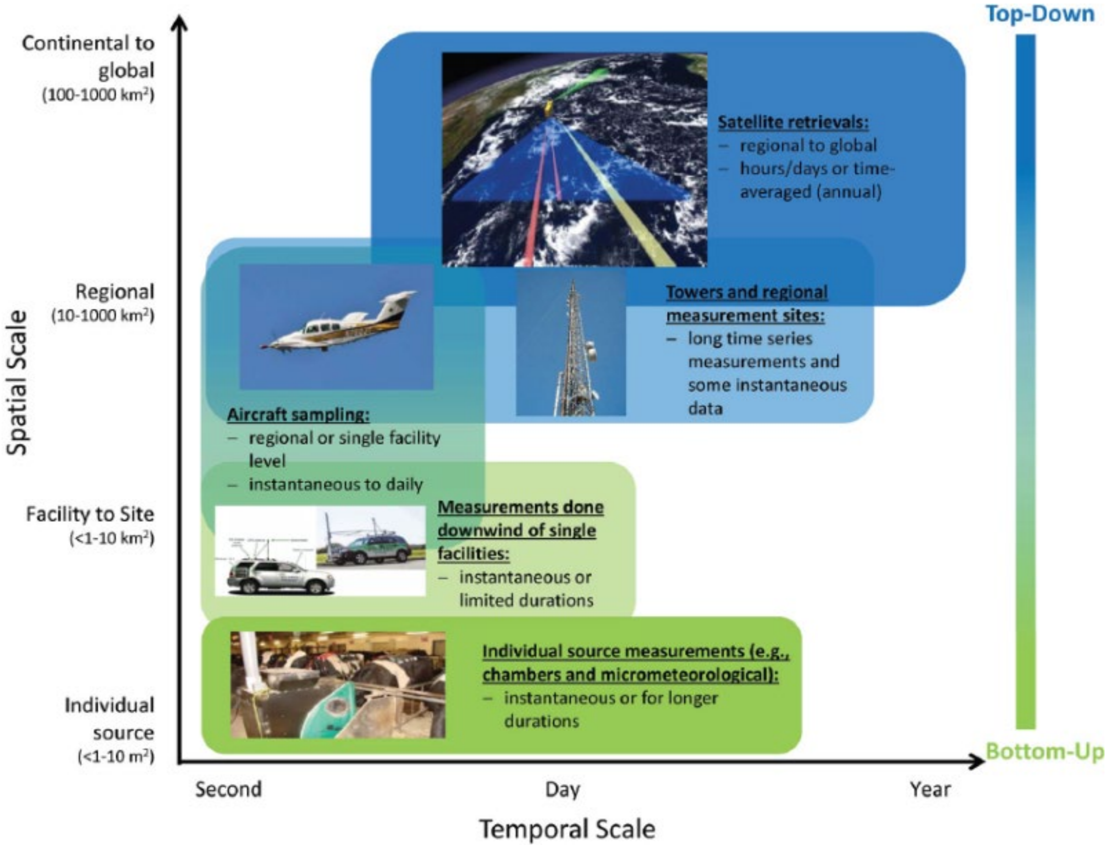


Figure 1. Examples of methane measurement platforms operating across a variety of spatial and temporal scales.

Source: National Academies of Sciences, Engineering, and Medicine et al. (2018), Figure 3.1.

Table 1. Bottom-up techniques for measuring methane emissions

Technique	Applicability	Advantages	Disadvantages
Point-source measurements	Individual point sources	Captures temporal trends if deployed for extended time	Limited number of methane sources are point sources Limited to measurements from “normal” operations Labor intensive to quantify spatial and temporal variability
Enclosure (chamber) techniques	A small source area (individual or small groups of animals)	Quantifies diffusive emission rates during day or night Does not rely on atmospheric modeling to derive fluxes Quantifies soil oxidation of atmospheric methane	Single enclosures may not capture all variability in emissions Instantaneous; must be repeated to capture temporal trends Labor intensive to quantify spatial variability
Micrometeorological techniques	Individual sources/ small open source areas	Captures temporal trends when measured continuously Measures uptake of atmospheric methane	Difficult to measure the variability, may over- or underestimate Reliant on appropriate topographic and meteorological conditions Nighttime measurements are a challenge
Perimeter facility line measurements	Source areas	Capture temporal trends with continuous monitoring	Difficult to isolate the different sources in source area Reliant on appropriate topographic and meteorological conditions Difficult to determine the area contributing to flux
External tracer	Source areas	Measures complex sources or quantifies the uncertainty in the emission estimate	Difficult to isolate individual sources within source area Reliant on appropriate meteorological conditions Vulnerable to bias if the locations of tracer release differ significantly from the location of methane release Labor intensive to measure the spatial and temporal variability
Inverse dispersion modeling	Point and area sources	Captures temporal trends when measured continuously	Difficult to isolate various sources within the source area Reliant on modeled meteorological conditions Regional-scale methods are not fully developed Accuracy may vary depending on the source to be measured

Facility-scale *in situ* aircraft measurements	A source area/facility	Captures temporal trends with repeated overflights Does not rely on the operational status or safety conditions of the facility	Generally cannot isolate individual sources within source area Reliant on appropriate meteorological conditions Requires multiple flights to capture temporal trends in emissions Generally limited to higher-emitting sources Labor intensive to measure the spatial and temporal variability

Note: Table summarizes information in National Academies of Sciences, Engineering, and Medicine et al. (2018), Table 3.1.

Table 2. Top-down techniques for measuring methane emissions

Technique	Applicability	Advantages	Disadvantages
Remote observatories	Regional	High precision Consistent measurements across multiple sites Long time series	Limited spatial coverage
Towers	Regional	High precision Consistent measurements across multiple sites Long time series	Sparse spatial coverage Methods are not fully developed Challenging to apply to individual facilities and distinguish confounding sources
Aircraft mass balance measurements	Regional	Ability to target specific emission source regions and obtain vertical profiles of methane concentrations Analyzed using simple flow-through models and/or sophisticated inversion modeling	Limited spatial coverage Temporal coverage limited to a snapshot Challenging to account for transient plumes through the “box” Labor intensive to measure the spatial and temporal variability
Aircraft remote sensing measurements	Regional	Ability to map methane plumes at the 1-to-5-meter scale; direct source attribution	Limited spatial and temporal coverage Not as accurate as *in situ* data
Satellite	Regional to global	Global, complete spatial coverage; frequent revisit time with a single instrument	Relatively coarse spatial resolution Not as accurate as *in situ* data; emissions not cleanly resolved Limited to sunlit, cloud-free, snow-free scenes

Note: Table summarizes information in National Academies of Sciences, Engineering, and Medicine et al. (2018), Table 3.2.

Since 2018, remote sensing technologies have advanced rapidly and include new and expanded categories. Facility-scale aerial remote sensing technologies that use reflected sunlight can survey hundreds to thousands of sites per day and have demonstrated reliable controlled release testing results, such as Kairos Aerospace and CarbonMapper. Equipment-resolution aerial remote sensing technologies that use light detection and ranging (LiDAR) can survey fewer sites such as Bridger Photonics, but provide greater sensitivities. Higher-resolution area flux mapper satellites such as MethaneSAT can also quantify and aggregate regional methane emissions at square-kilometer resolution. Other key advances include drone-based methane sensing for facility-level measurements, long-path laser tower/reflect networks and point sensor continuous monitoring networks for continuous monitoring.

The advances in measurement technologies are also leading to updates in reporting and verification protocols. More recently, the Oil & Gas Methane Partnership 2.0 (OGMP 2.0), the United Nations Environment Program's measurement-based reporting framework for the oil and gas industry established five reporting compliance levels for participating companies. This ranges from level one, with one methane emissions figure reported for all operations in an asset or all sets within a region; to the most rigorous level 5, which requires the use of site-level measurements to reconcile source- and site-level emission estimates.

Agriculture

Enteric fermentation and manure management are the two sources of methane emissions from livestock. These methane emissions can have large temporal and spatial variability as the emission is driven by microbial activity, which heavily depends on the availability of substrate and other conditions (National Academies of Sciences, Engineering, and Medicine et al., 2018). Thus, to accurately measure emissions, it is vital to ensure that temporal, spatial, and animal variability is captured (National Academies of Sciences, Engineering, and Medicine et al., 2018).

Enteric fermentation

Microbial fermentation-related activities in the gastrointestinal tract of animals generate methane, referred to as enteric methane (for more details, see Hristov et al., 2013). Ruminant animals are the largest contributor to methane emissions from agriculture (National Academies of Sciences, Engineering, and Medicine et al., 2018). They emit methane through eructation, expiration, or flatulence. Techniques for measuring enteric methane emissions from livestock include enclosure chambers, tracer techniques, "sniffer" techniques, and handheld laser methane detectors (National Academies of Sciences, Engineering, and Medicine et al., 2018). The respiration chamber, a type of enclosure chamber, is the "gold standard": when properly calibrated and operated, respiration chambers are accurate, capable of capturing all methane emissions, and can account for diurnal variation. However, respiration chambers are expensive, place animals in an "unnatural" environment, and cannot be used to measure emissions from many large animals simultaneously. The sulfur hexafluoride (SF_6) tracer method is also widely used; it has lower costs than respiration chambers and allows for methane measurements of many animals in their natural environment. While this method once had notoriously high variability (Clark, 2010; Pinares-Patiño and Clark, 2008; Pinares-Patiño et al., 2010), Deighton et al. (2014) significantly modified and improved the technique such that it now produces methane measurements with a similar level of accuracy to respiration chambers.

Manure management

Manure management systems may include open areas for drying, stacking, and composting manure, as well as systems for liquid/slurry storage involving separation bins, mechanical separators, tanks, pits, and lagoons (National Academies of Sciences, Engineering, and Medicine et al., 2018). Emission estimation techniques vary depending on the specific system used. Open-house systems use techniques like mass balance, external tracer methods, inverse dispersion modeling, and micrometeorology. Enclosed barns with mechanical ventilation use mass balance methods. Manure storage systems use external tracer methods, inverse dispersion modeling, micrometeorology techniques, or chambers. Facility-level emissions measurement typically use larger magnitude tools like airplane-mounted sensors or inverse dispersion modeling. Given emissions' temporal and spatial variability in livestock housing and manure management, comprehensive measurements over a longer duration are crucial to accurately capturing temporal and seasonal variabilities in measuring annual emissions levels.

Oil and Gas

Methane emissions from the oil and natural gas supply chain, as reflected in national inventories, encompass multiple sources from the initial stages of oil wells to the final points of fuel utilization. These supply chain emissions explicitly exclude those associated with end-uses, such as emissions of unburned methane from electricity generation (National Academies of Sciences, Engineering, and Medicine et al., 2018).

The diversity of emission sources is reflected in the measurement methods employed. Particularly in the domain of oil and gas, there exists a close connection between activity data and emission factor data (National Academies of Sciences, Engineering, and Medicine et al., 2018). This connection becomes particularly notable when using emissions data to develop average emission factors for entire source populations. Conversely, when emissions patterns display significant variations across different subpopulations, customized and accurate data collection methods are needed. This might involve stratified sampling across distinct subpopulations or covering the entire spectrum of subpopulations to ensure fair representation in the sample. However, the complexity of these methods often presents logistical and technical challenges requiring careful consideration.

In recent years, there has been a pronounced shift in the pattern of emission factor data for petroleum and natural gas systems. Prior to 2013, the derivation of emission factors primarily relied on a comprehensive study conducted in the 1990s by the Gas Research Institute and the U.S. EPA (Harrison et al., 1996). But since then, a series of independent studies has reported updated data about emission factors. These studies have typically been conducted by university-affiliated researchers and supervised by impartial advisory committees, sometimes with the support of industry partners.

The core of these studies is the identification of high-emitting sources that have a disproportionate impact on cumulative emissions (National Academies of Sciences, Engineering, and Medicine et al., 2018). This approach is not limited to a single category and extends across various source classifications. The underlying factors causing certain subpopulations to become high emitters remain unclear, necessitating focused research efforts to uncover the driving mechanisms and consequently develop accurate estimation methods. At the same time, international standards are being developed for leak detection and quantification of methane emissions from oil and gas by Total Energies Anomaly Detection Initiatives (TADI) of the Pôle d'Etudes et de Recherche de Lacq and the Colorado State University Methane Emission Technology Evaluation Center (METEC).

Given the evolving situation, collaboration with facility owners and operators has been increasingly emphasized. These efforts, conducted during measurement campaigns, ensure the convergence of real-time operational insights with data collection, enhancing both the quality and relevance of collected data (National Academies of Sciences, Engineering, and Medicine et al., 2018). China, for instance, already has two satellites, Ziyuan-1 and Gaofen-5, that have demonstrated to be particularly helpful for accurately measuring larger methane-emitting point sources (Sherwin et al., 2023) and can potentially be a data-source for third-party quantification of oil and gas emissions. As part of the Oil and Gas Methane Partnership 2.0 voluntary industry commitment, oil and gas companies are also setting upstream methane intensity targets and reporting data needed to calculate methane emission intensity for different segments of oil and gas production.

