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AN OVERVIEW OF GHG MONITORING: OBJECTIVES AND TECHNOLOGIES

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ACRONYMS AND ABBREVIATIONS

AI	Artificial Intelligence
AMLD	Advanced mobile leak detection
APEC	Asia-Pacific Economic Cooperation
CARB	California Air Resources Board
CEMS	Continuous emissions monitoring system(s)
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DOAS	Differential Optical Absorption Spectrometer
EPA	Environmental Protection Agency (United States)
FTIR	Fourier transform infrared spectrometer
GF-5	Gaofen-5
GHG	Greenhouse gas
HFC	Hydrofluorocarbon
HVAC	Heating, ventilation, and air conditioning
IOS	International Organization for Standardization
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act of 2022 (United States)
LEO	Low Earth orbit
LDAR	Leak detection and repair
LIDAR	Light Detection and Ranging
MoEF	Ministry of Environment and Forestry (Indonesia)
n.d.	No date / undated
N_2O	Nitrous oxide
NASA	National Aeronautics and Space Administration (United States)
NDIR	Nondispersive Infrared Sensor
NIST	National Institute of Standards and Technology (United States)
OCO	Orbiting Carbon Observatory
PEMS	Predictive emissions monitoring system
PFC	Perfluorocarbon
PPB	Parts per billion
SF_6	Sulfur hexafluoride
TCCON	Total Carbon Column Observing Network
THEOS	Thailand Earth Observation System
UAV	Unmanned aerial vehicle
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development

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EXECUTIVE SUMMARY

Climate change constitutes an exigent global crisis and a shared challenge for Asia-Pacific Economic Cooperation (APEC) economies. While APEC stakeholders worldwide recognize the need to reduce greenhouse gas (GHG) emissions, mitigating the impacts of anthropogenic climate change poses numerous challenges (APEC 2023a). As such, establishing accurate and widely accepted GHG measurement and monitoring tools and techniques is fundamental to meeting those challenges. Measurement can serve as a valuable tool for analyzing a given emissions source, evaluating bottom-up emissions accounting, and for developing emissions inventories (Enivronmental Protection Agency (EPA) 2023a). Additionally, government or industry personnel can use emissions measurement to evaluate the performance of control strategies and to determine compliance with regulations that limit the amount of pollution a source may emit (EPA 2023a). Therefore, using a system of emissions measurement that is accurate, interoperable, reliable, and traceable is essential.

Global cooperation in addressing climate change necessitates an accurate—and widely accepted—assessment of emission inventories. Domestic and regional air emission inventories for GHGs are one of the primary sources of information for international climate change agreements and trading (Intergovernmental Panel on Climate Change (IPCC) 2006), providing key sources of information for policymakers and regional environmental protection agencies to assess the state of the environment (La Notte et al. 2018). Current emissions and removals of GHGs from various source and sink categories are estimated using a variety of methodologies, including emission factors, activity data, reporting data, and even direct emissions measurements (EPA 2023b). However, estimating GHG emissions involves inherent uncertainties due to a variety of factors, including the limited availability of sufficient and suitable data, as well as the absence of techniques for processing them (White et al. 2011). Additionally, there is a policy gap between standards for GHG measurement technologies and the methodologies and practices for developing emission inventories. Consequently, emissions inventories seek measurement technologies and data that support complete, well referenced, and quality-assured emissions profiles of air pollution to populate emissions databases and demonstrate compliance (EPA 2023c). Moreover, using atmospheric measurements in conjunction with other sources of emissions data and models proves to be a challenge when analyzing emissions sources and sinks.

As economies work to compile complete inventories of GHGs, measurement works to provide useful quality assurance of estimates, advance additional scientific verifications of inputs and results for particular gases and emissions categories, and help target areas of uncertainty (Calvo Buendia et al. 2019). Integrating proven and emerging measurement technologies into developing emission inventories can bolster efforts to reduce GHG emissions in APEC economies.

PROJECT OVERVIEW

This background paper explores the potential for APEC economies to implement innovative technologies to aid the measurement of atmospheric GHG emissions and the associated protocols for their adoption.[1] It provides an overview of the current suite of atmospheric measurement systems and devices, emerging technologies in the field, and key examples of what APEC economies are currently using to measure atmospheric GHG emissions. Additionally, this paper dives into the importance of

[1] According to the EPA, environmental measurement is any data collection activity or investigation involving the assessment of chemical, physical, or biological factors in the environment which affect human health or the quality of life (EPA 2023d).

aligning technologies with regulatory frameworks of emissions inventories to support the adoption and integration of effective measurement and monitoring practices.[2]

TECHNOLOGY OVERVIEW

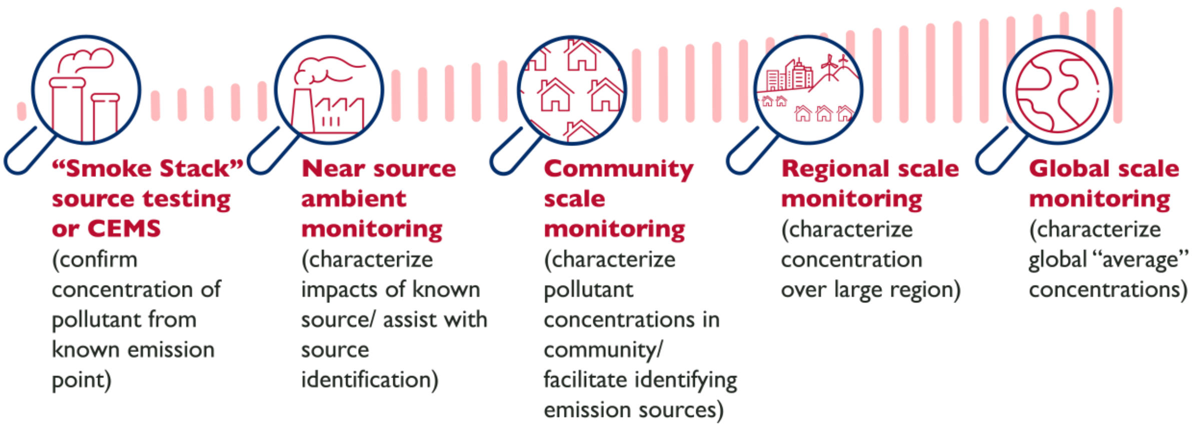
A robust, diverse, evolving set of sensors, platforms, and techniques are being employed globally to measure and monitor GHG emissions. This background paper provides APEC member economies with an overview of technologies related to GHG measurements, highlighting their integrative capabilities and their role in monitoring objectives. These technology applications include characterizing and quantifying GHG emissions, measuring air quality against domestic standards, identifying trends in emissions concentrations, providing real-time air quality information, assessing community exposure, and validating GHG models and emission inventories. Additionally, this paper summarizes the general capabilities and limitations of analytical field devices, remote sensing, surface-level monitoring, emissions analysis tools, and other technologies. It also describes measurement and monitoring technologies and methods in the following key categories:

- *Analytical Field Devices and Sensors.* These measurement technologies are the workhorses of the monitoring industry and are employed across a variety of use cases for a diverse portfolio of applications, many of which can further support GHG reduction efforts in APEC economies.
- *Remote Sensing Technologies.*
    - *Satellite Technology.* Satellite data can identify GHG emission plumes from land use, wildfires, biological activity, leakages, fossil fuel combustion, and other activities. Satellites provide the broadest geographic coverage for emissions detection and can detect larger releases of GHGs.
    - *Aerial Survey Technologies.* Analytical sensors attached to planes and unmanned aerial vehicles (UAVs), such as drones or balloons, are examples of aerial survey technologies that can be deployed to measure regional gas plumes or to spot smaller emissions sources.
    - *Unmanned Aerial Vehicles.* UAVs are capable of detecting minute leaks while monitoring a large area and are a useful tool for investigating, quantifying, and localizing leaks that are initially detected by other technologies.
    - *Tethered Balloons.* Tethered balloons are able to carry heavier payloads and have greater weather resistance at extreme altitudes, working in conjunction with other surface-level and aerial-survey instruments to collect atmospheric data.
- *Surface-Level Monitoring.* Ground-based, or equipment mounted, instruments located at or near the worksite that are capable of GHG detection or measurement. These instruments may be stationary or mobile and can be networked to provide more complete spatial coverage.

[2] According to the EPA, monitoring is a general term for on-going collection and use of measurement data or other information for assessing performance against a standard or status with respect to specific requirement (EPA 2023e).

Anthropogenic emissions of the seven Kyoto[3] gases come from a myriad of sources ranging from small emitters, such as personal vehicles, to large emitters, such as fossil-fueled power plants. Across these sources, measurement can be integrated and achieved on different scales—from the smokestack level to the global level (Figure 1). Accordingly, monitoring objectives will vary depending on the scale. These scopes, sources, and measurement objectives then inform the tools and techniques deployed to assess GHG emissions.

Figure 1: Monitoring Scales



Note: CEMS = continuous emissions monintoring system.
IMAGE SOURCE: AUTHOR

DEPLOYMENT

Economies are continuing to establish and implement measures to manage and address air quality (United Nations Environment Programme 2021). Moreover, economies are working to strengthen their initiatives to reduce emissions and align with pledged commitments, such as the Paris Agreement (Paris Agreement 2015). Collectively, these measures drive GHG emissions reductions and require the need for further pollution control equipment, technology, and measurement devices.

While there are several challenges to deploying GHG measurement technologies, one of the most significant is using atmospheric measurements in tandem with other sources of emissions data and models to infer sources and sinks. While these methods are continuing to emerge, they are still unproven at many scales and applications, making it a challenge to collate and integrate spatially explicit estimated fluxes of GHGs (Holmberg et al. 2021). Other challenges include implementation costs, estimation uncertainties, technology availability, lack of user experience, data accessibility, technology reliability and durability, and disparities in technological advancement.

CONCLUSION

[3] Kyoto as used here refers to the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). Among other things, the initial Kyoto Protocol set emissions standards for six categories of GHG emissions—carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (UNFCCC 2008). The Doha amendment to the Kyoto Protocol added nitrogen trifluoride (NF3) as a seventh gas, which entered into force in 2020 (The Doha Amendment n.d.).

Measurement and monitoring play a pivotal role in understanding and managing the sources and sinks of GHGs, helping to identify atmospheric GHG concentrations and fluctuations over time. As a result, these processes empower economies with the information to better mitigate future climate change events. Currently, many APEC economies are in the early stages of exploring GHG measurement methods, necessitating better understanding and increased adoption of technologies to more effectively manage emission sources. While there are many existing tools to measure GHG emissions, coupling the monitoring objective with the appropriate tool determines the equipment and strategy used to measure GHGs.

Domestic regulations and standards surrounding conventional pollutants have traditionally driven measurement and monitoring applications. However, many APEC economies are beginning to identify, develop, and strengthen their policies to measure GHGs, develop emission inventories, and contribute to global climate goals quality (United Nations Environment Programme 2021). Going forward, government incentives, new regulations and legislation, and voluntary carbon markets will continue to drive measurement and monitoring technology applications. Analyzing the measurement devices currently in use, the emerging technologies, and the protocols driving additional measurement adoption and integration provides APEC economies with the information needed to help mitigate future impacts of climate change.

INTRODUCTION

APEC economies account for about 60 percent of GHG (APEC Policy Support Unit 2021). They have also recognized the urgent need to combat climate change. However, reversing climate change caused by anthropogenic GHG emissions poses multiple challenges. While measuring emissions alone will not reverse the current impacts of climate change, establishing accurate and widely accepted GHG measurement tools and techniques is fundamental to meeting those challenges. Measurement and monitoring are needed to characterize the sources and sinks of GHGs, the atmospheric GHG concentrations, and fluctuations over time (National Academic Press 2010). Measurement and monitoring are also needed to evaluate emissions inventories, which can help determine significant sources of air pollutants and establish emission trends over time (EPA 2022). In turn, APEC economies can use this information to take action to mitigate the future impacts of climate change events.

While there are numerous measurement methods and technologies currently deployed to support the monitoring objectives of policymakers and governments (EPA 2022), APEC economies are still in the preliminary stages of integrating GHG measurement and developing emissions reductions protocols (APEC 2022). To gain further understanding of the various sources, sinks, and fluxes of GHGs, APEC economies need a deeper understanding of the effective and emerging array of measurements at each scale of atmospheric monitoring. Moreover, APEC economies need additional insight regarding the limitations of existing measurement devices and technologies.