Coal Mines

Methane occurs in coal as a result of either thermogenic or biogenic processes. Thermogenic methane forms through chemical and thermal reactions at elevated temperatures, whereas biogenic coalbed methane arises from microbial activity at lower temperatures. The methane content within coal exhibits variations that depend on differences in coalification levels and geological parameters. Lower coalification levels tend to facilitate biogenic methane, while higher levels may encompass thermogenic methane (e.g., Mastalerz, 2014). Deeper coal deposits generally exhibit elevated methane content, whereas shallow coal extracted from surface mining operations tends to possess diminished methane levels. Furthermore, the methane content within coal can vary among distinct coal basins and individual coal beds within these basins (e.g., Strąpoć et al., 2008). These complexities make predicting methane emissions from coal mines a challenge (National Academies of Sciences, Engineering, and Medicine et al., 2018).

Active underground mines

In underground coal mining, activity data such as the count of mines and the amount of coal produced are well-known metrics. Estimating emissions relies on collecting samples from mine ventilation systems and measuring degasification volumes.

In operational underground mines, the primary source of methane emissions is the ventilation system and assessing methane emissions is based on factors such as airflow and concentration. Although measurements of airflow tend to remain consistent, fluctuations in methane content occur due to variations in coal properties and daily coal production levels.

Samples are collected near the main ventilation fans, simultaneously measuring airflow rates. Coal mines also conduct frequent methane emission measurements to ensure safety compliance: methane emissions are typically measured every week using handheld detectors and flowmeters at the mine's ventilation shaft, while continuous monitoring devices alert miners if concentrations exceed a certain limit.

Mines prone to high gas content conduct pre-mining degasification of coal seams as a preventive measure against elevated methane levels. This reduces coal gas content and mitigates the risk of gas outbursts by reducing pressure within rock formations (Karacan et al., 2011; Noack, 1998). Degasification is carried out through horizontal boreholes within the mine or vertical boreholes from the surface, either before or after mining. Horizontal boreholes commonly capture methane, while surface boreholes often release it into the atmosphere. Post-mining wells also recover methane from the overlying rock.

In addition to the assessment methods mentioned earlier, research groups in the United States and other regions have developed various empirical models for underground mines (Kirchgessner et al., 1993; Lunarzewski, 1998). These methods generally require only a few input parameters (e.g., coal production, gas content, and methane emission rate). However, due to the multitude of parameters influencing emissions, the accuracy of these methods is not always optimal (Karacan et al., 2011). To enhance emission predictions from longwall mines, software called "Methane Control and Prediction" was developed. This software employs artificial neural networks in conjunction with statistical and mathematical techniques (Dougherty and Karacan, 2011). It predicts emissions based on various parameters relating to coal attributes, mining conditions, and productivity, and can conduct sensitivity analyses (Karacan et al., 2011).

Abandoned underground mines

Methane emissions can continue to be released from gassy underground mines, even after they are closed. Although these emissions generally decrease compared to the mine's active phase, they can still be significant. Emission levels vary due to factors such as coal gas content, mine flooding, conduits, seal quality, and time since closure. The U.S. EPA developed a method for abandoned underground mines to report annual methane emissions (EPA, 2004). Typically, estimates are based on active-phase emissions and assume a hyperbolic decline post-closure. A key challenge is accurately modeling this decline curve, which requires data for methane adsorption, coal permeability, and abandonment pressure. Mine-specific data inform the development of decline curve equations (Karacan et al., 2011).

Estimates from abandoned underground mines carry uncertainty tied to decline-curve modeling. As underground mine closures rise, this category becomes crucial for advancing methane emission predictions.

Surface mines

Surface coal mines release methane when coal is exposed during mining. Both coal and surrounding rocks affected by mining can emit methane. Surface mines emit less methane compared to underground mines due to the lower gas content in shallow coals. Estimating emissions from surface mines relies on production and coal/gas data, as direct measurements are challenging. For instance, the U.S. Greenhouse Gas Inventory (GHGI) employs Tier 2 country-specific emission factors along with coal production amounts (EPA, 2005).

Efforts have been made to directly measure methane emissions from surface coal mines. Methods such as infrared spectroscopy and plume dispersion modeling have been attempted, but practical limitations have hindered their effectiveness (Saghafi et al., 2004). A new Tier 3 method for estimating emissions from Australian surface mines has also been proposed (Saghafi, 2012). This method is based on an emission model that considers coal seams and surrounding layers as individual gas reservoirs, and requires input data including *in situ* gas content, gas composition, and layer thickness. The method provides gas emission factors or gas emission density outputs.

These efforts show that estimating methane emissions from surface mines – based on production data, imprecise gas content, and assumed gas emission factors – is desirable but challenging due to variability in gas content and difficulty in accessing enough sites for statistically sound coverage. Underground mining, which contributes significantly more to total methane emissions than surface mines, is therefore a priority area for improved methane emission estimates.

Landfills

The conventional method of using simple calculations (i.e., multiplying activity data by emission factors) is often inadequate for estimating landfill methane emissions, due to the intricate processes of soil-gas transport and oxidation in landfill cover soils. For specific landfill sites, two main factors for methane emissions are seasonal climate and site engineering and operational practices, including the thickness and physical characteristics of cover materials, as well as the extent of engineered biogas recovery (Gebert et al., 2011; Goldsmith et al., 2012; Scheutz et al., 2009; Spokas et al., 2011, 2015). In recent years, large-scale field investigations and the development of process-based models have produced valuable insights into landfill methane emissions and improved approaches to inventorying them.

The geographical scale of on-site measurement techniques for landfill methane emissions is large, spanning from square meters to square kilometers, and methods range from chambers, tracer techniques, micrometeorological approaches, and vertical radial plume mapping (VRPM) to aircraft mass balance approaches (National Academies of Sciences, Engineering, and Medicine et al., 2018). Using static chambers in parallel with other methods is desirable, as chambers can be deployed at any time of day or night, can directly measure without atmospheric modeling, and can quantify spatial and temporal variations in emissions across specific cover types. Moreover, static chambers can even quantify “negative” emissions including the uptake of atmospheric methane in landfill cover soils (Bogner et al., 1997, 2011; Scheutz et al., 2009). Using soil gas probes alongside static chambers facilitates the characterization of molecular and isotopic profiles, enabling a better understanding of methane generation, transport, and oxidation processes. Innovative techniques in landfill environments include the deployment of double tracer techniques (Scheutz et al., 2011), soil gas “push-pull” tests for quantifying oxidation (Streese-Kleeberg et al., 2011) and refined micrometeorological methods for better capturing atmospheric transport dynamics (Taylor et al., 2016).

Over the past decade, a new process-based model known as the California Landfill Methane Inventory Model (CALMIM) has been developed and validated in the field for quantifying “whole-landfill” methane emissions over an annual cycle. CALMIM provides improved site-specific estimates by summing up cover-specific methane emissions with and without oxidation, accounting for 10-minute time steps and 2.5 cm depth increments during a typical annual cycle. Furthermore, CALMIM can also be used to support other research and engineering applications when coupled with local annual weather data for analyzing emission trends or assessing proposed alternative cover materials, or when paired with climate projections to estimate future emissions (Bogner et al., 2011, 2014; Spokas and Bogner, 2011; Spokas et al., 2011, 2015). International field validation for CALMIM involved direct comparisons of results with independent field measurements conducted using various techniques across 40 cover materials at 29 landfill sites on six continents (e.g. Bogner et al., 2011, 2014; Goldsmith et al., 2012; Spokas et al., 2011, 2015).

The utilization and ongoing enhancements of field-validated, process-based models (e.g., CALMIM) that provide insight on site-specific factors such as cover-specific oxidation and climate conditions for emissions can offer more realistic methane emission estimates than current methodologies (National Academies of Sciences, Engineering, and Medicine et al., 2018).

Improving Methane Data: The Role of Satellites

Satellites can estimate atmospheric methane concentrations across regions, providing insights into emissions levels and sources. Satellite examples include Sentinel 5P from the European Space Agency’s Copernicus program, GHGSat, and PRISMA from the Italian Space Agency. These satellites offer readings with varying levels of resolution, coverage, and detection thresholds, which allow them to capture a wide range of methane sources (see Figure 2, Table 3, and Table 4). For example, Sentinel 5P provides frequent readings with a resolution of 7 km by 3.5 km (ESA, 2023), while GHGSat covers a much smaller area (50 m by 50 m) but provides more detailed data at a much lower detection threshold (ESA, 2023). PRISMA provides even finer spatial resolution readings of 30 m by 30 m (ESA, 2023).

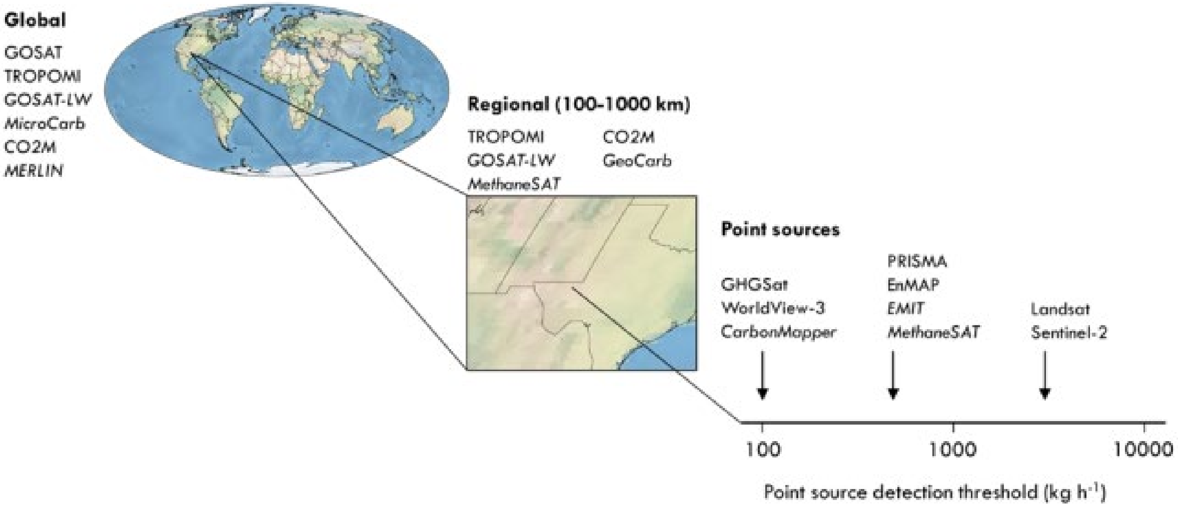


Figure 2. Classification of satellite instruments by their capability to observe atmospheric methane on global scales, on regional scales with high resolution, and for point sources.

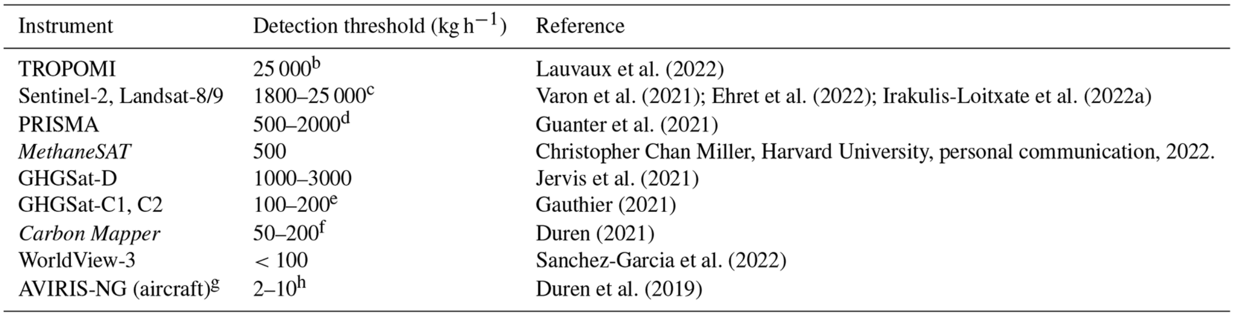
Source: Jacob et al. (2022), Figure 4.

Table 3. Attributes and data availability for satellite instruments observing atmospheric methane

Instrument	Attributes
Area flux mappers	
GOSAT	Long-term record of high-quality data
TROPOMI	Global continuous daily coverage
GOSAT-GW	High-resolution mapping of urban areas
MethaneSAT	High-resolution mapping of oil/gas/agricultural source regions with imaging of large point sources
Sentinel-5	Global continuous daily coverage including the 1.65 µm band
GeoCarb	Continuous coverage for methane-CO_2-CO over North and South America with subdaily observations
CO2M	High-resolution global continuous coverage
MERLIN	Arctic and nighttime observations
Point source imagers	
Sentinel-2, Landsat	Global continuous data acquisition, long-term records
WorldView-3	Very high spatial resolution
GHGSat	High sensitivity ($\sim 100\,\mathrm{kg\,h^{-1}}$), established constellation
PRISMA, EnMAP	Medium sensitivity (100–$1000\,\mathrm{kg\,h^{-1}}$), extensive coverage
EMIT	Medium sensitivity (100–$1000\,\mathrm{kg\,h^{-1}}$), extensive coverage of low-latitude arid regions
Carbon Mapper	High sensitivity ($\sim 100\,\mathrm{kg\,h^{-1}}$), high observing system completeness

Source: Jacob et al. (2022), Table 2, Columns 1 and 2.

Table 4. Point source detection thresholds for different satellite instruments



Instrument	Detection threshold (kg h^{-1})	Reference
TROPOMI	25 000[b]	Lauvaux et al. (2022)
Sentinel-2, Landsat-8/9	1800–25 000[c]	Varon et al. (2021); Ehret et al. (2022); Irakulis-Loitxate et al. (2022a)
PRISMA	500–2000[d]	Guanter et al. (2021)
MethaneSAT	500	Christopher Chan Miller, Harvard University, personal communication, 2022.
GHGSat-D	1000–3000	Jervis et al. (2021)
GHGSat-C1, C2	100–200[e]	Gauthier (2021)
Carbon Mapper	50–200[f]	Duren (2021)
WorldView-3	< 100	Sanchez-Garcia et al. (2022)
AVIRIS-NG (aircraft)[g]	2–10[h]	Duren et al. (2019)

Source: Jacob et al. (2022), Table 4.

Satellites already contribute significantly to improving methane measurements by identifying major leaks and pinpointing emission hotspots. As advancements in satellite technology continue and more satellites are launched – e.g., Carbon Mapper, EnMAP (German Aerospace Center), and MethaneSAT (Environmental Defense Fund) – the accuracy and coverage of methane emission data are expected to improve, offering a complementary perspective to ground-based measurements and enhancing the understanding of methane's role in climate change mitigation. For instance, in 2023, a joint effort between Carbon Mapper and NASA's Jet Propulsion Laboratory will result in the launch of satellites to monitor methane emissions from individual facilities. These satellites will provide detailed, high-resolution imagery capable of uncovering previously undetected methane sources, which is expected to enhance transparency for decision-makers in both the public and private sectors (White House, 2021). Concurrently, the UNEP International Methane Emissions Observatory (IMEO) has introduced the Methane Alert and Response System (MARS) to expand the detection of significant emission events and track progress in methane mitigation.

While they provide valuable information and data about methane emissions and mitigation opportunities, satellites also face limitations. Notably, they lack coverage in certain areas like equatorial regions and offshore operations, leaving emissions in these areas undetected. For instance, roughly a quarter of 2020 emissions from global oil and gas production lack direct satellite coverage due to geographic constraints, according to the International Energy Agency's Global Methane Tracker (IEA, 2021).

Weather conditions, such as cloud cover and adverse weather patterns, can also disrupt satellite measurements (IEA, 2021). The 2020 readings from Sentinel 5P, for example, were impacted by data outages (IEA, 2021). Moreover, satellite instruments can provide data for larger emitting sources but may overlook smaller-scale emissions, such as those originating from malfunctioning components (IEA, 2021). Emissions from these omitted small-scale sources can accumulate over time and contribute to a substantial volume of unaccounted emissions (IEA, 2021).

Uncertainties also play a significant role in satellite-based methane emission measurements (Table 5). These uncertainties arise from a variety of sources, including the accuracy of input data, modeling assumptions, and the effectiveness of inversion techniques used to infer emissions from atmospheric measurements (Cooper et al., 2022). In general, satellite-derived methane measurements are less accurate than *in situ* ones (NASEM, 2018). Biases persist in spatial and temporal dimensions, impacting data reliability (e.g., Bergamaschi et al., 2013; Houweling et al., 2014). Strategies to reduce biases, like improved retrieval algorithms and instrument specifications, can help but may not eliminate them entirely (NASEM, 2018). Overall, while satellites enhance global monitoring, recognizing and addressing their limitations and uncertainties are vital for developing accurate emission estimates and effective reduction strategies.

Table 5. Sources of data uncertainty in satellite and inversion modeling

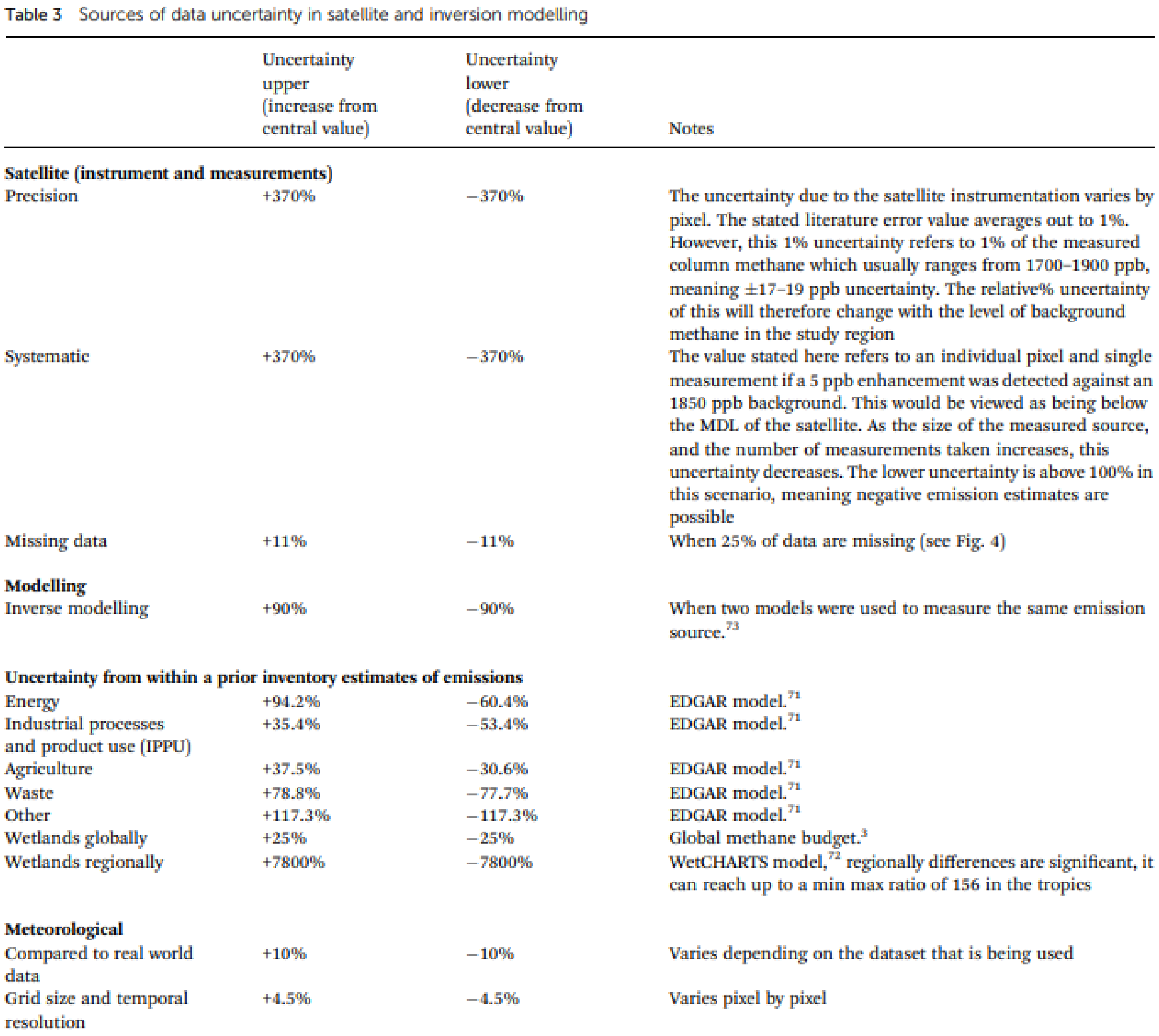


Table 3 Sources of data uncertainty in satellite and inversion modelling

	Uncertainty upper (increase from central value)	Uncertainty lower (decrease from central value)	Notes
Satellite (instrument and measurements)			
Precision	+370%	−370%	The uncertainty due to the satellite instrumentation varies by pixel. The stated literature error value averages out to 1%. However, this 1% uncertainty refers to 1% of the measured column methane which usually ranges from 1700–1900 ppb, meaning ±17–19 ppb uncertainty. The relative% uncertainty of this will therefore change with the level of background methane in the study region
Systematic	+370%	−370%	The value stated here refers to an individual pixel and single measurement if a 5 ppb enhancement was detected against an 1850 ppb background. This would be viewed as being below the MDL of the satellite. As the size of the measured source, and the number of measurements taken increases, this uncertainty decreases. The lower uncertainty is above 100% in this scenario, meaning negative emission estimates are possible
Missing data	+11%	−11%	When 25% of data are missing (see Fig. 4)
Modelling			
Inverse modelling	+90%	−90%	When two models were used to measure the same emission source.[73]
Uncertainty from within a prior inventory estimates of emissions			
Energy	+94.2%	−60.4%	EDGAR model.[71]
Industrial processes and product use (IPPU)	+35.4%	−53.4%	EDGAR model.[71]
Agriculture	+37.5%	−30.6%	EDGAR model.[71]
Waste	+78.8%	−77.7%	EDGAR model.[71]
Other	+117.3%	−117.3%	EDGAR model.[71]
Wetlands globally	+25%	−25%	Global methane budget.[3]
Wetlands regionally	+7800%	−7800%	WetCHARTS model,[72] regionally differences are significant, it can reach up to a min max ratio of 156 in the tropics
Meteorological			
Compared to real world data	+10%	−10%	Varies depending on the dataset that is being used
Grid size and temporal resolution	+4.5%	−4.5%	Varies pixel by pixel

Source: Cooper et al. (2022), Table 3.

2.1.2 Nitrous Oxide (N_2O) Measurement

In national GHG inventories, nitrous oxide (N_2O) emissions are quantified by employing models that establish a connection between emissions and specific activities. These models rely on emission factors that are derived from experimental data. The accuracy of these models relies heavily on the quality and reliability of the experimental data on which they are based. However, measuring N_2O emissions through experimentation is complex and entails consideration of diverse sources, including agricultural practices, industrial processes, fuel combustion, and waste management, while also requiring a comprehensive understanding of intricate soil and environmental dynamics. Factors such as soil type, humidity, temperature, and nutrient management can influence N_2O emissions, and making accurate measurements requires thorough on-site research and sustained monitoring across various scenarios.

Efforts to enhance measurement precision involve the adoption of advanced techniques such as eddy covariance and chamber methods. Continuously improving sensor technologies and remote sensing capabilities also improve the accuracy of data collection, while collaborative initiatives and data sharing among institutions on a global scale have helped to refine inventory compilation methods. Given the significant role of N_2O in climate change, gaining a deeper understanding of its emission patterns in conjunction with robust measurement techniques is crucial for formulating effective emission reduction strategies.

Figure 3 shows how different N_2O measurement methods provide data across varying spatial and temporal scales.

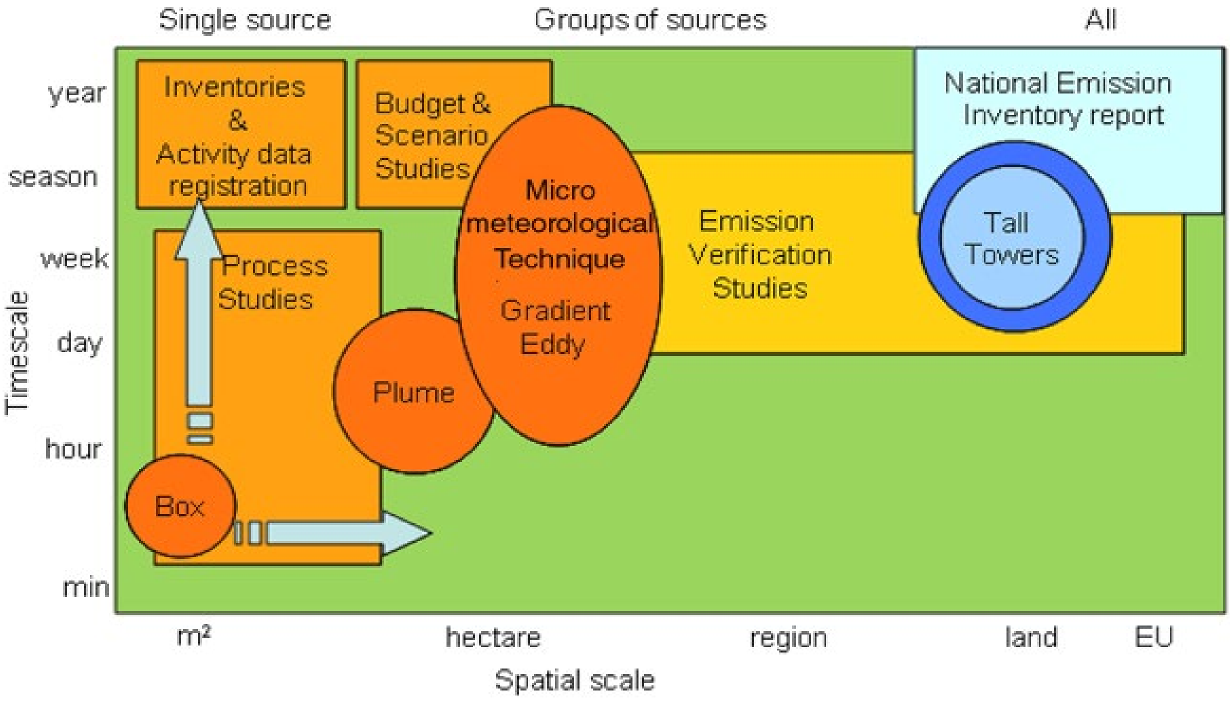


Figure 3. Different N_2O measurement methods used across varying spatial and temporal scales.