No single measurement tool or method will work for all monitoring objectives or GHGs (Jonas et al. 2019). The capabilities and limitations of available measurement and monitoring equipment vary, and different equipment combinations may be needed depending on the objective of the monitoring activity (Christen 2014). For example, an existing technology may be designed to measure carbon dioxide (CO_2) at the ambient level, while the same technology may demonstrate greater performance variability when measuring CO_2 at the smokestack (i.e., a stationary source) (EPA 2023e). Adopting new and emerging technologies for GHG measurement will require integration into existing emissions data and models to infer sources and sinks, as well as an understanding of the appropriate technologies to achieve objectives.

APEC economies have noted the importance of combatting climate change and reducing GHG emissions. The Putrajaya Vision 2040, developed by APEC economies in 2020, calls for "promot[ing] economic policies, cooperation and growth which support global efforts to comprehensively address all environment challenges, including climate change… for a sustainable planet" (APEC 2022). In support of these goals, this background paper provides APEC member economies with an overview of GHG measurement technologies and highlights their integrative capabilities and roles in monitoring objectives. This overview includes summarizing the general capabilities and limitations of various types of measurement technologies and presenting a general guide that illustrates measurement solutions by sector. Last, it summarizes the current suite of technologies used and demand drivers of measurement.

IMPORTANCE OF MEASUREMENT AND MONITORING

Currently, most emissions and removals of GHGs from various sources and sinks are estimated using emissions factors, activity data, and reporting data (EPA 2023b). However, information gaps in emission factors and other data can embed uncertainty into these calculations, leading to inaccuracies, biases, or even gaps in emissions assessments (Frey 2006). Even for sources with continuous monitoring data, uncertainty can exist from predictions of future emissions that are informed from historical data (Frey

2006). Therefore, reinforcing emissions calculations with real-world information, existing sources of data, and emerging measurement technologies can help overcome the information gaps needed to reduce uncertainty and provide more accurate emissions calculations.

Global cooperation in addressing climate change also necessitates an accurate and accepted assessment of emission inventories. For example, the United Nations Framework Convention on Climate Change (UNFCCC) enshrines the importance of emission inventory reporting requirements (UNFCCC 2008). International cooperation to address climate change requires confidence in the integrity of reported progress to measure against reduction targets, to which emission inventories are the baseline.

Moreover, within individual economies, measurement is essential for evaluating the success of emission reduction targets, incentives, and protocols. Private sector-driven, voluntary emission reduction targets will depend on coupling emission factors and activity data with atmospheric measurements to validate and improve data; measurement is needed to support ambitious emission reduction efforts. As more measurement tools are deployed, growing datasets can be integrated with modeled estimates or economic data-based assessments to further reduce the inherent uncertainty, compared to using any one approach alone.

WHY MONITORING NETWORKS ARE VALUABLE

Assessing GHG emissions and their fluxes require a thoughtful approach to measurement and monitoring. While using a single technology can provide targeted measurement at a particular scale, the complexity of the global atmospheric system, diversity of emission sources, and gaps in currently available data make systematic emissions estimation more challenging. As a result, the most effective monitoring systems are likely to include multiple technologies operating at varying distances from potential leak points.

For APEC economies, the optimal use of components from individual measurements systems likely occurs when they are networked—sharing data and communicating with a central facility. For example, GHG monitoring for fugitive emissions typically involves a three-step process: detection, localization, and quantification. The optimal technology, or approach, for each step in the process may be different. An open path perimeter monitoring system or satellite-based tool might be optimal for initial detection, but neither is likely to provide precise localization or an accurate measure of leak rate. Similarly, a handheld optical gas imaging (OGI) camera may be the best technology for finding a precise leak point, but due to the labor-intensive nature of that technology, it would be a less effective choice for early detection.

Creating networks of measurement data can improve the analysis of data from existing sensor systems and emission models. Combining multi-scaled approaches of measurement improves understanding of GHG sources and provides more tailored solutions to reducing emissions (Allen 2014). In turn, these monitoring networks are essential to establishing a more robust and verifiable understanding of anthropogenic emissions, providing us the “ability to accurately measure, and model, carbon stocks and fluxes throughout the Earth [sic] system and across a range [of] spatial and temporal scales,” (Hurtt et al. 2022, 1).

MEASUREMENT AND MONITORING DEPLOYMENT

Conventional pollutant regulations have driven measurement technology deployment in many APEC economies. Specifically, these protocols have targeted emissions estimations and inventories at the member economy government scale, tracking GHGs across governments or sectors using typical emissions calculations, such as activity data and emissions factors, known as a "bottom-up" approach (UN Environment Programme 2022). While APEC economies have begun identifying pathways to reduce emissions from sectors, more work is required to set policy that will increase GHG measurement across value chains (APEC 2023b). Many APEC economies are looking to establish more comprehensive sets of domestic air quality-related standards and regulations to target particular industries and sources—these policies will simultaneously address GHG emissions and open opportunities for GHG monitoring. Folding these initiatives into emissions monitoring occurring from international protocols will drive demand for more measurement deployment and more innovative technologies that are critical for GHG reductions.

TECHNOLOGY OVERVIEW

A robust, diverse, evolving set of sensors, platforms, and techniques are being employed globally to measure and monitor GHG emissions. This section provides an overview of the primary measurement platforms and general capabilities of sensor equipment deployed for these purposes. This section also covers selected technology applications and offers examples to illustrate some of the most common approaches for quantifying GHG sources, sinks, and concentrations. This short review is necessarily incomplete, but it gives readers an introduction to measurement technologies and deployment strategies. All stakeholders would benefit from more detailed documentation of GHG measurement technology applications, capabilities, costs, and limitations. Coupling current and emerging technologies with published research, governing bodies, and industry experts will more effectively diffuse information and reduce roadblocks.

The initial Kyoto Protocol set emissions standards for six categories of GHG emissions: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (UNFCCC 2008). Additionally, the Doha amendment to the Kyoto Protocol added nitrogen trifluoride (NF_3) as a seventh gas, which entered into force in 2020 (United Nations Climate Change n.d.). While these emissions all trap heat in the atmosphere, these gases are emitted from a variety of sources at varying magnitudes, exist at different concentrations in the atmosphere, remain in the atmosphere for different amounts of time, and reflect different Global Warming Potentials (GWPs) (EPA 2023f).[4] Consequently, monitoring the accumulation of these gases in the atmosphere requires using a diverse class of high-precision devices at a variety of measurement points. Collectively, technologies can be integrated to provide a more accurate emissions portfolio and inventory across sources and sinks of GHGs. An integrated technological approach to emissions source detection can combine several techniques to detect, localize, and pinpoint emissions locations for repair or monitoring. For example, aerial measurements can calibrate and verify satellite measurements and identify sources needing better terrestrial or waterborne measurements. Without an integrative approach, the risk that researchers, policymakers, and stakeholders will misunderstand emissions and emission reduction progress remains significant. An integrated approach using several technologies to detect GHGs can produce more resilient and consistently verifiable data. Additionally, the development of standards and regulations that recognize this array of technologies must ensure interoperability for the highest potential for impact.

ANALYTICAL FIELD DEVICES AND SENSORS

Analytical field devices and sensors are used to measure common GHG emissions and pollutants, often used in environmental measurement applications where accurate and timely evaluation of air quality is

[4] The latest GWP values will be based on AR6 produced by IPCC (Smith et al. 2021).

needed to mitigate exposure or analyze purity. These devices use a variety of technologies which offer unique characteristics that make them effective tools to provide additional measurement data on GHG emissions from various sources and sinks. These measurement technologies are the workhorses of the monitoring industry and are used across a variety of use cases for a diverse portfolio of applications, many of which can further support GHG reduction efforts in APEC economies.

REMOTE SENSING TECHNOLOGIES

Remote sensing technologies include a variety of systems such satellites and various forms of aerial surveillance including piloted aircraft, unmanned aerial vehicles, and tethered balloons.

SATELLITE TECHNOLOGY

Satellite data can identify GHG emission plumes from land use, wildfires, biological activity, leakages, fossil fuel combustion, and other activities. They provide high-resolution, global observations of Earth's surface and atmosphere, providing the broadest geographic coverage of any monitoring approach. Although there are limitations on spatial resolution and sensitivity, the technology is sufficient to detect larger releases of methane and carbon dioxide. Moreover, satellites allow third party monitoring without requiring access to the desired site, enabling greater investigation of emission plumes.

Initially, satellite measurements of GHGs were focused on subcontinental scale characterization of land ecosystems and regional emissions, such as the GOSAT, GOSAT-2, TanSat, and OCO-2 satellites. Newer satellites have been developed with footprints on the scale of tens of meters and can evaluate emissions plumes from smaller scale sources, such as the GHGSat, PRISMA, EMIT, CarbonMapper, and MethaneSAT satellites. These satellites continue to offer the ability to analyze and illustrate the flow of GHG emissions across ecosystems, estimate the spatial distribution of energy consumption, and detect large-scale patterns and trends in ecosystem productivity (Hardwick and Graven 2016).

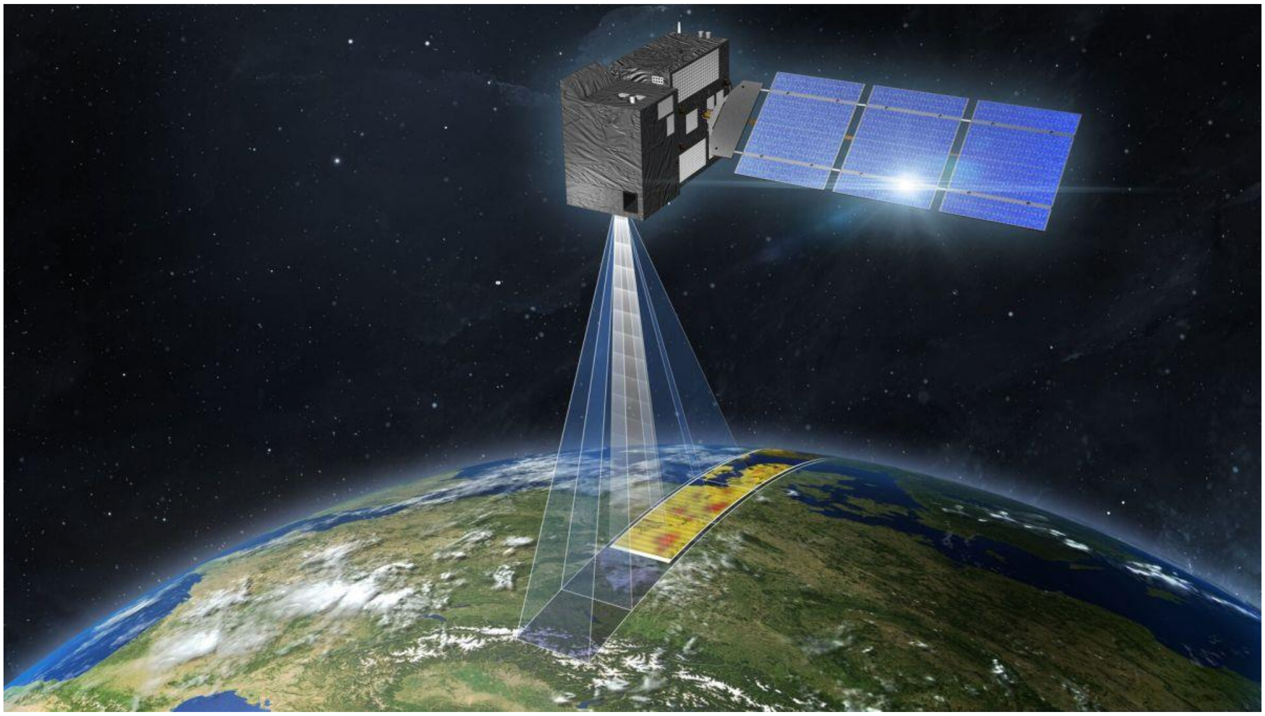
Satellite-based sensors primarily use spectrometers to measure the radiation at specific wavelengths from the solar radiation reflected from Earth's surface (Reddy 2018). Molecules of atmospheric gases absorb particular wavelengths of light, and each specific wavelength corresponds to a type of gas (National Aeronautics and Space Administration (NASA) 2023). Spectrometers use several wavelengths to measure methane and carbon dioxide in accordance with their absorption spectra (Lee and Wang, 2023). Satellite-based sensor platforms can be geostationary platforms or low Earth orbit (LEO), meaning they either continuously observe a particular location on earth or monitor activity from pole to pole (Reddy 2018). LEO orbits are sun-synchronous with a fixed crossing time, usually around local noon for best GHG retrieval performance, and other LEO orbits include processing ground tracks that result in the sensor sampling over the daylight interval. While less optimal in spectroscopy, these orbits can provide more insight into diurnal variability.

The Gaofen-5 (GF-5) civilian satellite is one of seven satellites part of the Chinese High-resolution Earth Observation System (CHEOS) program for land-use planning and environmental monitoring (NASA 2018). The GF-5 is the highest spectral resolution satellite operated by China and was its first satellite mission designated for atmospheric pollution (Chen 2016). It uses six onboard sensors to monitor atmospheric aerosol, sulfur dioxide, nitrogen dioxide, methane, water quality, and other components. These sensors include an Advanced Hyperspectral Imager (AHSI), a Visual and Infrared Multispectral Sensor (VIMS) for environmental monitoring, an Environment Monitoring Instrument (EMI) for monitoring pollutant gas columns, a Greenhouse Gas Monitoring Instrument (GMI) for measuring CO_2 and CH_4 concentrations, an Atmospheric Infrared Ultraspectral Sensor (AIUS) for measuring atmospheric emissions, and a Directional Polarimetric Camera (DPC) for observing atmospheric pollution (Chen et al. 2022). Together, these instruments use many pathways that enable the GF-5 to effectively detect the distribution, variation, and transportation process of major atmospheric pollutants, allowing it to monitor global climate change effectively (NASA 2018).

The Thailand Earth Observation System-2, or THEOS-2, is a remote sensing satellite developed by Thailand's Geo-Informatics and Space Technology Development Agency (GISTDA) (eoPortal, 2023). It is the successor to the first Thailand Earth Observation Satellite, THEOS-1, launched in 2008. THEOS-2 is designed to provide high-resolution imagery of the Earth's surface for various applications, such as land use management, natural resource management, disaster monitoring, and urban planning. It carries a multispectral camera with a resolution of 0.5 meters and a swath width of 16 kilometers, and a panchromatic camera with a resolution of 0.25 meters and a swath width of 10 kilometers (Thailand Geo-Informatics and Space Technology Development Agency 2005).[5] The satellite launched in 2023 from the Guiana Space Centre in French Guiana aboard an Arianespace Vega rocket (eoPortal 2022). It will operate in a sun-synchronous orbit at an altitude of 622 kilometers and has a mission life of five to seven years (Thailand Geo-Informatics and Space Technology Development Agency 2005). THEOS-2's space-based remote sensing technology and high-resolution imagery can support climate change mitigation efforts by enabling better monitoring and management of natural resources, detection and response to natural disasters, and support of urban planning and infrastructure development. THEOS-2 is expected to play a crucial role in helping Thailand address its environmental development challenges and meet its sustainable development goals (eoPortal 2022).

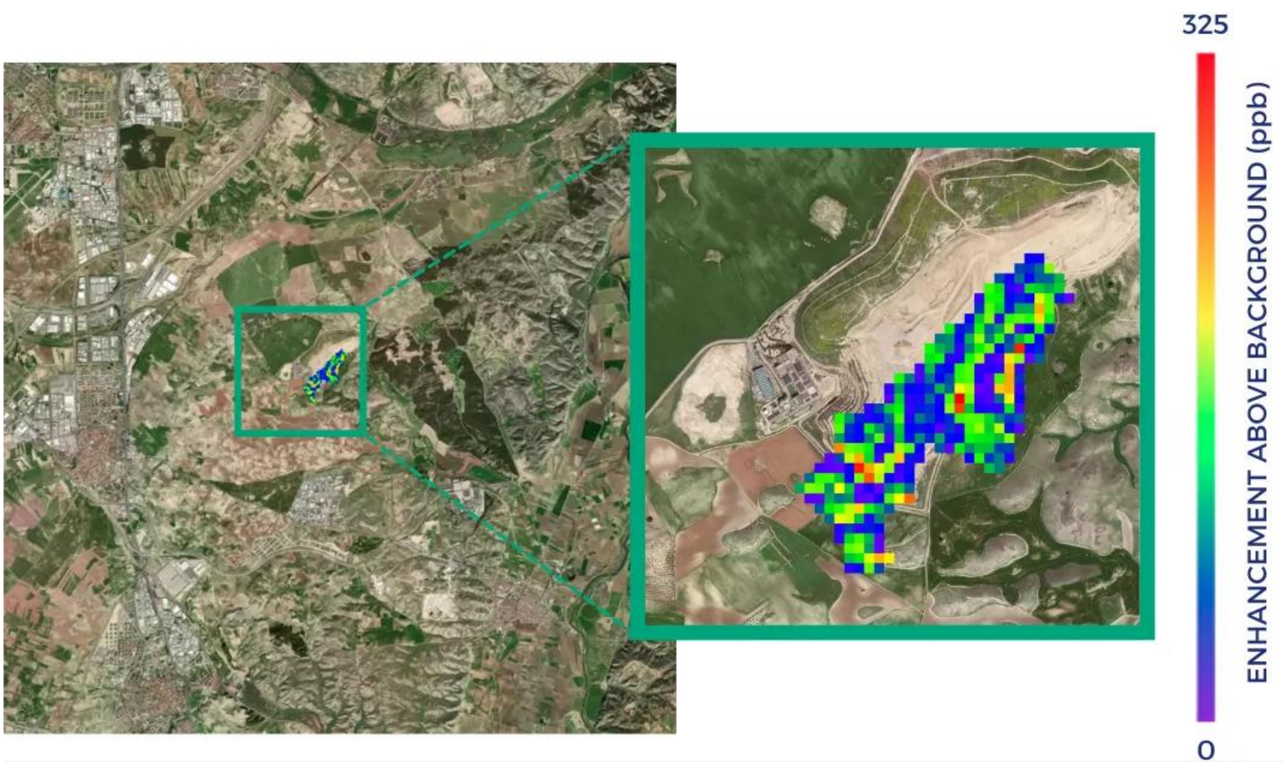
Satellites play a key role in monitoring networks by providing the broadest scale identification of emissions detection that enables better on-ground measurement of GHG emissions. While deploying satellites is costly, the information they gather is critical for GHG monitoring networks. Satellites can identify larger releases of GHG emissions, which are often the most impactful, providing complementary data for surface and aerial observations. Information about specific sources of methane and carbon dioxide can be incorporated into statistical models to verify and improve modeling accuracy. Additional tools may be needed to clarify the discrepancies in information when satellite results are at odds with surface-level measurement sources.

[5] Swath width refers to the strip of Earth's surface from which the data are collected by the satellite.



The Copernicus Carbon Dioxide Monitoring mission (CO_2M) will be able to spot individual sources of anthropogenic emissions of carbon dioxide.

IMAGE SOURCE: EUROPEAN SPACE AGENCY (ESA)



Plumes of methane leaking from a landfill in Spain were detected by Canadian company GHGSat.

NOTE: PPB = parts per billion
IMAGE SOURCE: ESA/GHGSAT

AERIAL SURVEY TECHNOLOGIES

Analytical sensors attached to planes and unmanned aerial vehicles (UAVs), such as drones or balloons, are examples of aerial survey technologies that can be deployed to measure regional gas plumes or to spot smaller emissions sources. Aerial surveying can detect emissions that are ten times smaller than those visible to satellites (Kairos Aerospace 2022). At a regional scale, aerial surveying measurements can perform better than surface-level measurements for applications with complex, large, or inaccessible structures. Like satellite systems, aerial surveys are useful for covering broader areas and detecting large leaks. However, compared to satellite-based monitoring, aerial surveys improve resolution and can also detect smaller releases.

There are two primary methods for aerial emission surveys. The first method involves collecting air samples to analyze later in a laboratory, such as the AirCore, invented by the National Oceanic and Atmospheric Administration (NOAA). The AirCore is an innovative atmospheric sampling system that can be deployed on an airplane, balloon, or UAV to sample the surrounding atmosphere and preserve a profile of the trace gas of interest from the middle stratosphere (12–50 kilometers) to the ground (Andersen et al. 2017). The second method involves using LIDAR (Light Detection and Ranging), NDIR (Nondispersive Infrared Sensors), or other spectrometers mounted on an airplane or UAV, measuring the absorption of reflected sunlight by gas molecules (Lee and Wang, 2023). LIDAR and NDIR can provide measurements of type-specific concentrations of GHGs with range resolution, allowing operators to visualize emissions with the human eye (Abshire et al. 2010). Once data from these instruments are analyzed, crews can be dispatched to repair any leaks.

UNMANNED AERIAL VEHICLES

Drones, also known as UAVs, are capable of detecting minute leaks while monitoring a large area. Mounted with sensors, these devices are capable of developing a "three-dimentional image" of methane plumes, allowing for greater accuracy in calculating release rates. For example, rather than surveying and measuring diffuse emissions from landfills using handheld sensors, deploying UAVs enables more frequent and efficient monitoring of landfills. UAVs are a useful tool for investigating, quantifying, and localizing leaks that are initially detected by other technologies (Gålfalk et al. 2021).

Australia's Carbon Dioxide Monitoring Rotorcraft Unmanned Aerial Vehicle is an example of a CO_2 sensing and monitoring device (Poppa et al. 2013). This device creates detailed gas distribution maps of larger areas using an NDIR sensor with high accuracy and fast measurement times. This device is more economical than using several stationary surface-level monitors or deploying handheld mobile sensors, and offers space to accompany other sensors as well.

T-Rex 700E flying over a CO_2 source.

IMAGE SOURCE: BEN COUGHLAN, DEVELOPMENT OF A CARBON DIOXIDE MONITORING ROTORCRAFT UNMANNED AERIAL VEHICLE

It is important to note that drone-based emissions measurements are still a relatively new technology with some limitations. For example, the accuracy of the measurements taken by drones may be affected by environmental factors and the distance from the emissions source. Although aerial surveying techniques can verify satellite data and provide information about regional carbon sources, these technologies can be weather dependent. Additionally, the regulations regarding drone use may vary between jurisdictions, so it is important to check the laws of where the measurements will be taken. Integrating surface-level measurement technologies further reinforces data collected by UAVs for small GHG emissions and leaks.

TETHERED BALLOONS

Tethered balloons are used in China for GHG monitoring. These systems provide the distinct advantage of carrying heavier payloads and having greater weather resistance at extreme altitudes, working in conjunction with other surface-level and aerial-survey instruments to collect atmospheric data (United States Department of Energy 2021). For example, the Jimu 1 is a series of giant helium-filled tethered airships developed by Chinese scientists to collect atmospheric data and study the effects of climate change. Known as aerostats, the Jimu 1 Models I–III carry numerous scientific instruments to measure moisture transportation, soot, dust, methane, ozone, and carbon dioxide in the atmosphere (Zhang 2022). In the United States, restrictions imposed by the Federal Aviation Administration make it nearly impossible to deploy tethered systems.

SURFACE-LEVEL MONITORING

Routine gas detection is essential to evaluate GHG emissions. For known potential emission sources and sinks, detection may be accomplished most efficiently and cost-effectively by using surface-level measurement tools. Sensors like in situ sensors, portable handheld gas analyzers, fixed-point or fenceline gas detection, and vehicle-based technologies are able to measure smaller sources of GHG emissions continuously compared to satellite and aerial counterparts. Moreover, these detection technologies can range from simple low-cost sensors to high-performance photometers, open path spectrometers, and hyperspectral imaging cameras. Instruments may be stationary or mobile and can be networked to provide more complete spatial coverage, rapid leak detection, improved sensitivity, and to potentially localize leaks to a specific piece of equipment. However, data analysis and modelling used by these systems is complex, and published results from independent field testing suggests that performance is inconsistent.