Source: Hensen et al. (2013), Figure 11.

Sampling methods

N_2O sampling methods can be broken into two broad groups: chamber and micrometeorological. Table 6 briefly summarizes the advantages and disadvantages of the various sampling methods available (Rapson and Dacres, 2014). A comprehensive overview of sampling methods is available in the review by Denmead (2008).

Table 6. Sampling methods for N_2O

Technique	**Advantages**	**Disadvantages**
Chamber Methods		
Manual chambers	Low cost Easy to deploy Allow for off-line sample analyses Do not require the use of extremely accurate or rapid analytical techniques	Labor intensive to quantify spatial and temporal variability Limited number of readings Cause soil disturbance and disrupt the soil microclimate
Automated chambers	Allow more readings than manual chambers Easy to deploy Allow for off-line sample analyses Do not require the use of extremely accurate or rapid analytical techniques	Higher operating requirements and cost than manual chambers Suitable only for small areas (< 25 m^2) Cause soil disturbance and disrupt the soil microclimate
Micrometeorological Methods		
Eddy covariance	Provides a direct measurement of the vertical flux at the point of measurement No problem with different footprints for different measurement heights Independent of atmospheric stability Does not require many simplifying assumptions used in other micrometeorological approaches	Requires fast-response (10 Hz or higher), sensitive gas analyzers
Eddy accumulation	Provides a direct measurement of gas flux at a given point No problem with different footprints for different sensor heights Independent of stability conditions Does not need fast-response gas analyzers Air samples can be preconditioned before gas analysis	Needs clean measurements of vertical wind speed Needs high-quality electronics, plumbing and flow control
Flux-gradient methods	Low cost Can rely on slower sensors	Need to use common instrumentation for readings of gas concentrations from different heights with some sort of interchange gear Corrections are needed to account for the effects of atmospheric stability
Integrated horizontal flux	Fills the gap between chamber methods and classical micrometeorological methods	Limited to small areas (<1 ha) with a well-defined shape

	Does not require gas analyzers with a rapid response	
Backward Lagrangian stochastic dispersion technique	Can be used for both point and line-averaged concentration measurements Particularly appropriate for measuring emissions from treated fields or intensive animal-production systems	Limited to small, well-defined source areas
Moving platforms	Allow measurement in both horizontal and vertical directions with high spatial and temporal resolution Provide a method to study the transport dynamics of N_2O within the troposphere and even stratosphere	Instruments employed must be immune to vibrations and variable environmental conditions (e.g., temperature, pressure, humidity)

Source: Rapson and Dacres (2014).

Analytical methods

The analytical techniques used to measure N_2O can be broken into three broad groups: chromatographic, optical, and amperometric. Table 7 provides a summary comparison of these three groups. A comprehensive overview of analytical techniques is available in Trevor and Dacres (2014).

Table 7. Analytical techniques for measuring N_2O

	Sensitivity	Advantages of technique	Disadvantages of technique
Chromatography			
Electron Capture Detector	30 ppb LOD Precision: 0.18–0.4 ppb	Lower cost	Non-continuous
		Widely used, allowing easy data comparisons	Frequent calibration required
		If linked to IRMS, isotope analysis can be carried out	Drift means reference needs to be run every 3 samples
			Long run time (∼5 min)
Optical methods			
FTIR	Precision: 0.1 ppb (1 min)	Continuous measurements	High cost of instruments
		Lower calibration requirements	Low brightness of light source
	0.03 ppb (10 min)	Broadband spectrum allowing the measurement of multiple components and spectra can be reanalyzed	Slower measurements compared to lasers
		Direct detection of isotopomers with the same molecular mass	Analysis of data can be more complicated
		Mid IR used at atmospheric pressure	
		Portable	
Laser absorption spectroscopy			
Lead Salt Lasers	Precision: <1 ppb in 5 sec	Allows rapid and highly sensitive measurements	Cryogenic cooling required
		Lower interference from other trace gases	Narrowband, can only measure a single species or pair per laser
			Low pressure required
			Expensive
Quantum Cascade Lasers	Precision: 0.05 ppb in 1 Hz	No cryogenic cooling required making lasers more portable	Spectral quality not as high as Lead Salt Lasers
		Higher power than lead salt lasers giving a higher signal to noise ratio and faster measurements	Narrowband, can only measure a single species or pair per laser
		Can be linked with high finesse optical cavities such as CRDS and ICOS	Low pressure required
		Carry out isotopic analysis without pre-concentration	Expensive
Amperometric			
Microsensor	22 ppb LOD		
		Low cost	Sensor drift, therefore not suitable for long term monitoring
		Extremely portable	Only dissolved N_2O can be measured

CRDS, Cavity ring-down spectroscopy; ICOS, Integrated cavity-output spectroscopy; IRMS, Isotope-ratio mass spectrometry, LOD, Limit of detection.

Source: Rapson and Dacres (2014), Table 1.

Agriculture

Significant sources of N_2O emissions in the agricultural sector include soil management practices, such as the use of both synthetic and organic nitrogenous fertilizers, as well as other agronomic activities (EPA, 2023). Additional sources include animal waste management and the combustion of agricultural residues (EPA, 2023).

Figure 4 presents a conceptual framework outlining the sources and nitrogen pathways responsible for both direct and indirect N_2O emissions from soil and water systems (IPCC, 2006). The bulk of N_2O emissions can be attributed to the application of nitrogen-based fertilizers (EPA, 2023). Mitigation strategies include the reduced application of nitrogen fertilizers and improvements in the efficiency of fertilizer use (EPA, 2005), in addition to modifying existing manure management protocols on agricultural lands.

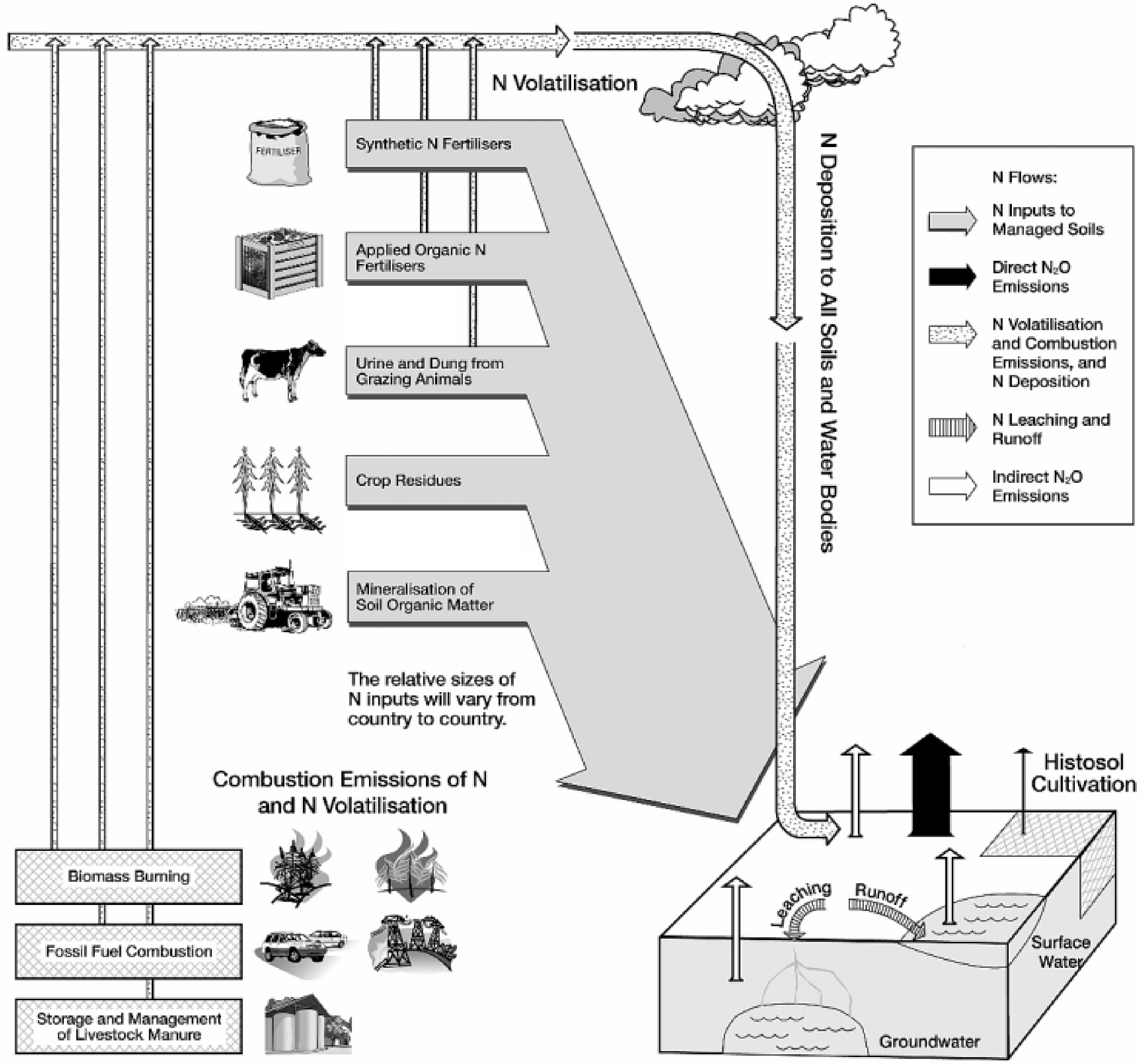


Figure 4. Schematic diagram illustrating nitrogen sources and pathways that result in direct and indirect N_2O emissions from soils and waters.

Source: IPCC (2006), Figure 11.1.

IPCC guidelines (2006, 2019) include a three-tiered system for evaluating N_2O emissions from agriculturally managed soils. Tier 1 involves simplified analysis that does not consider factors such as variations in land cover, soil type, climatic conditions, or specialized management practices (IPCC, 2006). The Tier 1 methodology also does not consider any delayed nitrogen emissions that might come from crop residues; instead, it attributes these emissions to the year the residues are incorporated back into the soil (IPCC, 2006). Tier 1 is simplistic largely because it is designed to be applicable when only limited data are accessible.

Countries with more comprehensive data can progress to Tier 2 methods. This more advanced approach allows for the disaggregation of emission factors, making them specific to a country's unique conditions (IPCC, 2019). Tier 2 goes beyond Tier 1 by considering the impact of specialized mitigation strategies (e.g., nitrification inhibitors) on emission factors as supported by various studies (Akiyama et al., 2010; Ruser and Schulz, 2015; Gilsanz et al., 2016). Tier 2 also allows for a nuanced understanding of how N_2O emissions might respond exponentially to applications of nitrogen, and site-specific emission factors can be developed to capture this complexity (van Groenigen et al., 2010; Shcherbak et al., 2014; Gerber et al., 2016). Moreover, Tier 2 methods can address other influential environmental conditions, such as the freeze-thaw cycles that can affect N_2O emissions (Wagner-Riddle et al., 2017).

Tier 3 methods leverage either advanced modeling techniques or direct measurement for estimating emissions. The models can derive relationships between variables causing the emissions to the size of those emissions and can be scaled to estimate total emissions for countries or regions. Models must undergo empirical validation through experimental measurements before being applied on a broad scale for national or regional emission estimates (IPCC, 2019).

Uncertainty in measuring N_2O emissions from agricultural sources is a multifaceted challenge with important implications for both research and policy. A variety of factors contribute to the uncertainties in estimates for both direct and indirect emissions from managed soils. These can range from inconsistencies in emission factors, to natural variations in conditions such as climate, to differences in the partitioning of substances in soils. Even data on farming activities, while generally more reliable than emission factors, can be plagued by gaps or lack of representativeness, adding uncertainty. Moreover, spatial considerations, including the scope and scale of measurements and the aggregation of spatial data, further complicate the issue. Human factors also add a dimension of uncertainty, ranging from compliance with regulations governing fertilizer and manure use to dynamic changes in farming practices, for which data is often incomplete or outdated. Regulatory compliance itself can be nebulous, as monitoring the application of fertilizers and manure and measuring their real-time effects on N_2O emissions are often challenging.

Notably, emission factors are often the most dominant variables among these diverse sources of uncertainty, overshadowing all others in terms of their impact on the reliability of emission estimates. These layers of uncertainty collectively hamper the accurate assessment of N_2O emissions in the agricultural sector, making it a complex problem that requires a multi-disciplinary approach to mitigate effectively.

Industry

Industrial sectors also emit nitrous oxide in significant quantities. Specifically, the production of chemicals like nitric acid, a key component in synthetic commercial fertilizers, and adipic acid, used for manufacturing fibers like nylon, are notable sources. Beyond the chemical industry, N_2O also finds its way into the atmosphere from specialized applications like anesthesia in medical settings and even semiconductor manufacturing.

Measurement methodologies for capturing industrial N_2O emissions are multifaceted and often dictated by available resources and national protocols. As discussed previously, Tier 1 of the IPCC Guidelines for National Greenhouse Gas Inventories (2006, 2019) uses default emission factors and is straightforward but less accurate. Tier 2 customizes emission factors based on national or industry-specific technology mixes. Tier 3, the most rigorous, relies on real-time or high-frequency measurements, usually through Continuous Emissions Monitoring Systems (CEMS).

One of the key challenges in measuring industrial N_2O emissions is the inherent variability and uncertainty in the emission factors. While activity data, such as the amount of nitric or adipic acid produced, are generally reliable, the emission factors can introduce significant uncertainties. This is further complicated by the fact that emission factors can vary based on the specific technologies used for abatement, the level of adherence to regulations, and even operational practices within plants.

To mitigate emissions, technological upgrades and abatement equipment are often employed. Over time, as plants adapt to newer technologies for operational efficiency or to meet environmental regulations, it becomes crucial to update emission factors and measurement methods. Even high-accuracy methods like CEMS are resource-intensive and may not be practical for all industrial settings, making periodic audits and updates a balanced approach to maintaining both accuracy and feasibility.

In summary, measuring and reducing N_2O emissions from industrial sectors is a complex task that requires a multi-pronged approach. Accurate measurements, technological advancements, and consistent monitoring are all vital to adapting to evolving industrial landscapes.

Fuel Combustion

N_2O is emitted during fuel combustion. The quantity of N_2O emissions depends on various factors such as the type of fuel and combustion technology used, as well as maintenance and operational practices (EPA, 2023). For example, older combustion engines that are poorly maintained are likely to emit more N_2O compared to newer, more efficient engines with advanced emission control systems.

Measurement and estimation of N_2O emissions from fuel combustion are guided by the IPCC Guidelines for National Greenhouse Gas Inventories (2006, 2019). The guidelines provide methods for estimating N_2O emissions not just from direct combustion, but also from the atmospheric deposition of nitrogen compounds from fuel combustion, industrial processes, and burning of crop residues and agricultural wastes. These advanced estimation techniques are especially useful where data on NO_x (nitrogen oxides) and NH_3 (ammonia) emissions are available, as they provide a more comprehensive picture of N_2O emissions.

Efforts to mitigate N_2O emissions from fuel combustion include both reducing fuel use and implementing emission control technologies (EPA, 2023). On one hand, reducing overall fuel consumption, especially in sectors like transportation, can directly lead to fewer emissions. Technologies like electric or hybrid vehicles and policies setting improved fuel efficiency standards aim to reduce the amount of fuel needed for combustion in the first place. On the other hand, pollution control technologies such as catalytic converters in passenger cars have been successful in reducing exhaust pollutants, including N_2O. Accurate measurement is essential for tracking mitigation progress and informing policies aimed at reducing N_2O emissions.

Waste and Wastewater

The generation of N_2O from waste treatment processes, particularly from domestic wastewater systems, has drawn increased attention. Treatment processes like nitrification and denitrification, aimed at breaking down urea, ammonia, and proteins, can produce N_2O emissions as a byproduct. Moreover, recent research indicates that emissions from sewer networks and wastewater treatment plants (WWTPs), once considered to be minor sources, might be contributing more substantially to overall N_2O emissions than previously thought (IPCC, 2019).

Several factors can influence N_2O emission rates from wastewater treatment. The temperature and dissolved oxygen levels in the water, for instance, can affect how much N_2O is produced during the treatment process. Operational conditions, such as the rate of flow and treatment protocols, also play a role. In addition, untreated wastewater and effluent discharged into aquatic environments can further contribute to N_2O emissions. These emissions can be especially difficult to measure due to their diffuse and irregular nature.

As discussed previously, the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories provides methodologies for estimating N_2O emissions in three tiers. Tier 3, meant for countries with advanced data collection mechanisms, can incorporate plant-specific or even process-specific data to enable more accurate estimations. This might involve direct measurement methods that give a more reliable account of N_2O production from individual treatment plants. For example, an advanced Tier 3 method might involve continuous monitoring systems in large WWTPs to measure N_2O levels in real time. This is particularly beneficial for understanding temporal variations in emission levels and how they correlate with specific operational conditions. A Tier 3 approach could also consider the nutrient-impacted status of aquatic environments receiving nitrogen discharges, thus giving a more comprehensive picture of emissions.

In summary, N_2O emissions from waste, particularly wastewater, present both a challenge and an opportunity. While they are influenced by a multitude of factors and are inherently variable, advancements in measurement methodologies and treatment technologies offer pathways for better management and reduction of these potent greenhouse gases. Given their complexity and significant environmental impact, an evidence-based, methodologically sound approach to both measurement and mitigation of N_2O is crucial.

2.1.3 Hydrofluorocarbon (HFC) Measurement

Hydrofluorocarbons (HFCs) have been increasingly adopted as substitutes for ozone-depleting substances like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). HFCs (a category of fluorinated gases, or F-gases) are commonly used in refrigeration systems or as foam-blowing agents. While they do not deplete the ozone layer, their high Global Warming

Potential (GWP) makes them potent contributors to climate change. The Kigali Amendment to the Montreal Protocol, which entered into force in 2019, aims to phase down the production and consumption of HFCs. Accurate and reliable emission estimates are needed to monitor and track progress towards the phase-down goals.

To quantify HFC emissions, two predominant methods are utilized: bottom-up and top-down approaches (Figure 5). The bottom-up method relies on product inventories and chemical sales data to estimate emissions. However, this approach has limitations. As pointed out by Nisbet and Weiss (2010), bottom-up emission estimates are often more susceptible to errors and manipulation. They depend on accurate reporting, which may not always be the case due to lack of oversight, deliberate misinformation, or other reasons. In contrast, the top-down approach utilizes atmospheric measurements coupled with inverse modeling or interspecies correlation to estimate emissions. This method employs meteorological data, such as wind speed and direction, to project how HFCs are transported in the atmosphere. Because it is based on actual atmospheric concentrations, the top-down approach is often considered more reliable than bottom-up estimates. However, the approach is also more complex, requiring specialized equipment and expertise in atmospheric science.

The considerable variance in emission estimates reported by these two methods highlights the challenges in obtaining accurate data for HFC emissions (Flerlage et al., 2021). The discrepancies between the two approaches can be quite large, leading to uncertainty about how effectively the Kigali Amendment's phase-down goals are being met. For example, a recent study of top-down inversion estimates for HFC-23 emissions in eastern Asia from 2014 to 2017 and comparison with bottom-up emissions inventories identified significant discrepancies that could be attributed to unsucessful factory-level abatement (Park et a. 2023). Thus, continuous refinement in measurement techniques and greater international cooperation are essential for accurately monitoring and consequently reducing HFC emissions.

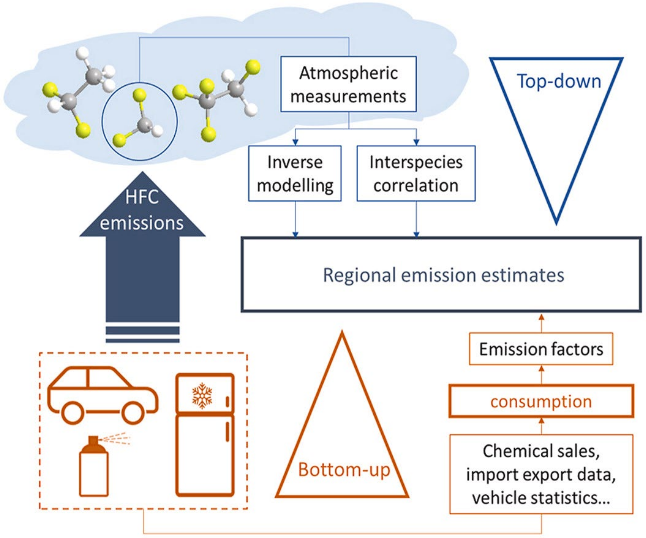


Figure 5. Bottom-up and top-down approaches for estimating HFC emissions.

Source: Flerlage et al. (2021).

Top-down Emission Estimation

The top-down approach for estimating HFC emissions leverages atmospheric measurement data and is particularly suitable for HFCs since they are entirely synthetic compounds with no naturally occurring fluxes. This method uses either simple box models or three-dimensional models to estimate emissions on a global scale, even from individual measurement sites (Stohl et al., 2010). Given their long lives, HFCs are relatively uniformly distributed in the troposphere.

Estimating regional or national HFC emissions requires the use of a network of atmospheric measurement stations with different sensitivities to emissions from various sources (Brunner et al., 2017). Estimates can be derived through inverse modeling, which uses chemical transportation models and inversion algorithms to trace emissions back to their origins on a spatial grid (Stohl et al., 2009). Interspecies correlation, another method, uses ratios between measured HFC concentrations and concentrations of substances with known emission fluxes, such as carbon monoxide, to estimate emissions (Stohl et al., 2010).

These approaches rely on atmospheric measurements, some taken from several networks of *in situ* measurement stations worldwide such as the Advanced Global Atmospheric Gases Experiment (AGAGE) and the National Institute for Environmental Science (NIES) in Japan (Prinn et al., 2000; Yokouchi et al., 2006). These networks provide high-frequency measurements of HFCs, obtained through advanced analytic techniques like automated low-temperature pre-concentration and re-focusing, followed by automated Gas Chromatography-Mass Spectrometry (GC-MS) analysis (Graziosi et al., 2017; Lunt et al., 2015; Miller et al., 2008; Stohl et al., 2009).

One of the advantages of the top-down approach is its greater spatial resolution (Ghandehari et al., 2017), which enables better control and enforcement of regulations on sub-national scales. This granular data improves the understanding of emission sources and can support local regulatory action.

The precision of atmospheric measurements of HFC mole fractions has only minor errors, around 2%, from the GC-MS analysis (Flerlage et al., 2021). Nonetheless, there are significant sources of uncertainty. For example, inaccurate model simulations contribute to high uncertainties in emission values derived by inverse modeling (Yao et al., 2019). Furthermore, HFCs with shorter atmospheric lifetimes are systematically underestimated, as some HFCs can be lost during the backward simulation due to natural atmospheric degradation (Flerlage et al., 2021).

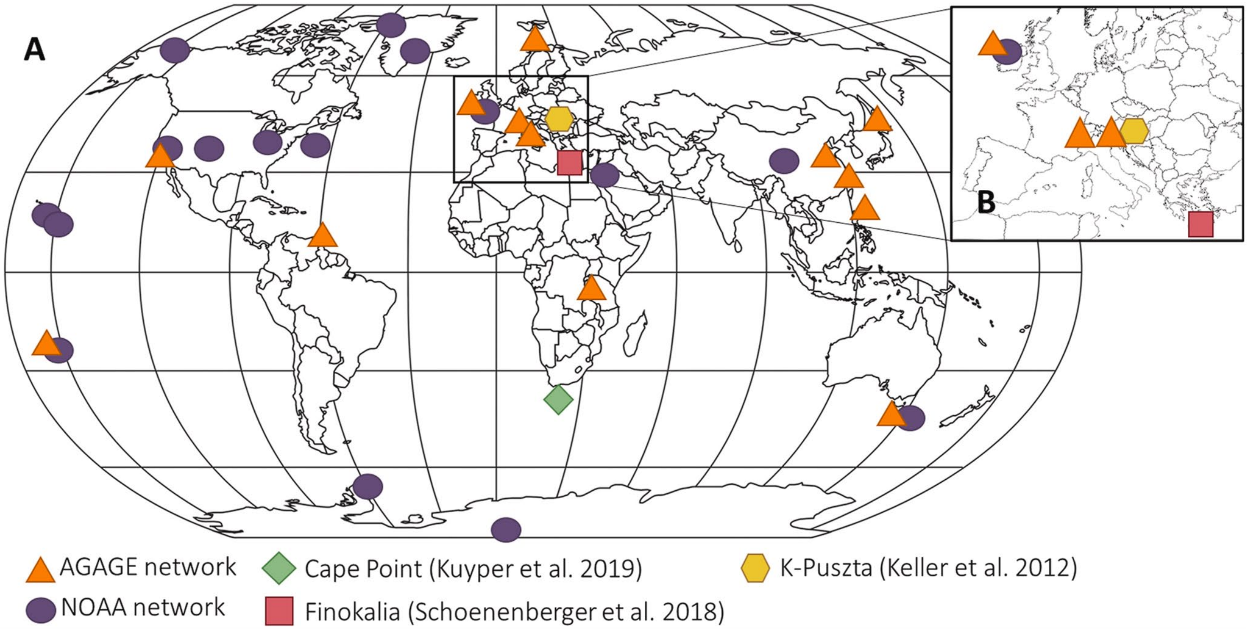


Figure 6. Geographical distribution of HFCs sampling sites

Source: Flerlage et al. (2021).

Bottom-up Emission Estimation

Again, bottom-up methods primarily rely on the guidelines set forth by the Intergovernmental Panel on Climate Change (IPCC, 2006). Tier 1 involves a more general approach, often used when only aggregated data are available, whereas Tier 2 provides a more detailed assessment by considering specific emission factors for, in this case, each sub-sector or sub-application of HFCs.