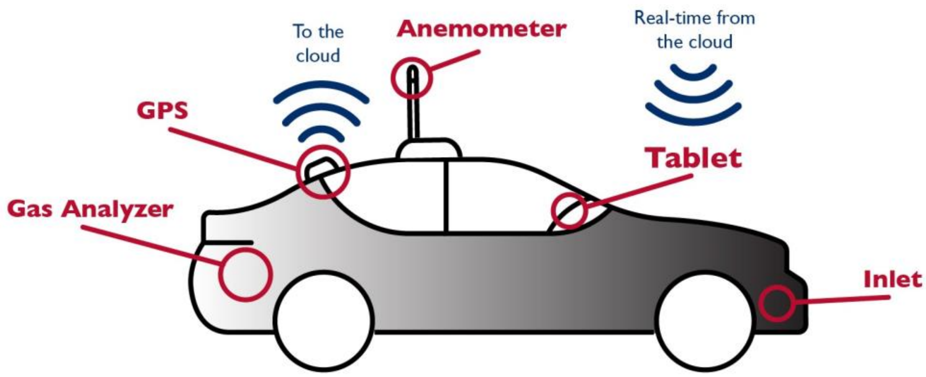
HANDHELD

Handheld greenhouse gas measurement devices are portable instruments that are commonly used for a variety of applications, such as monitoring industrial emissions, measuring greenhouse gas emissions from vehicles, and performing environmental surveys. These applications are widely used to detect and or quantify emissions concentrations directly above a site's surface and are applied as point measurements or random or systematic walkovers. For example, handheld or backpack-mounted Leak Detection and Repair (LDAR) applications (VOC (volatile organic compound) sniffers) are used to survey refineries and gas plants continuously for leaks (Pipeline and Hazardous Materials Safety Administration 2023). In facilities where fugitive emissions monitoring and detection are required for safety and operational reasons, mobile devices can quickly identify small leaks for repair, preventing exposure.

ADVANCED MOBILE LEAK DETECTION (AMLD)

Advanced mobile leak detection (AMLD) systems are devices or systems that involve the use of portable equipment to detect and locate leaks of greenhouse gases, such as methane, from pipelines and other industrial facilities. These systems use various technologies to detect and locate leaks, including infrared imaging, laser-based sensing, and acoustic sensing (Chen 2023). AMLD can include sensors that are carried or wheeled around a facility, or can consist of a vehicle or vessel equipped with a detector, GPS, anemometer, and proprietary software loaded onto the vehicle's computer or tablet. AMLD can be useful in situations where fixed sensors are not practical, such as outdoor areas or in facilities with frequently changing configurations. The spectrometer resolution, using a sensitivity of parts per billion (ppb) allows the operator to differentiate pipeline leaks from naturally occurring biogenic, swamp, marsh, decomposition, or sewer gas emissions. Other emissions surveying equipment has parts per million (ppm) sensitivity and must be used closer to the source.

AMLD systems are often used with other detection systems, such as fixed sensor networks and aerial surveys, to provide a more comprehensive view of leaks from industrial facilities. However, advanced mobile leak detection systems have some limitations, such as generating false alarms due to environmental factors such as temperature changes or vibrations. Additionally, these systems can be costly to operate and maintain, and the data analysis can be complex and require specialized training (Hollenbeck 2021). Overall, AMLD systems are a powerful tool for identifying and locating GHG leaks, but their limitations should be taken into account when considering their use.



Example of Advanced Leak Detection (ALD) system hardware.

IMAGE SOURCE: AUTHOR

FIXED-POSITION TECHNOLOGIES

In contrast to handheld and mobile GHG measurement technologies, fixed-position monitoring solutions include continuous emissions monitoring systems (CEMS), fenceline monitoring, total carbon column observing networks (TCCON), and long-range laser networks.

CONTINUOUS EMISSIONS MONITORING SYSTEM (CEMS)

A continuous emissions monitoring system (CEMS) is a device or system used to continuously monitor and measure the emissions of pollutants, typically from industrial sources. A CEMS collects, records, and reports emissions data invariably, even if there is no active emission, producing a continuous data record of gas concentrations (EPA 2023g). In addition, emission rates using a series of gas CEMS data can be used to maintain or optimize the industrial system and equipment performance, monitor compliance with permitted operational limits, and provide accurate measurements for emissions trading programs and data for emissions inventories. It is worth noting that a CEMS must be calibrated and maintained frequently to ensure accurate measurements, and that the cost of operating and maintaining a CEMS can be high.

The 8-path ultrasonic flow meter is used as the flow reference in the smokestack simulator during its calibration versus NIST-traceable critical flow ventures.

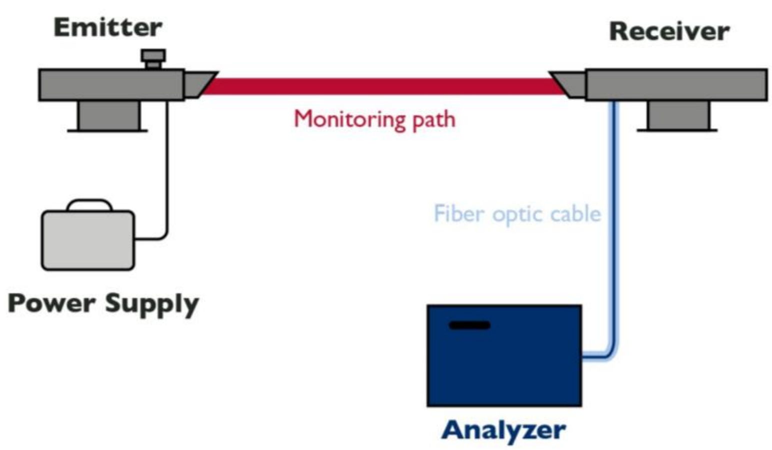
IMAGE SOURCE: NIST

Continuous emissions monitoring system (CEMS). Samples are extracted from the stack by probes (orange) and transported to a gas analyzer for measurement. (NIST = National Institute of Standards and Technology.)

FENCELINE

Not all GHG emissions come from a point source like an exhaust, stack, or flue. Fugitive emissions cannot be measured and tracked in the same way nor with the same technology used for measuring stationary emission sources (EPA 2023e). Fenceline monitors can identify fluctuations in gas concentrations around a facility regardless of the specific point of origin within the facility. They can help evaluate the effectiveness of emission controls that are in place, validate data collected from other technologies, and provide information about potential community public health exposures.

There are two types of fenceline monitoring instrumentation: point measurements and remote sensing open path optical instrumentation (EPA 2011). These instruments can be used separately or together depending on the monitoring objective. Point-sample monitoring systems require multiple-point sensors to obtain spatial data and ensure pollutant detection. An open-path system uses a light beam that has its spectrum altered by pollutants, and the light is transmitted from the emitter to its paired receiver (EPA 2011). When the monitored gases are present, some wavelengths of light are absorbed, indicating that those gases are indeed present. Open path systems cannot determine emissions sources, and if the system is placed incorrectly, it will fail to detect pollutants. The local climate, emission sources, and source geometry must be evaluated to determine the best site for the instrumentation.



UV DOAS system for fenceline monitoring.

NOTE: UV DOAS = ultraviolet differential optical absorption spectrometer
IMAGE SOURCE: AUTHOR

TOTAL CARBON COLUMN OBSERVING NETWORK

The Total Carbon Column Observing Network (TCCON) is a network of ground-based, upward-looking spectrometers used to validate satellite emissions data (Wunch et al. 2011). This system uses Fourier transform infrared spectrometers (FTIR) to record direct solar spectra in the near-infrared spectral region. FTIR uses the mathematical process, Fourier transform, to translate the raw data, interferogram, into the actual spectrum. From these spectra, an accurate and precise column-averaged abundance of GHGs is obtained. While TCCON helps verify satellite measurements made over land, there is a need for better calibration of satellite measurements made over the ocean. As a result of its dependence on daylight measurements, one limitation of this technology is its inability to take measurements on cloudy days or at night. Some of the current TCCON sites are located in Australia; Canada; China; Japan; Korea; New Zealand; and the United States.

LONG-RANGE LASER NETWORKS

A long-range laser network is a series of laser sensors and cameras installed at fixed locations around a source to collectively detect GHGs. A laser beam looks for the infrared absorption fingerprints of various GHGs, the lasers emit beams of light that are directed at the source, and the backscattered light is collected by the sensors and analyzed to determine the concentration of pollutants (Poulton et al. 2019). Long-range laser networks are effective for detection of leaks over a large area and have capabilities of classifying leaks as small, medium, or large. Long-range laser networks are often used in combination with other types of monitoring systems, such as CEMS, to provide a more comprehensive view of emissions from sources.

Long-range laser networks do present some limitations, however. Precise quantification and localization of emissions is difficult, and these networks are easily affected by atmospheric conditions, which can decrease the accuracy of the measurement. Additionally, these networks can be costly to install and maintain, and the data analysis can be complex. Overall, long-range laser networks can be a useful tool for detecting emissions from industrial sources, but their limitations should be taken into account when considering their use.

EMISSIONS ANALYSIS TECHNOLOGIES

In-situ sensors can collect staggering quantities of data. To ensure that these data can be well used, additional technology applications are required. Emissions analysis tools are system software that provide the means to generate digestible data with analytics capabilities so that they can be understood, optimized, and integrated into emissions databases.

MODELING AND ARTIFICIAL INTELLIGENCE

A predictive emissions monitoring system (PEMS) uses statistical and machine learning methods to assess emissions from a manufacturing process based on a facility's operating parameters or net-regional atmospheric loadings based on emission and sink data from sensors (EPA 2023g). Data collected from emissions measurement can be used to improve modeling tools and techniques. Models that use data from surface-level measurement technologies can be verified using aerial or satellite data. Similarly, surface-level measurement technologies can verify modeling data collected from satellites or aerial surveys.

INTERNET OF THINGS

Internet of things (IoT)-based environmental monitoring has countless applications and can support the detection of GHGs and enable governments and enterprises to abate emissions (Digi International Lin n.d.). IoT delivers information from System on Modules (SOM) measuring technologies to remote systems using a private network. These monitors can operate automatically in harsh environments, ensure that equipment works correctly, and prevent failures leading to increased GHG emissions (Digi International Lin n.d.). This process requires a high rate of connectivity among enormous IoT devices to collect, manage, and route data securely.

DISTRIBUTED LEDGER TECHNOLOGY

As emission trading markets become a more important tool for decarbonization, demand will likely grow for systems that can validate emission reduction claims and chain-of-custody transactions for environmental attributes. A blockchain is a distributed ledger technology (DLT) that records transactions conducted among various parties in the network (Bakarich, Castonguay, and O'Brien 2020). Blockchain technology can be used in tandem with IoT to make carbon credits more reliable by verifying carbon emissions rights in carbon markets (Kim and Huh 2020). Consequently, blockchain technology can provide real-time reporting and validation by internal or external auditors (Bakarich, Castonguay, and O'Brien 2020).

In the example illustrated below, the data collected are stored in the blockchain and can be continuously updated and verified by users. The total carbon footprint is automatically calculated using smart contracts and generates a report (Bakarich, Castonguay, and O'Brien 2020). The carbon footprint report is securely stored on the blockchain (Figure 2).