Advanced models, such as the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model by the International Institute for Applied Systems Analysis (IIASA), provide further granularity. These models adjust emission factors based on specific national conditions, such as the type of transportation fleet and maintenance practices in a given country (Tohka, 2005).

The data for bottom-up estimates often come from specialized databases. For example, the Emissions Database for Global Atmospheric Research (EDGAR) offers HFC emission estimates on a country-level basis. The EDGAR database is a joint initiative of the European Commission Joint Research Centre (EC-JRC) and the Netherlands Environmental Assessment Agency (PBL) (PBL and EC-JRC, 2022).

While bottom-up methods can offer a detailed view of HFC emissions, they come with their own set of uncertainties. The most significant source of uncertainty is usually the quality and completeness of foundational data such as records related to the import and export of chemicals, or market sales data (IPCC, 2006). Additional sources of uncertainty include the specific emission factors chosen for various sub-applications and any further assumptions made during the calculation process. The issue of selecting appropriate emission factors becomes especially pertinent in the disaggregated (Tier 2) form, where emissions are estimated at the sub-application level or in greater detail (IPCC, 2006).

2.2 Reporting and Verification

2.2.1 United States

The United States Environmental Protection Agency (US EPA) characterizes GHG emissions using two complementary programs: the U.S. Inventory of Greenhouse Gas Emissions and Sinks (known as “the Inventory”) and the Greenhouse Gas Reporting Program (GHGRP).

U.S. Inventory of Greenhouse Gas Emissions and Sinks

The Inventory provides a comprehensive account of total U.S. greenhouse gas emissions across all sectors. This includes emissions from sources like fossil fuel burning, industrial processes, and agriculture, as well as sinks, like carbon uptake and storage in forests, plants, and soils. The Inventory covers seven greenhouse gases: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride. It is submitted to the United Nations each year as per requirements of the UN Framework Convention on Climate Change (UNFCCC) and has been compiled by the EPA annually since the 1990s, providing over 25 years’ worth of data about national GHG emissions and trends.

The Inventory calculates emissions and sinks using the methods outlined by the Intergovernmental Panel on Climate Change (IPCC) in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and its supplements and refinements. The Inventory includes a thorough explanation of the methods used for calculation and is presented in accordance with the UNFCCC reporting guidelines.

Greenhouse Gas Reporting Program (GHGRP)

The Greenhouse Gas Reporting Program (GHGRP) was established in response to a Congressional mandate in 2008. It requires reporting of greenhouse gas emissions data and additional relevant information from large emitting facilities across the U.S. The program covers carbon dioxide, methane, nitrous oxide, and various fluorinated gases (namely, HFCs, PFCs, SF_6, NF_3, Other Fully Fluorinated GHGs, HFEs, Very Short Lived Compounds, and Other).

Facilities must typically submit annual reports if:

- Their GHG emissions from covered sources surpass 25,000 metric tons of CO_2 equivalent per year, or
- Supply of certain products would lead to more than 25,000 metric tons CO_2 equivalent of GHG emissions if those products were burned, oxidized, or released.

The EPA provides an Applicability Tool on its website to help facilities determine if they need to report their greenhouse gas emissions annually under the Mandatory GHG Reporting Rule (40 CFR Part 98) (EPA, 2023). The tool accounts for various factors such as source categories at the facility, emission levels, production capacity, and other factors. The GHGRP covers forty-one reporter categories (EPA, 2023) but some sectors are exempt (e.g., agriculture, land use). Around 8,000 facilities are required to report their emissions annually, accounting for 85-90% of total U.S. GHG emissions. The GHGRP has collected data annually since 2010 and makes it available to the public each October through data portals on the GHG Data Sets webpage. The data, which covers the years 2010 to 2021, can be used by businesses, states, cities, and communities to track and compare emissions, identify ways to reduce pollution, and save energy and money. Communities can also use the data to find high-emitting local facilities, compare emissions among facilities, and develop climate policies.

Facilities determine their emissions using the methodologies outlined in 40 CFR Part 98. Reporters typically have multiple options for calculating their GHG emissions and can choose the method that best suits their needs, considering factors such as their existing environmental monitoring systems. They can also change their emission calculation methods from year to year or within the same year, as long as they comply with requirements for the chosen method.

Facilities report their GHG emissions to the EPA using the e-GGRT system. They must submit their annual reports covering emissions from the previous year by March 31. The EPA then carries out a multi-step verification process to validate the accuracy, completeness, and consistency of the reported data. Reports undergo electronic validation and verification checks. If errors are detected, the EPA will notify the facility, which can either explain why the issue is not an error or correct it and resubmit their report.

The U.S. GHGRP and GHG inventory are currently in the process of updating its reporting and verification process and requirements, and will likely include greater emphasis on direct emission measurements in the coming years.

2.2.2 European Union

EU Regulation on the Governance of the Energy Union and Climate Action and EU Greenhouse Gas Emissions Inventory

The European Union (EU) has a robust framework for monitoring and reporting GHG emissions, in line with its obligations as a party to the United Nations Framework Convention on Climate Change (UNFCCC). Previously, the EU Climate Monitoring Mechanism Regulation dictated the process and required annual reports covering emissions from a range of sectors including energy; industrial processes; land use, land-use change and forestry (LULUCF); waste; and agriculture. Annual reports also had to provide projections for future emissions, discuss climate policies and adaptation measures, outline low-carbon strategies, and specify the support extended to developing countries. However, this mechanism was superseded by the Regulation on the Governance of the Energy Union and Climate Action in January 2021. Alongside this change, previous regulations on national reporting and the EU inventory systems were repealed and replaced by Commission Implementing Regulation 2020/1208 and Commission Delegated Regulation 2020/1044. In support of EU's methane strategy, the Commission also adopted a proposal for a regulation aimed at reducing methane emissions in the energy sector that builds on the OGMP 2.0 framework for improved MRV, including consideration of adopting level 5 reporting compliance levels.

The European Environment Agency (EEA) prepares the EU's official GHG inventory, which is submitted to the UNFCCC each spring and covers emissions dating back to 1990, up to two years prior to the current year. The EEA's inventory is built on data submitted by individual EU member countries through the EU Climate Monitoring Mechanism and the Regulation on the Governance of the Energy Union and Climate Action, ensuring consistency and reliability.

To support additional transparency and public engagement, the EU has developed the Emission Monitoring and Reporting website to share information on monitoring regulations, historical GHG inventories, and climate progress reports. The website also includes National Communications and Biennial Reports to the UNFCCC, along with other valuable resources and studies.

2.2.3 California

Mandatory Greenhouse Gas Emissions Reporting (MRR)

In California, the Mandatory Reporting of Greenhouse Gas Emissions (MRR) regulation is a cornerstone of the state's climate efforts. Initially established under the California Global Warming Solutions Act of 2006 (AB 32), the MRR has been revised multiple times, with the most recent changes taking effect on April 1, 2019. This regulation mandates the annual reporting of greenhouse gas emissions from various sectors including electricity generators, industrial facilities, fuel suppliers, and electricity importers. The objective is to create an exhaustive database that can both inform the public and guide regulatory policies.

Data collected under the MRR framework, which is made publicly available each year, is integral to initiatives such as the Cap-and-Trade Program and the California Greenhouse Gas Inventory, both of which are described below. The California Air Resources Board (CARB) provides a dedicated Mandatory GHG Reporting website where emissions data from 2008 to 2021 can be accessed.

To ensure the accuracy and integrity of reported data, the MRR process is strictly regulated. All submissions must adhere to guidelines and must be made through the California Electronic Greenhouse Gas Reporting Tool (Cal e-GGRT) system. CARB offers guidance documents and training materials to facilitate compliance with these reporting requirements. CARB also oversees a third-party verification program to further enhance data credibility.

Cap-and-Trade Program

The California Cap-and-Trade Program is vital to California's strategy to reduce GHG emissions. Targeting sectors that account for about 80% of the state's overall emissions, the program sets an annually decreasing cap on allowable emissions. By doing so, it provides economic incentives for companies to invest in cleaner technologies. Moreover, the program aligns with existing air quality regulations requiring entities to comply with criteria and toxic air pollutant limits. The program relies on data from the above-mentioned MRR process, which ensures tracking and accountability. All reports submitted for the Cap-and-Trade Program must be independently verified by CARB-accredited verification bodies and individual verifiers.

Cap-and-Trade Program effectiveness hinges on ensuring market transparency and fairness. To safeguard market integrity, CARB maintains rigorous surveillance protocols, employing a specialized team to monitor the market and work alongside an independent monitor (Monitoring Analytics) to oversee the auction and trading of compliance instruments. Collaborative efforts extend to various state and federal agencies such as the California Independent System Operator (CAISO), Commodity Futures Trading Commission (CFTC), and Federal Energy Regulatory Commission (FERC), bolstering market oversight. Involvement by the California Attorney General's office also provides valuable expertise for regulation and potential future enforcement actions.

California Greenhouse Gas Emission Inventory Program

The California Greenhouse Gas Emission Inventory is a valuable tool for assessing the state's climate efforts. Established under the guidelines of the California Global Warming Solutions Act of 2006 (AB 32), the inventory aims to measure progress toward achieving California's GHG reduction targets. The inventory calculates emissions generated from anthropogenic activities within the state's borders and includes emissions from imported electricity, but excludes emissions from natural sources (e.g., wildfires).

The inventory encompasses a broad spectrum of GHGs, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), as well as high-GWP fluorinated gases like hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). To ensure accuracy and reliability, the program relies on an array of data sources at the state, regional, and federal levels and utilizes aggregated facility reports from California's Mandatory GHG Reporting Program. For standardization, the inventory employs calculation methodologies based on the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines and uses 100-year GWP values from the IPCC's Fourth Assessment Report.

Consistency and accuracy are central to the inventory's integrity. Recalculations are regularly performed for each new edition to correct errors, update methodologies, and/or incorporate new statistical data. This ensures the entire data set, dating back to 1990, is uniformly re-evaluated, providing a coherent, actionable time series for policymakers and the public alike. This extensive archive of data and accompanying documentation is publicly accessible, fostering transparency and enabling informed decisions in climate action planning.

3. Review of China's MRV System for Non-CO_2 GHGs

3.1 Current Efforts

Greenhouse Gas Emissions Inventories

China, as a party to the United Nations Framework Convention on Climate Change (UNFCCC), has complied with its obligation to submit national communication reports on climate change. These reports have detailed China's GHG emissions for specific years (i.e., 1994, 2005, and 2010) and provided biennial updates for 2012 and 2014 (MEE, 2018).

The Ministry of Ecology and Environment (MEE) in China is responsible for organizing the development of the national GHG inventory and submitting the inventory report to the UNFCCC. Currently, there is no single organization designated for the compilation of the inventory and preparation of compliance reports; instead, the inventory and reports are mainly outsourced to various research institutions (Feng, 2022). These include prominent institutions like the National Climate Strategy Center, Tsinghua University, and various academies focusing on agricultural sciences, environmental sciences, and forestry, among others. Data for the inventories are collated from multiple channels, including the National Bureau of Statistics, relevant ministries, and industry associations (Feng, 2022).

Methodologically, China has adopted the "2006 IPCC Guidelines for the Preparation of National Greenhouse Gas Inventories," signaling a robust and internationally aligned approach. The scope of emissions sources has also been broadened to include six key GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and high-global-warming-potential fluorinated gases like hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Moreover, the inventory has evolved to encompass a broader array of sectors including energy, industrial processes, land use, land use change and forestry (LULUCF), waste, and agriculture (Table 8). This has also involved an evolution in methodology, transitioning from low-level to high-level methods for calculating emissions.

At the same time, MEE is increasingly beginning to focus on monitoring and evaluation systems for GHGs in its recent policies, including its *Outline of Ecological and Environmental Monitoring Plan (2020 – 2035)*, *14th Five-Year Ecological and Environmental Monitoring Plan (2021), Implementation Plan on Accelerating the Establishment of A Unified and Standardized Carbon Emission Statistics and Accounting System (2022)*, and *the Medium- and Long-term Development Plan for Eco-Satellites (2022).* For methane specifically, for instance, MEE is exploring the use of remote sensing satellite data for understanding the concentrations and spatial and temporal distributions of global methane emissions. In the oil and gas industry, pilots have been launched to explore methane leakage detection in production processes through integrated satellite and unmanned aerial vehicle and cruise monitoring systems. Coal mining industry pilots are also exploring collaboration in monitoring technology through the use of existing coal mine safety monitoring systems (MEE, 2023a). Most recently, the need to improve MRV systems for methane has also been emphasized in China's National Methane Action Plan released in November 2023.

However, the current multi-institutional approach to compiling the inventory does have its drawbacks. The UNFCCC Secretariat’s technical analysis has highlighted areas for improvement, such as the transparency of China’s inventory reports, completeness of emission sources, and consistency in time-series data. Further, some basic data relies on expert collection or estimation through surveys, which can lead to significant challenges in the continuity of work and data reliability (Feng, 2022). These issues are crucial to address, given China’s significant role in global GHG emissions and its potential impact on international climate change mitigation efforts.