Figure 2: How IoT Works with Blockchain to Calculate Carbon Emissions

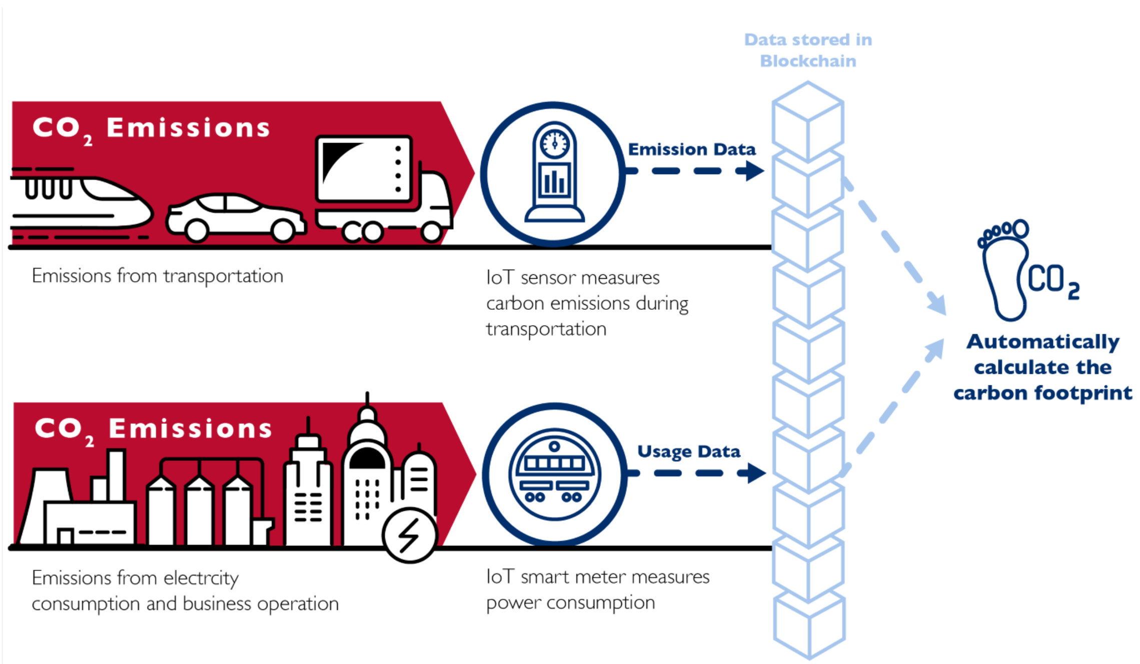


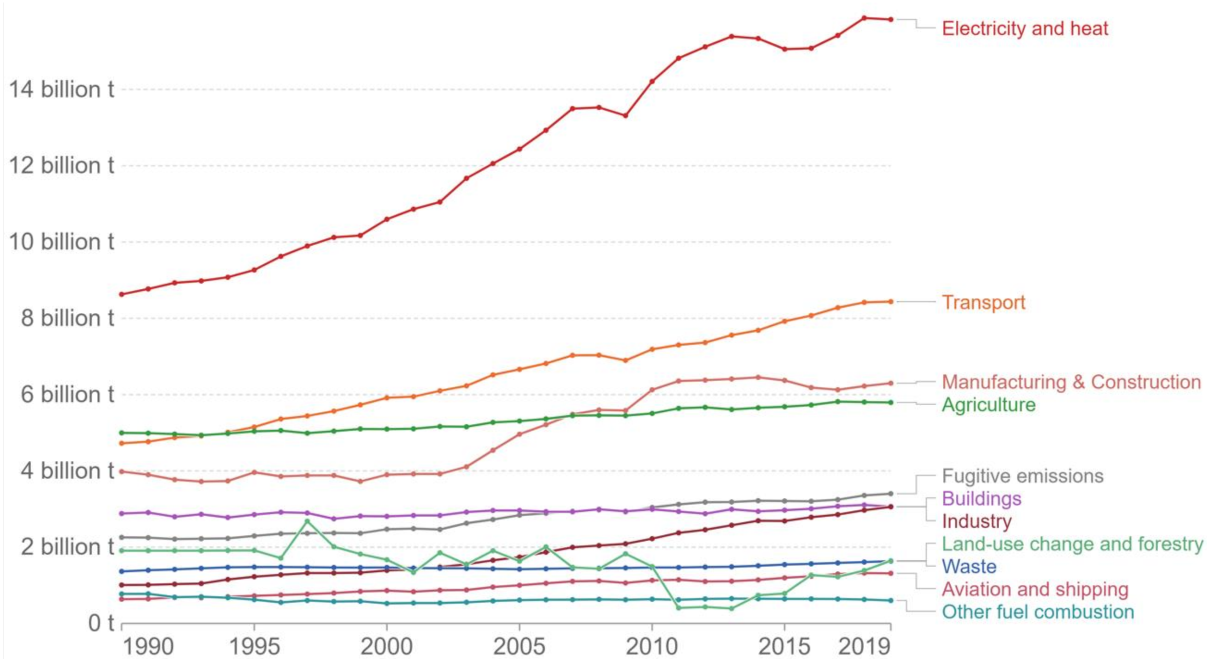
IMAGE SOURCE: AUTHOR

Blockchain technology can improve transparent documentation in carbon emission trading, climate finance flows, or GHG emission reporting (Kim and Huh 2020). Blockchains can be used for sustainability reporting and facilitating an accountability audit for air pollution. To optimize carbon credits and minimize issues with double counting, a blockchain platform could enable cryptographic tokens to contain a tradable value (Bakarich, Castonguay, and O'Brien 2020). Relentless connectivity, automation, and control are necessary for detailed reporting and rapid alerts; IoT and blockchain for GHG monitoring can benefit various sectors by efficiently using digital technologies in their solutions.

TECHNOLOGY SUITE BY SECTOR

Globally, economies are developing solutions to measure their emissions in real time. The suite of technologies used to measure and monitor GHG emissions can vary by region, sector, and individual objectives. Climate variations, political and regulatory environments, and locale play a large part in determining which technology solutions for GHG monitoring are viable. Figure 3 details the global trends in GHG emissions from 1990 through 2019 in each sector.

Figure 3: Greenhouse Gas Emissions by Sector (world)



NOTE: t = ton
IMAGE SOURCE: OUR WORLD IN DATA BASED ON CLIMATE ANALYSIS INDICATORS TOOL (CAIT)

The distribution of emissions by sector varies for specific regions and subregions. An economy's measurement and monitoring needs will also vary with its sectoral emissions. This section provides examples of how measurement and monitoring networks vary by sector, including the primary and secondary tools involved.

ELECTRICITY

- Primary tools: Continuous emissions monitoring system (CEMS)
- Supporting tools: Satellite remote sensing, aerial surveys, mobile surface-level tools, modeling, and Artificial Intelligence (AI)

CEMS are required by regulation for power generators in some economies to record post-combustion emissions and flow rates. Usually more affordable than CEMS, predictive emissions monitoring systems (PEMS) are software solutions that provide accurate emission monitoring data using advanced machine learning and statistical methods (EPA 2023g). PEMS are faster to configure, operate, and maintain than CEMS. PEMS estimate air pollutant emissions by considering process parameters such as pressure, temperatures, and flow and by ensuring compliance with environmental standards and regulations (ABB n.d.). PEMS are used across sectors, in industrial facilities, power plants, and motor vehicles.

Remote sensing technologies have also been used to quantify emissions from the power sector. For example, researchers in Europe used satellites known as orbiting carbon observatories to quantify emissions from Europe's largest fossil fuel power plant in Poland during 2017–2022, demonstrating the capacity of existing satellites to collect close-to-real-time data from larger spatial scales (Nassar et al. 2022).

AGRICULTURE

- Primary tools: Satellite remote sensing
- Supporting tools: Aerial surveys, surface-level tools

Establishing accurate emissions accounting and quantifying emission reductions in the agriculture sector is complex. Agriculture emissions from land use, livestock operations, and crop production create N_2O, CH_4, and CO_2 emissions and sinks (EPA 2023h). Additionally, supply chains, on-farm energy use, food processing, and refrigeration contribute additional emissions. While techniques such as reduced tillage, precision fertilization, winter cover crops, manure collection, and numerous others are proven methods of reducing agricultural GHG emissions, they can only be deployed intermittently and cannot be uniformly employed throughout the sector, even within a single economy.

Opportunities for emissions measurement exist throughout the agricultural sector. For example, measuring the exchange of gases between soil and the atmosphere, or GHG flux from soils, can include using chamber techniques, micrometeorological approaches, satellite observations, and aerial surveys (Collier et al. 2014). In 2022, satellites from the company GHGSat detected methane emissions from livestock, but a different suite of tools can be used for measuring and monitoring these emissions (GHGSat 2022). Precision agriculture technologies (PAT) deploy aerial surveying devices and in-field electronic sensors to allow farmers to gather precise data in order to predict and monitor trends of various environmental and yield parameters (Digiteum Team 2021). Measuring soil GHG emissions is challenging and costly, but collecting more data provides more opportunities for emissions reductions.

Using a network of GHG measuring technologies provides the benefits of covering continuous, controlled, and representative emissions measurement while overcoming any challenges that one technology presents on its own. For example, In New Zealand, technologies such as respiration chambers, SF_6 tracer techniques, portable accumulation chambers, GreedFeed hoods, and paddock-scale micro-meteorological techniques provide effective surface-level methane measuring when used together, combining soil chambers and micrometeorological techniques to effectively monitor nitrous oxide emissions within livestock (New Zealand Agricultural Greenhouse Gas Research Centre and Pastoral Greenhouse Gas Research Consortium 2016).

SF_6 tracer technique – Sheep are fitted with a lightweight "yoke", which carries a canister that captures the released SF_6 and CH_4 when the animal belches. Scientists can use the measured ratio of SF_6 to CH_4 to calculate how much methane the sheep has released.

IMAGE SOURCE: PASTORAL GREENHOUSE GAS RESEARCH CONSORTIUM

TRANSPORTATION

- Primary tools: modeling and Artificial Intelligence (AI)
- Supporting tools: aerial surveys and continuous emissions monitoring system (CEMS)

Emissions from the transportation sector can be direct, such as exhaust from internal combustion engines burning fossil fuels, or indirect, such as electricity generated along the value chain. Transportation activities include road transport, aviation, shipping, and rail, and GHGs emitted throughout these modes can vary significantly by scale and location. Modeling emissions using a bottom-up approach can and often is the most common and cost-effective manner to estimate transportation emissions at a regional or domestic level.

Surface-level and aerial surveying tools can also help enhance the availability of data used to confirm or improve modeled outputs. Vehicle-specific testing, onboard sensors, and remote sensing devices have all been used for measuring transportation emissions (Smit and Kingston 2019). CEMS can quantify the emissions from a vessel's exhaust in the marine shipping industry. Aerial surveying with unmanned aerial vehicles and surface-level sensors can detect individual vessel emissions or multi-modal emissions from a port, airport, or other transportation hub.

BUILDINGS

- Primary tools: modeling and Artificial Intelligence (AI)
- Supporting tools: fixed and mobile surface-level tools

Building emissions can include building materials, construction, and offsite and onsite energy consumption. While the building sector is a key driver of GHG emissions, given the complexity and variety of small-scale building emission sources, modeling is the primary tool for measuring emissions in this sector. Models can give predictive data on a single building or larger numbers of buildings using data regarding on-site energy use and building equipment specifications for boilers, chillers, and HVAC (heating, ventilation, and air conditioning) units. Appliance-level sensors can provide advance notice of potential leaks of HFCs but can be cost-prohibitive. Models can efficiently drive on-site maintenance practices and can be combined with surface-level handheld gas analyzers or mobile leak detection monitors. These measurement tools can complement the bottom-up approach currently used to calculate embodied carbon emissions in construction materials as well.

MANUFACTURING EMISSIONS

- Primary tools: fixed and mobile surface-level tools
- Supporting tools: satellite remote sensing and aerial surveys

Manufacturing emissions tend to be concentrated based on onsite energy use and large-scale production processes from cement, iron, steel, chemical, and petrochemical manufacturing. A bottom-up approach of using fixed tools like CEMS and handheld gas analyzers can offer a robust and reliable means of monitoring manufacturing GHG emissions. These instruments can quickly and accurately measure GHG emissions, generating data for safety, production management, and compliance reporting. Aerial and satellite surveillance can complement these bottom-up measurement tools by identifying manufacturing emissions plumes.

FUGITIVE EMISSIONS

- Primary tools: aerial surveys, mobile and handheld surface-level tools
- Supporting tools: fixed surface-level tools, modeling, Artificial Intelligence (AI), and satellite remote sensing

Fugitive methane emissions can occur throughout the economy, including the oil and gas sector, waste management sector, and the agriculture sector. For example, pipeline leak detection is crucial to any oil and gas company's incident management workflow. Pipelines cover hundreds of miles and usually rely on a combination of workforce vigilance and advanced leak detection equipment to monitor potential leaks. Aerial surveying, stationary continuous emissions monitors, and advanced mobile leak detection can assist in identifying and quantifying fugitive emissions at active or closed extraction sites, along transportation networks, and at storage and manufacturing facilities. Moreover, satellites are particularly effective at identifying some of the largest and most significant emissions leaks, detecting the largest releases of GHGs quickly and with a broad geographic coverage.

DEPLOYMENT

DRIVERS

HISTORICAL DRIVERS OF APEC EMISSIONS MEASUREMENT

Globally, conventional air pollutants such as particulate matter (PM), photochemical oxidants, carbon monoxide (CO), sulfur oxides (SO_x), and nitrogen oxides (NO_x) have driven air quality standards. Emissions standards vary worldwide; however, conventional pollutants have set standards based on scientific information regarding their effects on health and welfare. Generally, these standards have been for vehicle or transportation emissions and emissions related to fossil-fired power plants and industrial facilities (EPA 2023i). Pollution from these sources has driven measurement demand, specifically simplified emissions calculations for transportation, sensor networks, and fixed technologies like continuous emissions measurement systems (CEMS) in stationary sources. Many APEC economies have emissions standards and regulations related to conventional pollutants which require frequent written reports. For example, China has implemented regulations to reduce conventional pollutants such as sulfur dioxide, nitrogen oxides, and particulate matter. These regulations include the "Air Pollution Prevention and Control Action Plan," which was launched in 2013 and established an economy-wide network of air pollution monitors that increase the transparency of government reporting on air quality statistics (The Lancet Planetary Health 2018). Similarly, Indonesia's Ministry of Environment and Forestry (MoEF) Regulation No. 21/2008 (MoEF 2008) and MoEF Decree No. 15/2019 (MoEF 2019) policies require CEMS on coal-fired power plant stacks with a semi-annual report submitted to the relevant mayor, regent, or governor.