Greenhouse Gas Accounting and Reporting Guidelines

China has progressively developed and implemented industry-specific guidelines. Between 2013 and 2015, the National Development and Reform Commission (NDRC) introduced the “Guidelines for Accounting and Reporting of Greenhouse Gas Emissions (Trial)” specifically for 24 industries (NDRC, 2013; NDRC, 2014; NDRC, 2015). This initiative was extended in March 2021, when the Ministry of Ecology and Environment (MEE) promulgated an additional set of guidelines addressing power generation facilities (MEE, 2021).

The primary objective of these guidelines is to establish a standardized protocol, enabling enterprises to accurately account for and report their carbon emissions. Detailed within the guidelines are specific methodologies, encompassing both the demarcation of accounting boundaries and the exact calculation methods to be employed. Furthermore, the guidelines stipulate default parameter values, ensuring a consistent approach while also accommodating China’s unique industrial and environmental context. A notable feature of these guidelines is their grounding in the internationally recognized “GHG Protocol – Corporate Accounting and Reporting Standard” (WRI, 2004). However, the Chinese adaptation offers tailored provisions, reflecting the intricacies and nuances of the nation’s diverse industries.

The scope of application for these guidelines is expansive, encompassing all production entities and sites operating under the jurisdiction of domestic enterprises. Beyond their primary role, these guidelines serve many purposes, acting as a key reference for tasks such as the formulation of GHG information disclosure systems within sectors, the facilitation of carbon emissions trading, and the enhancement of enterprise-level GHG accounting frameworks.

Table 8. Sector-level GHG emission reporting guidelines and associated gases

Sector	GHGs reported
Aluminum Electrolysis Production	PFCs, CO_2
Power Grid	SF_6, CO_2
Power Generation	CO_2 only
Iron and Steel Production	CO_2 only
Chemical Production	CO_2, adipic acid and nitric acid (N_2O and CO_2)
Magnesium Smelting	CO_2 only
Civil Aviation	CO_2 only
Flat Glass Production	CO_2 only
Cement	CO_2 only
Ceramic Production	CO_2 only
Independent Coking	CO_2 only
Coal Production	CH_4, CO_2
Petrochemical	CO_2 only
Oil and Natural Gas Production	CH_4, CO_2
Pulp and Paper Production	CO_2, CH_4 (during wastewater treatment)
Other Non-Ferrous Metal Smelting and Processing Industry	CO_2
Electronic Equipment Manufacturing	CO_2, HFCs, PFCs, NF_3, SF_6
Mechanical Equipment Manufacturing	CO_2, SF_6, HFCs, PFCs (leakage from electronic or cooling or refrigeration facility manufacturing process)
Mining	CO_2
Food, Tobacco, and Alcohol, Beverage, and Refined Tea	CO_2, CH_4 (during wastewater treatment)
Public Building	CO_2
Land Transport	CO_2; CH_4 and N_2O (fossil fuel combustion in highway passenger, road freight, urban public bus and tram, and taxi transport)
Fluorine Chemical	CO_2, HFCs, PFCs, SF_6
Other Industrial	Industrial Wastewater: CO_2 and CH_4 (N_2O not included); CH_4 recovery and destruction: CH_4

Source: NDRC, 2013; NDRC, 2014; NDRC, 2015; MEE, 2021.

Enterprises can voluntarily release their emission reports through a public platform organized by the MEE. However, enterprises covered by the emission trading system must report their GHG emissions, including CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, and NF_3, to the local ecology and environmental department. These enterprises are also required to regularly disclose their annual GHG emission reports to the public (MEE, 2020).

Greenhouse Gas Emissions Standards

The National Carbon Emission Management Standardization Technical Committee (SAC/TC548) was established and is guided by the MEE. This body is responsible for revising and developing national standards related to carbon emissions, including carbon emissions management terminology, statistics, and monitoring; methods for compiling regional carbon emission inventories; carbon emissions accounting and reporting at the corporate and project levels; low-carbon technologies and equipment, such as low-carbon products, carbon capture, and carbon storage; and carbon neutrality and carbon sinks, among other related fields (SAC, 2023). The China National Institute of Standardization is the key player in providing technical support for the Technical Committee.

Currently, 16 national standards have been established to create a comprehensive system spanning six categories: basic principles, accounting and reporting, evaluation, verification, technology, and management services (SAC, 2023). This system standardizes the methodologies and protocols to which enterprises must adhere in calculating and disclosing their GHG emissions. Additionally, the standardization process is continuously evolving, with over 30 new or revised standards currently under development (SAC, 2023). These include not only industry-specific GHG accounting and reporting standards, but also project emission reduction accounting standards, verification standards, corporate carbon management standards, and product carbon emission limits. This suite of standards aims to provide a cohesive and unified framework to guide enterprises in their GHG accounting and reporting activities.

Key Enterprises Greenhouse Gas Emissions MRV System

Since 2014, China has implemented a reporting system targeted at key enterprises and institutions that are major GHG emitters (NDRC, 2014). This framework has been rolled out across eight critical industries: power generation, petrochemicals, chemicals, building materials, steel, non-ferrous metals, papermaking, and aviation.

Since 2018, regional initiatives have been implemented in Shaanxi, Sichuan, Jiangxi, Jilin, and Zhejiang. These provinces have issued management guidelines requiring companies in key industries that participate in carbon market transactions to disclose their GHG emissions information when their annual emissions exceed 26,000 tons of carbon dioxide equivalent (Shaanxi PDRC, 2018; Sichuan PDRC, 2018; Jiangxi PDEE, 2019; Jilin PDEE, 2018; Zhejiang PDRC, 2018). These regional efforts underscore the growing consciousness and administrative rigor at sub-national levels in managing and mitigating greenhouse gas emissions.

In a broader national context, the Ministry of Ecology and Environment further bolstered transparency and accountability in 2021 by issuing the “Administrative Measures for Enterprise Environmental Information Disclosure” (MEE, 2021). This national directive mandates that many entities – including key polluting units, companies subject to mandatory clean production audits, listed companies that meet specific criteria, and bond-issuing companies, among others

– to disclose their carbon emissions information. This represents a significant step toward greater corporate responsibility and a more holistic approach to environmental governance in China.

In addition, the “Notice on Strengthening the Management of Greenhouse Gas Emission Reporting for Enterprises” was released in 2021 to require a series of MRV actions in key emitting industries: power generation, petrochemicals, chemical industry, building materials, steel, non-ferrous metals, papermaking, and aviation (MEE, 2021). Covered enterprises have emitted greenhouse gases totaling 26,000 tons of carbon dioxide equivalent or more during any year from 2013 to 2020. For the power sector, covered enterprises are the key emitting units identified in the “List of Key Emitting Units Included in the National Carbon Emission Rights Trading Quota Management for 2019-2020” (MEE, 2020), as well as newly added key emitting units in 2020. Actions that must be undertaken under this notice include: GHG emission reporting via the aforementioned MEE environmental information disclosure platform; emission report verification; submission and publication of list of key emitting enterprises and related materials; emission allowances verification and compliance; and monitoring.

While the GHG emissions MRV system for key emitting units has laid a robust data foundation for quota allocation in the national carbon emissions trading market, it currently encompasses only around 10,000 key emitting units (Liu et al., 2022). This leaves a considerable number of general carbon-emitting units yet to be incorporated, signaling a gap in comprehensive data collection for policy formulation.

Clean Development Mechanism (CDM)

The Clean Development Mechanism (CDM), a provision under the Kyoto Protocol, offers a pathway for developed countries to offset their carbon emissions by financing carbon reduction projects in developing nations (UN, 2023). China has been a major participant in this program, hosting over 3,000 registered CDM projects, making it the world’s largest host country for such initiatives (Zhang et al., 2018). These projects span multiple sectors, including but not limited to renewable energy, energy efficiency, and waste management.

To maintain credibility and ensure environmental integrity, these projects are subject to stringent MRV requirements mandated by the UNFCCC. Complying with these standards allows the projects to generate Certified Emission Reductions (CERs), which are tradable credits that developed nations can purchase to fulfill their own emission reduction commitments under the Kyoto Protocol.

In China, the responsibility for CDM implementation falls under the National Development and Reform Commission (NDRC). The NDRC has set up a comprehensive system that includes the creation of baseline scenarios against which emission reductions can be measured, as well as detailed monitoring plans (NDRC, 2011). It also mandates regular verification processes and oversees the reporting of emissions reductions to ensure compliance with international standards.

The number of new CDM projects in China has dwindled in recent years. This decline is attributed to a decrease in global demand for CDM credits along with a simultaneous uptick in

China's own domestic carbon markets, which offer alternative avenues for emissions trading and reduction within the country.

China Certified Emission Reduction (CCER)

The China Certified Emission Reduction (CCER) is a domestic carbon offset mechanism within China's national voluntary greenhouse gas emission trading system (MEE, 2012). It enables enterprises to purchase verified emission reductions to offset their own carbon emissions. Modeled on the Clean Development Mechanism (CDM), the CCER process is rigorous and involves six main steps: project document design, approval, record-keeping, implementation and monitoring, emission reduction verification and certification, and finally, the issuance of emission reductions.

A notable feature of the CCER market is its inclusivity, allowing non-key emitting enterprises to participate. This expands the scope beyond the national carbon market, which primarily focuses on quota trading among key emitting enterprises. The CCER market thus acts as an alternative platform for voluntary emission reductions, making it easier for enterprises of any emissions profile to purchase CCERs as a means of offsetting emissions. Furthermore, the CCER market often offers a more cost-effective solution for compliance, as the price of CCERs is typically lower than that of quotas in the national carbon market.

CCER was launched in 2012, but due to reasons such as individual projects not being standardized and low trading volumes, new project approvals have been suspended since 2017 (NDRC, 2017). However, projects that have already registered can still proceed with trading.

In late 2021, the Ministry of Ecology and Environment integrated the CCER with the national carbon market for compliance obligations (MEE, 2021). This led to an increase in the market price of CCERs. To prevent an oversaturation of CCERs in the national carbon market, a cap of 5% has been imposed on the proportion of CCERs that can be used for offsetting purposes (MEE, 2021). This aims to strike a balance by expanding market participation and reducing compliance costs, while still maintaining the integrity of emission reduction efforts.

In July 2023, the Ministry of Ecology and Environment released the "Administrative Measures for the Management of Voluntary Greenhouse Gas Emission Reduction Trading (Trial) (Draft for Solicitation of Comments)" (MEE, 2023b). The "Administrative Measures" emphasize the voluntary nature of trading and streamline the management methods for five items requiring registration, namely, the original methodologies for voluntary greenhouse gas emission reduction, projects, emission reduction volumes, validation and verification organizations, and trading institutions. After a six-year suspension in approvals, CCER is expected to make a comeback in 2023.

3.2 Barriers

As China progresses in the establishment of its GHG MRV system, several significant barriers remain. These include insufficient legal and institutional support, which makes the enforcement and standardization of protocols difficult. Additionally, technical guidelines and standards are not yet fully developed, compromising the quality and reliability of collected data. Variability in the capabilities of third-party verification agencies adds another layer of complexity, eroding trust in the data generated. Finally, there is a pressing need for capacity building at both the governmental and enterprise levels to effectively implement and manage the MRV system. These barriers impact the efficiency and credibility of China's GHG MRV system.

3.2.1 Insufficient legal and institutional support

In the pursuit of effective GHG MRV, China faces a series of legal and institutional challenges that undermine the system's efficacy. These barriers can be organized into three primary categories: regulatory deficiencies, data collection limitations, and insufficient incentive structures.

Firstly, regulatory deficiencies manifest in the lack of a formalized framework that delineates the essential elements of an MRV system, such as timelines, technical requirements, and roles and responsibilities for participating entities. The absence of clear guidelines results in a piecemeal approach to GHG data reporting and verification, impeding standardization. Without a unified framework, local governments and corporations are left to navigate a complex and ambiguous set of requirements, thereby encountering unexpected challenges that hinder the MRV system's effective implementation (Qian et al., 2018).

Secondly, data collection limitations further exacerbate the system's inefficacy. Current practices mainly rely on public statistics and *ad hoc* corporate monitoring systems, which fail to provide comprehensive and granular data on GHG emissions (Qian et al., 2018). This gap in data quality and quantity restricts the MRV system's ability to offer transparent and accurate reporting. For the MRV system to function optimally, it needs a robust legislative framework that mandates detailed data collection at multiple operational levels, including facilities, specific processes, and product life cycles.

Lastly, the ineffectiveness of the MRV system is compounded by insufficient incentive structures. The existing policy framework imposes only minimal penalties for non-compliance, with fines not exceeding 100,000 yuan (MEE, 2021). These minimal penalties do not provide a compelling business case for enterprises to invest in comprehensive GHG accounting and reporting systems. They also breed a general lack of enthusiasm among enterprises for adhering to GHG emissions disclosure requirements, thus reducing the system's overall effectiveness (PwC, 2022).

3.2.2 Incomplete technical guidelines and standards

The primary goal of an MRV system is to secure accurate and measurable data on GHG emissions from companies that release carbon. To maintain trust in the system, it is essential that the processes for monitoring, measuring, reporting, and verifying this data follow uniform protocols. However, China has yet to develop a comprehensive set of technical guidelines and standards tailored for MRV systems.