Recently, many economies have established and implemented a more comprehensive set of economy-level air quality-related standards and regulations that simultaneously address air quality and climate concerns (United Nations Environment Programme 2021). These standards and regulations include a focus on GHGs, requiring pollution control equipment and technology installations in heavy-emitting industries. Furthermore, economies are strengthening their existing emissions mitigation efforts to meet their climate pledge under the Paris Agreement (Paris Agreement 2015).

INDUSTRIAL EFFICIENCY AND SAFETY

Some sensor demand is driven by the need for operational efficiency and safety in industrial operations. Companies have found that deploying operators to look for leaks on a daily basis is no longer cost-effective. Shifting the focus to identifying more chronic issues is a more economical way to deploy operators and field technicians. Large industrial facilities often employ a variety of sensors to monitor the flow of gaseous and liquid volumes in industrial processes to ensure systems operate within expected parameters and to provide needed alerts concerning potential maintenance or safety issues that may need to be addressed. For example, leak detection and repair (LDAR) is widely used throughout the natural gas supply chain to maintain the integrity of storage and transportation systems including pipelines. Oil and gas companies would be especially interested in identifying leaks to get more value from the methane, and active use of sensor data minimizes product loss, reduces operational safety risks in the gas sector, and achieves environmental improvement.

STANDARDS AND REGULATIONS

Currently, there is a policy gap between standards for GHG measurement technologies and the methodologies and practices for developing emission inventories. While there are several documentary management methods that guide emissions accounting and ISO (international Organization for Standardization) standards for quantifying and reporting emissions, technical documentary standards to guide the measurement technologies that support these protocols are sparce and insufficient; consequently, the absence of such guidance weakens efforts to identify, estimate, and subsequently reduce

GHG emissions. Importantly, developing technical standards to support GHG measurement that are adopted across economies will help increase the transparency, data quality, and interoperability of emission reports and encourage the deployment of GHG measurement technologies at a regional level.

Existing documentary management standards work to advance how emissions sources and sinks are calculated, estimated, and reported amongst participating economies (IPCC 2006). Rather than providing guidance on how atmospheric technologies should be used to measure and estimate emissions, these protocols aim to define domestic-scale reporting and accounting principles, sector-specific guidance for sourcing data and calculating emissions, and how inventories can be used to set mitigation goals and track performance over time (GHG Protocol 2021). These include frameworks such as the IPCC Guidelines for National Greenhouse Gas Inventories and the Global Protocol for Community-Scale Greenhouse Gas Inventories (GPC). Additionally, the ISO has developed ISO 14064, a three-part international standard for quantifying and reporting GHG emissions (ISO 2022). ISO 14064 is a policy-neutral technical specification that serves as a guide for the public and private sector to quantify and report emissions reductions, verify and validate GHG assertions, and develop emission inventories at the organization and project levels (Wintergreen and Delaney 2007).

While some of these frameworks have begun to bridge the gap between measurement technologies and documentary management standards, further development is necessary to drive improvement in emissions accounting. Governments and organizations are working to identify and establish opportunities to enhance measurement and quantification of GHG fluxes to inform local to economy-scale efforts, as well as improve organization's ability to measure and monitor. For example, the National Institute of Standards and Technology (NIST) has "initiated a documentary standards effort aimed at advancing the implementation of mature, measurements-based, scientific tools and methods, together with associated data, based on the research community's best practices" (Lin 2022). NIST's efforts to develop such technical documentary standards will support management standards, such as ISO 14064, to increase transparency and accuracy for users globally. Undertaking similar work within APEC economies will prompt similar improvements in data quality and interoperability of emissions measurement technologies and estimates across the region, aiding in effective GHG monitoring and development of emission inventories through the deployment of measurement technologies that meet approved standards.

Regulatory requirements are another significant demand driver for emission sensor deployment. In many economies, the license to operate large industrial facilities, including power generation or chemical manufacturing, includes measurement and monitoring requirements. Data reports from CEMS placed in fossil-fired power generation exhaust systems are commonly required by some government-issued operation permits. In a growing number of instances, GHG emission performance is also being measured or regulated.

Additionally, a carbon tax is a policy that places a price on carbon emissions, usually measured in terms of tons of carbon dioxide or CO_2 equivalent. It is a market-based approach that aims to reduce GHG emissions by creating an economic incentive for polluters to reduce their emissions. For example, under Singapore's carbon tax mechanism that has been implemented since 2019, taxable facilities are required to comply with robust measurement, reporting and verification requirements. This ensures that the taxable facilities are aware of their emissions (National Environmental Agency, n.d.). While carbon taxes do not regulate GHG emissions reduction (Center for Climate and Energy Solutions n.d.), the need to track emissions to capture the value from reductions strategies could be a future avenue for additional measurement opportunities.

EMISSIONS REPORTING

Many APEC economies are now requiring companies and organizations to report their GHG emissions as part of efforts to monitor and reduce carbon footprints (United Nations Environment Programme 2021). Chinese Taipei, for example, has implemented emissions reporting requirements for companies and organizations to report their GHG emissions and comply with emissions reduction targets as part of its efforts to monitor and reduce GHGs. In the United States, the Environmental Protection Agency (EPA) requires certain large facilities to report their GHG emissions under the Greenhouse Gas Reporting Program (GHGRP). Australia; Canada; China; Japan; and Korea are just a few other examples of economies that require emissions reporting. While these emissions inventories do not use atmospheric emissions measurement to quantify and estimate GHGs, the arrival of more emissions accounting mechanisms continues to highlight the need for accurate measurement to supplement emission calculations.

PUBLIC POLICY INCENTIVES

Public sector entities have, at times, directly funded the deployment and operation of measurement and monitoring networks to monitor air quality and pollution levels. Historically, these activities have focused mainly on human health concerns. In recent years, some significant investments have been made in GHG monitoring equipment and activities, ranging from launching satellites to aerial and surface-level monitoring to identify GHG sources. For example, the United States Inflation Reduction Act of 2022 (IRA) appropriates USD285.5 million for funding to address air pollution (Secs. 60105–06); this includes an allocation of substantial funding to deploy air measurement technologies, specifically in low-income and disadvantaged communities that have been historically impacted by emissions (Sec. 60105(c)) (US IRA 2022). The IRA also appropriates USD850 million to improve methane emissions monitoring and GHG emissions estimates (Sec. 60113). While some of these investments may not specifically target GHGs, air pollutant measurement couples many devices and technologies that are also capable of measuring GHG emissions.

Government incentives, such as favorable tax treatment, are another driver for measurement and monitoring. A government may decide to provide subsidies to encourage private-sector emission abatement activities. For example, Thailand's Climate Change Master Plan calls for tax exemptions or credits to incentivize power plant operators to "adopt environmentally friendly practices and technologies" to improve and increase electricity production efficiency (Office of Natural Resources and Environmental Policy and Planning 2015). Similarly, Singapore has launched the Genco Energy Efficiency Grant Call (Energy Efficiency Grant Call for Power Generation Companies) and Advanced Combined Cycle Gas Turbines incentive scheme (Incentive Scheme for Advanced Combined Cycle Gas Turbines (CCGTs) 2021), which encourages energy generation companies to reduce GHG emissions while improving efficiency. Firms seeking to access those incentives need data from measurement and monitoring systems to demonstrate their eligibility based on emission reductions or carbon intensity performance.

CARBON MARKETS

Another factor driving demand for measurement and monitoring deployment is public and private decarbonization initiatives. The emergence of government-driven and voluntary carbon markets necessitates expanded measurement and monitoring activities (United Nations Development Programme 2022). Economy-level emission market programs, such as China's domestic emissions trading system, the Korea Emissions Trading Scheme (KETS), and the Viet Nam carbon market incentivize emission reductions where the cost of abatement is the lowest. Firms that exceed required levels of abatement can sell emission credits to other market participants that choose to purchase available credits as part of their compliance strategy. Similar market activities have followed the efforts of large corporations to set and achieve voluntary GHG emission reduction targets as part of their corporate sustainability endeavors, reducing emissions associated with direct operations and supply chains. Measurement and monitoring are essential for validating emission reduction claims made in this context. Furthermore, voluntary carbon markets are continuing to grow; Japan created the economy's first domestic pilot market for trading carbon emissions in September 2022, which started trading credits in October 2023 (Obayashi and Golubkova 2023). Additionally, the United States has several regional and state emissions trading programs, such as the Regional Greenhouse Gas Initiative and Clean Fuel Standards.

BARRIERS

Deploying GHG measurement technologies poses many challenges, including dealing with estimation uncertainty, precise emissions quantification, and using measurements in conjunction with other sources of emissions data and models. Other barriers can slow deployment to the implementation of GHG measurement and technologies, including the following:

- Cost of implementing the new technology
- Availability or supply of various measurement tools
- Limitations in the flexibility of legal and regulatory environments to allow for the rapid adaptation of technology to emerging climate issues, including GHGs
- Lack of operator experience or familiarity with new monitoring technologies
- Workforce ability to calibrate, install, and maintain the technology to collect and analyze data
- Data use and accessibility constraints
- Technological reliability and durability
- Rapidly changing technology landscape
- Limitations in the willingness of industry to share data

While there are many ways to overcome these barriers, the most effective pathway for APEC economies is to improve on or create robust measurement and monitoring standards as well as funding opportunities to research and deploy technological advancements in GHG detection and quantification.

MONITORING OBJECTIVES

OVERVIEW OF MONITORING OBJECTIVES

Anthropogenic emission sources of the seven gases regulated under the Kyoto Protocol can range from small emitters, such as personal vehicles, to large emitters, such as fossil-fueled power plants. Across these sources, measurement can be integrated and achieved on different scales—from the smokestack level to the global level—and the monitoring objectives will vary depending on the scale. This section of the background paper provides a brief discussion of the various objectives.

MONITORING LARGE EMISSION POINT SOURCES

To be successful, emission reduction efforts must identify and address the largest sources of anthropogenic emissions. These can include industrial and power generation emissions from large-scale coal power plants, natural gas storage systems and pipelines, active or capped oil wells, waste landfills, and many other emission sources.

Understanding and managing high concentrations of GHGs is a significant focal point for already deployed measurement technologies. In some economies, current laws, regulations, or commercial contracts require industrial emissions monitoring. Many economies rely on existing monitoring networks as a central element in developing economy-wide emission inventories. In other cases, monitoring emissions may be a novel element of industrial activity and may introduce additional operation costs.

Different monitoring tools can be used to address concentrated GHGs.

- Fixed position, surface-level monitors can continuously track emissions from known or potential sources such as industrial exhaust stacks or pipelines.
- Aerial and mobile monitors can identify point sources and refer them to operators for follow-up site visits.

COMMUNITY-LEVEL GHG CONCENTRATION

Community-level GHG leakage events can also have significant impacts towards climate change. For example, the Aliso Canyon methane storage complex in California experienced a failure in 2015, resulting in approximately 6 billion cubic feet of methane emissions over 111 days (CARB 2018). In response, the California Air Resources Board (CARB) used fixed-position infrared sensors to monitor the leak over time and to confirm the success of efforts to seal the well permanently in early 2016. Additional monitors were used in the surrounding community to track localized methane concentrations.

Understanding community-level GHG concentrations requires unique measurement and monitoring approaches. Available and emerging technologies can be used to assess existing and evolving GHG concentrations at the community level. Moreover, local sensor data should be compared with global and regional concentration averages to identify near-source influences that may have localized implications. A variety of monitoring tools can be used, including the following:

- Fixed-position monitoring to track emissions from known and potential concentrated sources of GHG emissions.
- Mobile, surface-level measurement to verify fixed-position monitoring and periodically check possible sources of emissions not subject to continuous monitoring, as well as to identify new emission sources contributing to emission plumes found by aerial or satellite monitors.
- Aerial monitoring to detect larger emission plumes that may be problematic for communities.

- Satellite monitoring to provide the broadest geographic coverage to identify larger emissions releases.

EMISSIONS INVENTORIES

An emissions inventory is a quantitative estimate of gases emitted into the atmosphere over a specified period of time, typically by a region, sector, or activity. Precision in establishing and monitoring global-, regional-, and economy-level emission inventories is a necessary element of international climate dialogues and agreements. The need for widespread confidence regarding inventory accuracy will grow as international agreements and commitments become more consequential and binding. Satellite, aerial, and terrestrial or water-based monitoring networks will be essential to validate emissions from known sources, monitor fluctuations in sources and sinks over time, and identify emissions events. Networks of measurement devices on different platforms will also be essential for reducing uncertainties caused by variations in meteorological, atmospheric, and measurement equipment conditions.

NEAR-SOURCE MONITORING

In some economies, known sources are required to produce and make available data related to GHG emissions as a condition of operations. Both fixed-position and mobile monitoring devices are used to obtain necessary data. Various mobile, aerial, and satellite monitors can verify and identify emissions produced from fixed-position monitors. For known or potential industrial GHG emission sources exempt from on-site monitoring requirements, various combinations of monitoring tools can be used to establish and track emission performance. This includes fenceline, fixed-position, and mobile monitors.

EMISSIONS SOURCE IDENTIFICATION

Gaps exist in the effort to identify and characterize global GHG emission sources. The accuracy of—and general confidence in—economy-developed inventories will benefit from increased efforts to identify and measure fluctuating contributions to atmospheric concentrations, sinks, and sources. Integrated networks of measurement and monitoring tools will be needed for this task. For example, emission quantification or atmospheric concentration data are misaligned with modeling results, further measurement will be necessary to understand the inconsistencies and develop more accurate results that can be validated consistently.

CONCLUSION

Increased measurement and monitoring of GHGs are needed to provide APEC economies with the quality assurance needed for emissions estimates, to advance additional scientific verifications of inputs and results for particular gases and emissions categories, and to help target areas of uncertainty in emission calculations. Many APEC economies are in the early stages of exploring GHG measurement and monitoring and will require increased adoption of technologies to better understand and manage emission sources and sinks. In all cases, the monitoring objective will determine which equipment and strategy should be used to measure GHGs. As measurement tools continue to advance, and as more economies and organizations adopt their use, they will increasingly require their integration into existing environmental and quality management systems and better understanding about how they relate to voluntary and mandatory reporting systems.

Measurement has traditionally been driven by international protocols for emissions accounting and by regulations for conventional pollutants. While several APEC economies have adopted standards requiring measurement technologies for particular sectors, many more are beginning to strengthen existing policies or develop new policies to better characterize, identify, and quantity GHG emissions. Government incentives, new GHG regulations, and voluntary carbon markets will continue to drive measurement and monitoring technology applications.

As regulators consider the impact of policies on marginal emissions production and reduction, analyzing the measurement and monitoring methods currently in use, the emerging technologies, and the protocols driving additional adoption and integration will provide APEC economies with the information needed to help mitigate future impacts of climate change.

REFERENCES

ABB. n.d. "Predictive Emission Monitoring Systems (PEMS)." ABB. https://new.abb.com/products/measurement-products/analytical/continuous-gas-analyzers/predictive-emissions-monitoring-systems.

Abshire, J., H. Riris, G. Allan, C. Weaver, J. Mao, X. Sun, W. Hasselbrack, A. Yu, A. Amediek, Y. Choi, and E. Browell. 2010. "A Lidar Approach to Measure CO2 Concentrations from Space for the ASCENDS Mission." *Society of Photo-Optical Instrumentation Engineers* 7832. https://ssed.gsfc.nasa.gov/co2sounder/pdf/Co2AbshireSpie78320D(2010).pdf.

Allen, D. 2014. "Methane Emissions from Natural Gas Production and Use: Reconciling Bottom-Up and Top-Down Measurements." *Current Opinion in Chemical Engineering* 5: 78–83. https://www.sciencedirect.com/science/article/pii/S2211339814000525.

Andersen, T., B. Scheeren, W. Peters, and H. Chen. 2017. "A UAV-Based Active AirCore System for Accurate Measurements of Greenhouse Gases." *Atmospheric Measurement Techniques* (preprint). https://amt.copernicus.org/preprints/amt-2017-369/amt-2017-369.pdf.

APEC. 2022. "APEC Putrajaya Vision 2040." APEC. https://www.apec.org/meeting-papers/leaders-declarations/2020/2020_aelm/annex-a.

______. 2023a. "Achieving Carbon Neutrality through Bio-Circular-Green Economy Principle in APEC Region." APEC. https://www.apec.org/docs/default-source/publications/2023/11/223_ewg_achieving-carbon-neutrality-through-bio-circular-green-economy-principle-in-apec-region.pdf?sfvrsn=51446831_2#:~:text=Many%20APEC%20economies%20pledged%20to,commitment%20at%20a%20later%20stage.

______. 2023b. "Field Guide: Approaches to Decreasing Agriculturally Generated Greenhouse Gas Emissions in APEC." APEC. https://www.usda.gov/sites/default/files/documents/ppfs-field-guide-greenhouse-gas-reduction.pdf.

APEC Policy Support Unit. 2021. "APEC's Climate Challenge — Towards a Resilient Recovery: Policies Matter." APEC. https://www.apec.org/docs/default-source/publications/2021/11/apec-regional-trends-analysis---november-2021/221_psu_arta_november-2021.pdf?sfvrsn=a041a19_2.

Bakarich, K. M., J. J. Castonguay, and P. E. O'Brien. 2020. "The Use of Blockchains to Enhance Sustainability Reporting and Assurance*." *Accounting Perspectives* 19(4): 389–412. https://doi.org/10.1111/1911-3838.12241.

California Institute of Technology. n.d. "Total Carbon Column Observing Network." Webpage. California Institute of Technology. http://www.tccon.caltech.edu/.

Calvo Buendia, E., S. Guendehou, B. Limmeechokchai, R. Pipatti, Y. Rojas., R. Sturgiss., K. Tanabe., T. Wirth., D. Romano, J. Witi, A. Garg, M. Weitz, B. Cai, D. Ottinger, H. Dong, J. Douglas MacDonald, S. Michael Ogle, M. Theoto Rocha, M. Jose Sanz Sanchez, D. Bartram, and S. Towprayoon. 2019. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Overview*. Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/0_Overview/19R_V0_01_Overview.pdf.

California Air Resources Board (CARB). 2018. *Summary of and Responses to Public Comments Received by the California Air Resources Board Regarding the Aliso Canyon Mitigation Agreement*. CARB. https://ww2.arb.ca.gov/sites/default/files/2020-08/aliso_canyon_2018_10_09_final_summary_and_responses_to_public_comments.pdf.

______. n.d. "Ambient Air Monitoring – Regulatory." Webpage. CARB. https://ww2.arb.ca.gov/our-work/programs/ambient-air-monitoring-regulatory.

Chen, L. 2016. "Mission Overview GaoFen-5." Presentation at CEOS-ACC-12 Meeting, October 13–15. Chinese Academy of Sciences. https://ceos.org/document_management/Virtual_Constellations/ACC/Meetings/AC-VC-12/Day%201/5.%20Linagfu%20Chen%20-%20Gaofeng-5%201013.pdf.

Chen, L., H. Letu, M. Fan, H. Shang, J. Tao, L. Wu, Y. Zhang, C. Yu, J. Gu, N. Zhang, J. Hong, Z. Wang, and T. Zhang. 2022. "An Introduction to the Chinese High-Resolution Earth Observation System: Gaofen-1~7 Civilian Satellites." *Journal of Remote Sensing* 2022. https://doi.org/10.34133/2022/9769536.

Chen, S., N. Aubut, M. Frish, K. Bendele, P. Wehnert, and V. Aggarwal. 2023. "Versatile Advanced Mobile Natural Gas Leak Detection System." *Society of Photo-Optical Instrumentation Engineers* 12516, https://www.spiedigitallibrary.org/conference-proceedings-of-spie/12516/125160S/Versatile-advanced-mobile-natural-gas-leak-detection-system/10.1117/12.2663631.short#_=_.

Christen, A. 2014. "Atmospheric Measurement Techniques to Quantify Greenhouse Gas Emissions from Cities." *Urban Climate* 10(2): 241–60. https://doi.org/10.1016/j.uclim.2014.04.006.

Center for Climate and Energy Solutions. n.d. "Carbon Tax Basics." Webpage. Center for Climate and Energy Solutions. https://www.c2es.org/content/carbon-tax-basics/.

Collier, S., M. Ruark, L. Oates, W. Jokela, and C. Dell, 2014. "Measurement of Greenhouse Gas Flux from Agricultural Soils Using Static Chambers." *Journal of Visualized Experiments* 90: 52110 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4827936/.

Digi International. n.d. "IoT-Enabled Green Technology." Digi International. https://www.digi.com/resources/library/solution-briefs/iot-enabled-green-technology,

Digiteum Team. 2021. "Precision Agriculture Technology: The Future of Precision Farming Using IoT Technology." Digiteum Team. September 18. https://www.digiteum.com/precision-agriculture-technology/.

Department of Energy (United States) (DOE). 2021. "Tethered Balloon Systems." Factsheet. DOE. https://www.arm.gov/publications/fact-sheets/docs/doe-sc-arm-20-015.pdf.

Enerdata. 2023. "Japan Plans to Create a Pilot Emission Trading Scheme in September 2022." Enerdata. May 16, https://www.enerdata.net/publications/daily-energy-news/japan-plans-create-pilot-emission-trading-scheme-september-2022.html.

Energy Efficiency Grant Call for Power Generation Companies. 2023. Energy Market Authority. https://www.ema.gov.sg/partnerships/research-and-development-engagements/grant-calls/energy-efficiency-grant-call-for-power-generation-companies

Environmental Protection Agency (EPA). 2011. *EPA Handbook: Optical Remote Sensing for Measurement and Monitoring of Emissions Flux.* EPA. https://www3.epa.gov/ttnemc01/guidlnd/gd-052.pdf.

______. 2022. "Managing Air Quality – Emissions Inventories." Webpage. EPA. https://www.epa.gov/air-quality-management-process/managing-air-quality-emissions-inventories.

______. 2023a. "Managing Air Quality - Emissions Measurement." Webpage. https://www.epa.gov/air-quality-management-process/managing-air-quality-emissions-measurement.

______. 2023b. "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021." Webpage. EPA. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

______. 2023c. "Ambient Air Quality Source Measurement and Emissions Factors Research." Webpage. EPA. https://www.epa.gov/air-research/ambient-air-quality-source-measurement-and-emissions-factors-research.

______. 2023d. "Environmental Measurements and Modeling." Webpage. EPA. https://www.epa.gov/measurements-Modeling.

______. 2023e. "Basic Information about Air Emissions Monitoring." Webpage. EPA. https://www.epa.gov/air-emissions-monitoring-knowledge-base/basic-information-about-air-emissions-monitoring.

______. 2023f. "Overview of Greenhouse Gases." Webpage. EPA. https://www.epa.gov/ghgemissions/overview-greenhouse-gases.

______. 2023g. "EMC: Continuous Emission Monitoring Systems." Webpage. EPA. https://www.epa.gov/emc/emc-continuous-emission-monitoring-systems.

______. 2023h. "Sources of Greenhouse Gas Emissions." Webpage. EPA. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

______. 2023i. "Criteria Air Pollutants." Webpage. EPA. https://www.epa.gov/criteria-air-pollutants.

______. 2023j. "Global Greenhouse Gas Emissions Data." Webpage. EPA. https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data.

eoPortal. 2022. "THEOS-2 (Thailand Earth Observation System-2)". Quick facts page. eoPortal. https://www.eoportal.org/satellite-missions/theos-2#eop-quick-facts-section.

______. 2023. "THEOS-2 (Thailand Earth Observation System-2)." Webpage. eoPortal. November 30. https://www.eoportal.org/satellite-missions/theos-2.

Frey, H.C. 2006. "Quantification of Uncertainty in Emission Factors and Inventories." Conference paper. https://www3.epa.gov/ttn/chief/conference/ei16/session5/frey.pdf.

Gålfalk, M., S. Nilsson Påledal, and D. Bastviken. 2021. "Sensitive Drone Mapping of Methane Emissions Without the Need for Supplementary Ground-Based Measurements." *ACS Earth Space Chemistry* 5(10):2668-2676, https://doi.org/10.1021/acsearthspacechem.1c00106.

GHG Protocol. 2021. "Global Protocol for Community-Scale Greenhouse Gas Inventories." https://ghgprotocol.org/sites/default/files/standards/GPC_Full_MASTER_RW_v7.pdf.

GHGSat. 2022. "Cow Burps Seen from Space." Press release. GHGSat. May 2. https://www.ghgsat.com/en/newsroom/cow-burps-seen-from-space/.