While the NDRC has put forth some established guidelines and standards to maintain uniformity in GHG emissions calculations, these have shown limitations, particularly in complex sectors like chemicals, petrochemicals, iron, and steel (Qian et al., 2018). Specifically, there is a lack of agreed-upon criteria for defining the scope of a company's GHG emissions, its disclosure, and its management (PwC, 2022). As a result, the way data is processed can differ significantly among companies within the same industry, across different sectors, and among companies located in different regions (Qian et al., 2018). Moreover, existing technical standards for monitoring and verifying data are still incomplete. This leads to uneven quality in the disclosed information on GHG emissions, and a lack of data comparability allows companies to selectively report emission information that paints them in a favorable light. Thus, businesses might give the impression that they are effectively managing their carbon footprint, while often omitting less flattering emission data, thereby reducing the credibility of carbon information disclosure (PwC, 2022).

3.2.3 Shortage of qualified third-party verification

Third-party independent verification is essential for upholding data integrity and ensuring the quality of emission information. Given the intricate and specialized nature of carbon emission monitoring, various factors like the completeness of monitoring strategies, the precision of measuring devices, and the sampling frequency in labs can all influence the calculation of carbon emissions (PwC, 2022). The lack of external verification can cast doubts on the transparency and objectivity of the reported GHG emissions, jeopardizing their credibility. However, China has a deficit of skilled verification firms. While the NDRC has set forth guidelines for how to choose verification organizations (NDRC, 2016), real-world implementation often diverges from these guidelines. To meet deadlines, local authorities frequently focus on speed more than quality and employ bidding mechanisms, leading some verification companies to engage in cost-cutting competition, thereby diminishing the quality of their services (Qian et al., 2018).

In the realm of quality control, China lacks efficient supervisory methods for managing these verification entities. No frameworks exist for performance evaluation, and penalties for subpar performance are insufficient (Qian et al., 2018). Although localities may conduct evaluations or solicit expert opinions on verification firms, there is no national standard for quality control (Qian et al., 2018). The upshot is a significant oversight gap in the regulation of verification companies.

3.2.4 Gap in capacity building

Effectively implementing an MRV system requires both a detailed understanding of the industry at hand as well as a mastery of the specific rules, standards, and guidelines governing MRV procedures. While the NDRC has led efforts to train stakeholders in the national MRV system, there are still several areas that could be optimized, such as inter-agency coordination, budget allocation, educational content, and how training is carried out. On a regional level, although local governments, especially those with existing pilot programs aimed at capacity building, have contributed to training, the outcomes vary due to the absence of a cohesive national policy and standardized technical advice.

In the corporate arena, there is a significant gap in the expertise and talent needed to disclose GHG emissions effectively. The practice of carbon emissions disclosure is still relatively new for many local businesses, which often lack specialized teams or departments to handle this responsibility (PwC, 2022). This deficiency hinders their ability to accurately manage and report GHG emissions. Moreover, the labor market is short on experts who specialize in GHG emissions. Also, GHG emissions sources can differ considerably between industries, resulting in industry-specific barriers to monitoring and accounting for GHG emissions. Professionals responsible for GHG emission disclosure are therefore required to have specialized know-how in GHG-related matters, along with an in-depth understanding of their respective industry's production process (PwC, 2022).

4. Suggestions for China's MRV System for Non-CO_2 GHGs

The establishment of a GHG MRV system plays a vital role in assessing emissions, identifying reduction opportunities, informing policy decisions, attracting financial support, and meeting global climate obligations. By implementing an efficient MRV system, governments and industries can strengthen their commitment to combat climate change and foster a sustainable and greener future. We provide several recommendations for China to consider as it refines its non-CO_2 GHGs MRV system.

4.1 Identify responsible government agencies and provide institutional support

To date, no agency has been designated as being responsible for the MRV of non-CO_2 GHG emissions, which have been included in the overall GHG MRV. The government can identify the specific agencies dedicated to non-CO_2 GHGs, and these agencies can then coordinate stakeholder relationships and provide technical support, develop technical guidelines, and regulate policies.

It is also important to establish interdepartmental collaboration mechanisms. Government agencies, once identified, need to clarify their respective responsibilities to ensure that the monitoring, reporting, and verification of non-CO_2 greenhouse gas emissions is implemented effectively.

Importantly, government agencies can engage with stakeholders such as industry associations, non-governmental organizations, and academic institutions to build support for the development and implementation of MRV systems.

Over time, the government can increase funding for the monitoring, reporting, and verification of non-CO_2 greenhouse gas emissions to support the work of agencies, enterprises, and third-party institutions, and improve the quality and efficiency of monitoring and verification activities.

4.2 Develop relevant policies and regulations

Governments can develop policies and regulations to support the development and implementation of MRV systems for non-CO_2 greenhouse gas emissions. These policies could include mandatory reporting requirements, financial incentives, and penalties for non-compliance.

- Mandatory reporting: The MRV system should establish mandatory reporting requirements for certain sectors and activities that are significant sources of non-CO_2 greenhouse gas emissions.
- Voluntary reporting: The MRV system can also establish voluntary reporting programs to encourage participation from sectors and activities that may not be subject to mandatory reporting requirements.
- Reporting templates: Standardized reporting templates can be developed to ensure consistency and comparability of reported data.

4.3 Improve standards and technical guidelines

Improving China's technical guidelines and standards for MRV of non-CO_2 greenhouse gas emissions is important for several reasons. It can ensure consistency, accuracy, and reliability of emissions data, build trust and credibility in the MRV system, and enable easier comparison of data with other countries. To improve its technical guidelines and standards, China should develop sector-specific guidelines, incorporate international standards, enhance data quality, promote transparency, and involve stakeholders in the development process. Pilot projects can be conducted to test and refine the technical guidelines before widespread adoption. Capacity building programs can be developed to provide stakeholders with the skills and knowledge needed to implement technical guidelines effectively.

- Develop sector-specific guidelines: Technical guidelines should be tailored to specific sectors and emission sources, such as energy, transportation, agriculture, and waste management. This will help ensure that guidelines are practical and feasible for relevant stakeholders and can capture the unique characteristics of different emissions sources.
- Incorporate international standards: International standards, such as the Greenhouse Gas Protocol, should be incorporated into the technical guidelines and standards for non-CO_2 greenhouse gas emissions. This will help ensure that China's MRV system is consistent with international best practices and facilitate comparison of data with other countries.
- Enhance data quality: Technical guidelines and standards should provide clear requirements for data quality assurance and control, including regular calibration of instruments, data validation, and quality assurance procedures. Third-party verification should also be required to ensure the accuracy and reliability of data.
- Promote transparency: Technical guidelines and standards should promote transparency by requiring the disclosure of data and methodologies used in the MRV system. This will improve public trust and enable stakeholders to verify data accuracy.
- Involve stakeholders: Technical guidelines and standards should be developed in consultation with stakeholders, including industry associations, research institutions, and non-governmental organizations. This will help ensure that the guidelines and standards are practical and feasible and can be implemented effectively.

4.4 Enhance research and development for detection and quantification technologies

To effectively monitor GHG emissions, it is essential to strengthen research and development for detection technology equipment. This includes domestic development of key remote sensing technologies for methane measurement, which can help strengthen China's ability to measure and verify its methane emissions with greater rigor. Improving monitoring technologies translates into improvements in the accuracy, efficiency, and reliability of monitoring systems, thereby enabling more precise data gathering on GHG emissions.

4.5 Establish demonstration testing sites for sectors with less mature detection technologies

In recognition of the varying levels of technological maturity across different sectors, it is imperative to support and promote the development of monitoring capabilities in areas where such technologies are still in their early stages. This could include sectors like abandoned mines and fluorine industries, where environmental monitoring may be less mature or challenging due to sector-specific complexities. Establishing demonstration testing sites in these sectors would encourage the adoption and refinement of cutting-edge monitoring technologies. Such sites would serve as testbeds for experimenting with new equipment, methodologies, and best practices, ultimately leading to more comprehensive and reliable environmental monitoring across the board. Expanding the application of detection technology and fostering collaboration among government agencies, research institutions, and private enterprises will be key to building a robust and integrated environmental monitoring system.

4.6 Improve the reporting and data management system

A comprehensive reporting and data management system for MRV is critical on many levels: ensuring accurate and reliable emissions data, facilitating decision-making, enhancing transparency and accountability, supporting emissions trading and carbon markets, and improving efficiency and cost-effectiveness. Currently, GHG emission reports must be submitted via the MEE environmental information platform, which collects and stores emission data. But this system can be improved to store data in a more consistent and organized manner. China has started to develop a national monitoring system for carbon tetrachloride (CTC) by-product production where enterprise real-time emission monitoring systems for CTC are connected to a national online platform. Moreover, data analysis and visualization functions can also be incorporated.

- Data analysis: Procedures should be established to analyze emissions data and identify trends and patterns.
- Data visualization: Data visualization tools can be used to present emissions data in a clear and understandable format.

4.7 Improve the quality of third-party verification

Third-party verification is crucial for improving the MRV of non-CO_2 GHG emissions in China. Third-party verification helps to ensure that data reported by companies and organizations is accurate and reliable; builds trust between stakeholders, including regulators, companies, and the public; and identifies areas for improvement in emissions reporting and measurement.

- Capacity building: Capacity building programs can be developed in collaboration with international organizations and other countries to provide third-party verification organizations with the skills and knowledge needed to verify non-CO_2 greenhouse gas emissions effectively.
- Accreditation programs: Accreditation programs can be established to certify third-party verification organizations. Such programs could be developed in collaboration with relevant stakeholders and international organizations.
- Quality control and assurance: Quality control and assurance procedures can be established to ensure the accuracy and consistency of verification results.

4.8 Provide capacity building and training

Capacity building and training are essential for improving the MRV of non-CO_2 GHG emissions in China. Skilled personnel are needed to accurately measure and report GHG emissions, as well as verify reported data. Capacity building and training can also help align MRV systems across organizations and sectors, which is essential for comparing emissions data and tracking progress towards climate goals. In addition, capacity building and training can promote the adoption of best practices and technologies, which in turn can lead to more efficient and accurate GHG emission measurement and reporting.

- Training programs: Training programs can be developed to provide stakeholders with the skills and knowledge needed to develop and implement MRV systems for non-CO_2 greenhouse gas emissions.
- Technical assistance: Technical assistance can be provided to help stakeholders overcome any technical challenges they may encounter during the development and implementation of MRV systems.
- Stakeholder engagement: Stakeholder engagement activities can be organized to build support for the development and implementation of MRV systems and to address any stakeholder concerns or feedback.

4.9 Monitor and evaluate the MRV system

Monitoring and evaluating the MRV of non-CO_2 GHG emissions in China is critical to ensuring emissions reductions and progress towards climate goals. By regularly monitoring and evaluating the MRV system, it is possible to identify gaps, inconsistencies, and errors in reported data, which can lead to improvements and adjustments to the system. Monitoring and evaluation can also identify areas where additional capacity building and training are needed. Additionally, monitoring and evaluating the MRV of non-CO_2 GHG emissions in China can provide insights into the effectiveness of emissions reduction policies and programs, which can inform future policy decisions. For example, combining top-down and bottom-up approaches for measurements can help improve accuracy of emission estimates and reduce uncertainties. Overall, monitoring and evaluating the MRV system is crucial for ensuring that China is making progress towards its emissions reduction goals and for informing ongoing efforts to address climate change.

- Data reviews: Data quality checks can be performed regularly to identify gaps or inconsistencies in the data. Emissions data can be compared to national and international benchmarks to assess progress towards climate goals.
- Stakeholder consultations: Stakeholder consultations can be organized to gather feedback and input on the effectiveness of the MRV system and identify areas for improvement.
- Periodic assessments: Periodic assessments can be conducted to evaluate the effectiveness of the MRV system and identify areas for improvement.

5. Additional Resources

U.S. Greenhouse Gas Reporting Program (GHGRP)

- GHGRP Methodology Factsheet
- GHGRP BAMM Factsheet
- Subpart C Methodologies Factsheet
- GHGRP Verification Factsheet

California Mandatory Greenhouse Gas Emissions Reporting (MRR)

- GHG Mandatory Reporting Regulation
- Determining Rule Applicability
- Measurement Accuracy and Missing Data Provisions
- GHG Regulation Training Sessions and Materials
- Cal e-GGRT Reporting Tool and Training
- Verification and Audits

California Cap-and-Trade Program

- Cap-and-Trade Program: Allowance Distribution Factsheet
- Auction Settlement Prices and Results Summary
- Cap-and-Trade Program Data Dashboard
- Emissions Market Assessment Committee (EMAC)
- Market Simulation Group (MSG)

California Greenhouse Gas Emission Inventory Program

- Technical Support Document
- Supplemental Method Updates Document (Years 2017-2021)
- GHG Inventory Query Tool
- Short Lived Climate Pollutant (SLCP) Inventory

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California Air Resources Board. Mandatory Greenhouse Gas Reporting Regulation. https://ww2.arb.ca.gov/mrr-regulation

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