GOSAT. 2015. "About GOSAT." Webpage. GOSAT. https://www.gosat.nies.go.jp/en/about_1_goal.html.

Hardwick, S., and H. Graven. 2016 *Satellite Observations to Support Monitoring of Greenhouse Gas Emissions*. Grantham Institute Briefing Paper no. 16. Imperial College London. https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/Satellite-observations-to-support-monitoring-of-greenhouse-gas-emissions-Grantham-BP-16.pdf.

Hollenbeck, D., D. Zulevic, and Y. Chen. 2021. "Advanced Leak Detection and Quantification of Methane Emissions Using sUAS." *Drones* 5(4): 117. https://www.mdpi.com/2504-446X/5/4/117.

Holmberg, M., A. Akujärvi, S. Anttila, I. Autio, M. Haakana, V. Junttila, N. Karvosenoja, P. Kortelainen, A. Mäkelä, K. Minkkinen, F. Minunno, K. Rankinen, P. Ojanen, V. Paunu, M. Peltoniemi, T. Rasilo, T. Sallantaus, M. Savolahti, S. Tuominen, P. Vanhala, and S. Forsius, S. 2021. "Sources and Sinks of Greenhouse Gases in the Landscape: Approach for Spatially Explicit Estimates." *Science of The Total Environment* 781:146668. https://doi.org/10.1016/j.scitotenv.2021.146668.

Huang, J., X. Pan, X. Guo, and G. Li. 2018. "Health Impact of China's Air Pollution Prevention and Control Action Plan: An Analysis of National Air Quality Monitoring and Mortality Data." *The Lancet Planetary Health* 2(7): 313–23. https://doi.org/10.1016/S2542-5196(18)30141-4.

Hurtt, G., A. Andrews, K. Bowman, M. Brown, A. Chatterjee, V. Escobar, L. Fatoyinbo, P. Griffith, M. Guy, S. Healey, D. Jacob, R. Kennedy, S. Lohrenz, M. McGroddy, V. Morales, T. Nehrkorn, L. Ott, S. Saatchi, E. Carlo, S. Serbin, and H. Tian. 2022. "The NASA Carbon Monitoring System Phase 2 Synthesis: Scope, Findings, Gaps and Recommended Next Steps." *Environmental Research Letters* 17: 063010. https://iopscience.iop.org/article/10.1088/1748-9326/ac7407/pdf.

Intergovernmental Panel on Climate Change (IPCC). 2006. *IPCC Guidelines for National Greenhouse Gas Inventories. Volume 1: General Guidance and Reporting*. IPCC. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html.

International Organization for Standardization (ISO). 2022. *Climate Change Mitigation*. ISO, 2022, https://www.iso.org/files/live/sites/isoorg/files/store/en/PUB100271.pdf.

Incentive Scheme for Advanced Combined Cycle Gas Turbines (CCGTs). 2021. Energy Market Authority. https://www.ema.gov.sg/partnerships/calls-for-proposals/proposals/incentive-scheme-for-advanced-combined-cycle-gas-turbines

Jonas, M., R. Bun, Z. Nahorski, G. Marland, M. Gusti, and O. Danylo. 2019. "Quantifying Greenhouse Gas Emissions." *Mitigation and Adaptation Strategies for Global Change* 24: 839–52. https://doi.org/10.1007/s11027-019-09867-4.

Kairos Aerospace. 2022. "Methane Detection from a Unique Perspective." Kairos Aerospace. https://kairosaerospace.com/methane-detection/.

Kim, S., and J. Huh. 2020. "Blockchain of Carbon Trading for UN Sustainable Development Goals." *Sustainability* 12(10): 4021. https://www.mdpi.com/2071-1050/12/10/4021.

La Notte, A., S. Tonin, and S. Nocera. 2019. "A Screening Procedure to Measure the Effect of Uncertainty in Air Emission Estimates." *Mitigation and Adaptation Strategies for Global Change* 24: 1070–1100. https://doi.org/10.1007/s11027-018-9798-8.

Lee, J., and A. Wang. 2023. "NASA-Built Greenhouse Gas Detector Moves Closer to Launch." National Aeronautics and Space Administration. https://www.nasa.gov/centers-and-facilities/jpl/nasa-built-greenhouse-gas-detector-moves-closer-to-launch/.

Lin, E. 2022. "Assessing Federal Programs for Measuring Greenhouse Gas Sources and Sinks." Testimony. National Institute of Standards and Technology. June 23. https://www.nist.gov/speech-testimony/assessing-federal-programs-measuring-greenhouse-gas-sources-and-sinks.

Ministry of Environment and Forestry (MoEF). 2008. "State Minister of Environment Decree No. 17/2008." MoEF.

______. 2019. "State Minister of Environment Decree No. 15/2019." MoEF.

National Aeronautics and Space Administration (NASA). 2018. "Gaofen 5." Webpage. NASA. https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2018-043A.

______. 2023. "Energy: The Driver of Climate: The Greenhouse Gas Effect." NASA. https://www.ces.fau.edu/nasa/module-2/how-greenhouse-effect-works.php#:~:text=Carbon%20dioxide%20(CO2)%20is%20also,radiation%20region%20of%20the%20spectrum.

Nassar, R., O. Moeini, J. Mastrogiacomo, C. O'Dell, R. Nelson, M. Kiel, A. Chatterjee, A. Eldering, and D. Crisp. 2022. "Tracking CO_2 Emission Reductions from Space: A Case Study at Europe's Largest Fossil Fuel Power Plant." *Frontiers in Remote Sensing* (3). https://doi.org/10.3389/frsen.2022.1028240.

National Academies Press. 2010. *Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements*. National Academies Press. https://nap.nationalacademies.org/read/12883/chapter/5.

National Assembly (Viet Nam). 2014. "Law on Environmental Protection. No. 55/2014/QH13." National Assembly. https://climate-laws.org/geographies/vietnam/laws/law-on-environmental-protection-no-72-2020-qh14.

National Environment Agency (Singapore). n.d. "Measurement and Reporting Requirements for Greenhouse Gas Emissions" National Environment Agency. https://www.nea.gov.sg/our-services/climate-change-energy-efficiency/climate-change/carbon-tax/measurement-and-reporting-requirements-for-greenhouse-gas-emissions

New Zealand Agricultural Greenhouse Gas Research Centre (NZAGRC) and Pastoral Greenhouse Gas Research Consortium (PGgRc). 2016. *Agricultural Greenhouse Gases: Reducing New Zealand's Agricultural Greenhouse Gases: How We Measure Emissions (Edition 2)*. NZAGRC and PGgRc. https://www.pggrc.co.nz/files/1499904122151.pdf.

Obayashi, Y., and Golubkova, K. 2023. "Explainer: Japan's carbon pricing scheme kicks off at Tokyo Stock Exchange." Reuters. Online article. https://www.reuters.com/sustainability/japans-carbon-pricing-scheme-kicks-off-tokyo-stock-exchange-2023-10-11/

Office of Natural Resources and Environmental Policy and Planning, Ministry of Natural Resources and Environment (Thailand). 2015. *Climate Change Master Plan 2015–2050*. Office of Natural Resources and Environmental Policy and Planning, Ministry of Natural Resources and Environment. https://climate.onep.go.th/wp-content/uploads/2019/07/CCMP_english.pdf.

Paris Agreement to the United Nations Framework Convention on Climate Change. 2018."TIAS No. 16-1104." Paris Agreement publication. United Nations Framework Convention on Climate Change, https://unfccc.int/documents/184656.

Pipeline and Hazardous Materials Safety Administration (PHMSA) (United States). 2023. "Notice of Proposed Rulemaking (Pipeline Safety: Gas Pipeline Leak Detection and Repair)." PHMSA. May 18. https://www.federalregister.gov/documents/2023/05/18/2023-09918/pipeline-safety-gas-pipeline-leak-detection-and-repair.

Peanvijarnpong, C., D. Dowreang, N. Aphicholati, W. Kodchabudthada , M. Piboon. 2005. "Thailand Earth Observation System (THEOS): A New Dimension of Thailand Remote Sensing." Asian Association on Remote Sensing. https://a-a-r-s.org/proceeding/ACRS2005/Papers/D3-P23.pdf.

Poppa, F., U. Zimmer, A. Feitz, and H. Berko. 2013. "Development of a Carbon Dioxide Monitoring Rotorcraft Unmanned Aerial Vehicle." Workshop on Robotics for Environmental Monitoring (WREM) at Robotics: Science and Systems (RSS). https://www.researchgate.net/publication/260991963_Development_of_a_Carbon_Dioxide_Monitoring_Rotorcraft_Unmanned_Aerial_Vehicle.

Poulton, C., M. Byrd, P. Russo, E. Timurdogan, M. Khandaker, D. Vermeulen, and M. Watts. 2019. "Long-Range LiDAR and Free-Space Data Communication with High-Performance Optical Phased Arrays." *IEEE Journal of Selected Topics in Quantum Electronics* 25(5): 770108. https://ieeexplore.ieee.org/abstract/document/8678389/authors#authors.

Reddy, G. 2018. "Satellite Remote Sensing Sensors: Principles and Applications." *Geotechnologies and the Environment* 21: 21–43. https://link.springer.com/chapter/10.1007/978-3-319-78711-4_2.

Ritchie, H., M. Roser, and P. Rosado. 2020. "CO_2 and Greenhouse Gas Emissions." Our World in Data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

Sharma, N., and D. Panwar. 2020. "Green IOT: Advancements and Sustainability with Environment by 2050." International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions) (ICRITO). https://doi.org/10.1109/icrito48877.2020.9197796.

Smit, R., and P. Kingston. 2019. "Measuring On-Road Vehicle Emissions with Multiple Instruments Including Remote Sensing." *Atmosphere* 10(9): 516. https://www.mdpi.com/2073-4433/10/9/516.

Smith, C., Nicholls, Z.R.J., Armour, K., Collins, W., Forster, P., Meinshausen, M., Palmer, M.D., and Watanabe, M. 2021. "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material." *Climate Change 2021:The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07_SM.pdf.

United Nations Climate Change. n.d. "The Doha Amendment." UNFCC. https://unfccc.int/process/the-kyoto-protocol/the-doha-amendment.

United Nations Development Programme. 2022. "What are Carbon Markets and Why Are They Important?" Blog. United Nations Development Programme. May 18. https://climatepromise.undp.org/news-and-stories/what-are-carbon-markets-and-why-are-they-important.

United Nations Environment Programme (UNEP). 2021. *First Global Assessment of Air Pollution Legislation*. UNEP. September. https://www.unep.org/resources/report/regulating-air-quality-first-global-assessment-air-pollution-Legislation.

______. 2022. "How Do Countries Measure Greenhouse Gas Emissions?" Online article. UNEP. September 13. https://www.unep.org/news-and-stories/story/how-do-countries-measure-greenhouse-gas-emissions.

United Nations Framework Convention on Climate Change (UNFCCC). 2008. *Kyoto Protocol Reference Manual: On Accounting of Emissions and Assigned Amount*. UNFCC. https://unfccc.int/resource/docs/publications/08_unfccc_kp_ref_manual.pdf.

United States Inflation Reduction Act of 2022. Pub. L. 117–169. 1136 Stat. 1818. (2022). https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf.

White, T., M. Jonas, Z. Nahorski, and S. Nilsson. 2011. *Greenhouse Gas Inventories: Dealing with Uncertainty*. Springer. https://books.google.com/books?hl=en&lr=&id=jfNFYeWVxhQC&oi=fnd&pg=PA2&ots=O5KZtYi3PC&sig=7if6KrWj2dh-5x61WW8soWkqNQI#v=onepage&q&f=false.

Wintergreen, J., and T. Delaney. 2007. "ISO 14064, International Standard for GHG Emissions Inventories and Verification." First Environment, Inc. https://www3.epa.gov/ttnchie1/conference/ei16/session13/wintergreen.pdf.

Wunch, D., G. Toon, J. Blavier, R. Washenfelder, J. Notholt, B. Connor, D. Griffith, V. Sherlock, and P. Wennberg. 2011. "The Total Carbon Column Observing Network." *Philosophical Transactions of The Royal Society A* 368: 2087–2112. https://doi.org/10.1098/rsta.2010.0240.

Zhang, Z. 2022. "Chinese Scientists Break Aerostat Altitude Record." *China Daily*, May 16. https://www.chinadaily.com.cn/a/202205/16/WS6281a484a310fd2b29e5cdc6.html.

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