The future role of measurements in tracking progress on greenhouse gas emissions reductions and targets

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About CS NOW

Commissioned by the UK Department for Energy Security and Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5 million research programme, that will use the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation ambitions.

CS-N0W aims to enhance the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It will contribute to evidence-based climate policy in the UK and internationally, and strengthen the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by Ricardo and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

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0. Executive Summary

0.1 Introduction

As part of the wider programme Climate Services for a Net Zero Resilient World (CS-N0W), the consortium of Ricardo Energy & Environment, the National Centre for Earth Observation (NCEO), the National Centre for Atmospheric Science (NCAS) and the UK Centre for Ecology and Hydrology (UK CEH) has been commissioned by the Department of Energy Security and Net Zero (DESNZ) to carry out a study with the objective of exploring the opportunities for atmospheric measurements to improve the monitoring, reporting and verification (MRV) of UK greenhouse gas (GHG) emission estimates. This work is being done to understand how emerging capabilities and technologies could complement and enhance existing efforts to track and meet the 2050 Net Zero target, including compilation of GHG inventories and estimates inferred from atmospheric measurements collected by in situ scientific instruments.

0.2 Study methodology

To conduct the study firstly, an initial rapid situational review was carried out to provide a first draft response to the seven key research questions outlined by DESNZ (see Section 1.1 for the full list) based on the latest research. In parallel, a targeted online survey was run to collect insights from stakeholder experts, which have subsequently been integrated with the overview of the latest research in the field. This was followed by a stakeholder workshop to discuss as a wider group the findings of the literature review and to identify recommendations that represented key consensus viewpoints to take forward as actionable points.

0.3 Review of latest research

The following sections provide an overview of the latest research and insights from experts in response to the seven key research questions.

Question 1: What is the current landscape of activity on verification in the UK and internationally, and what has the impact of the activity been on understanding the accuracy of GHG inventories and assessing whether emissions reductions are leading to the anticipated reductions in atmospheric concentrations? This should identify the leading organisations, governments, and academic researchers that the UK should be engaging with routinely to collate and share and enhance best practice.

What is the current landscape of activity on verification in the UK and internationally?

There are a growing number of atmospheric measurement networks that have been, or are being, established with the purpose of eventually delivering long-term datasets to inform national GHG emissions estimates, complementing GHG inventories. Currently, only the UK and Switzerland use data collected from atmospheric networks to report top-down emission estimates to the United Nations Framework Convention on Climate Change (UNFCCC), but this is beginning to change rapidly with emerging national initiatives across the globe. There is also a growing number of field campaigns the UK and elsewhere to test GHG inventories on national to city-scale inventories. These campaigns are highlighting the value in using in situ and remote-sensing technologies to observe atmospheric GHGs to infer the associated surface fluxes. The next generation of satellite technology, with improved sensors and better spatial resolution, will play a larger role in estimating emissions on this spatial scale, complementing current satellites that provide information on (sub) national spatial scales.

What has the impact of the [verification] activity been on understanding the accuracy of greenhouse gas (GHG) inventories and whether emissions reductions are leading to the anticipated reductions in atmospheric concentrations?

Some of the best examples of atmospheric data being used to help with the verification of GHG inventories are those involving hydrofluorocarbons (HFCs). These compounds were subjected to emission controls a few decades ago as part of international efforts to minimise further human destruction of stratospheric ozone so that data records are typically much longer than for CO_2 and CH_4. These data have been used to confirm reduced UK emissions as reported by the UK inventory, consistent with the UK meeting its Kyoto Protocol commitment. More recently, the Covid-19 pandemic acted as a natural emission reduction experiment. In the absence of ratified atmospheric GHG data, some studies used proxies to report large changes in CO_2 emissions, but subsequent analysis showed that the temporary changes were too small to be verified using atmospheric measurements.

Identify the leading organisations, governments, and academic researchers that the UK should be engaging with routinely.

Generally, researchers responsible for this work reside in universities and research institutes, funded primarily by public money. However, the private sector is beginning to contribute to this field, incentivised by an emerging business case derived by new recommendations from the Task Force on Climate-Related Financial Disclosures and the US Securities and Exchange Commission.

Question 2: To what extent could improving atmospheric monitoring capability fill important gaps in knowledge and help reduce uncertainties in the inventory, including in offshore oil, gas and shipping emissions, diffuse emissions from the waste, agriculture and LULUCF (land use, land-use change and forestry) sectors, and diffuse fugitive sources of CH_4 and H_2 from energy and industry?

Current inventory gaps and uncertainties

The largest relative uncertainties in the UK National Atmospheric Emission Inventory (NAEI) are generally from sectors where emissions are controlled by complex biological processes such as LULUCF (CO_2), waste (CH_4) and agriculture (CH_4 and N_2O). Molecular hydrogen (H_2) is not currently included in the NAEI, and while it is not a direct GHG it indirectly affects the lifetimes of atmospheric CH_4 and ozone.

Current atmospheric monitoring capabilities

The in situ UK DESNZ funded 'DECC' (Deriving Emissions linked to Climate Change) measurement network has been used to successfully quantify emissions at the national scale for a variety of GHGs including CH_4 and HFCs, as well as the net CO_2 flux from the UK. However, the current surface network is biased towards southern England, so that inferred emissions originating from northern England and from Scotland have larger relative uncertainties. Current monitoring of atmospheric H_2 is limited but available measurements could be used to define the current global background level and estimate global or hemispheric emissions before we begin the transition to a hydrogen economy.

Potential improvements to reduce uncertainties in key sectors of the inventory

Expanding the surface network would allow better quantification of diffuse emissions. Improving the attribution of changing atmospheric GHGs to individual sectors. For example, measurements of isotopologues (e.g., $\delta^{13}CH_4$) and reactive trace gases (e.g., ethane) could further improve the differentiation of individual CH_4 source sectors, particularly diffuse fugitive sources from energy and industry.

Emissions of CH_4 from offshore oil and gas platforms have been detected and quantified in small-scale limited time campaigns using measurements on-board ships or aircraft. There is a need for an onshore monitoring capability for this sector.

Question 3: What is the current technological capability, and what is the likely future capability in the medium-term (i.e., next five years) and long-term, for monitoring GHGs in line with policy needs?

What is the current technological capability?

The UK DECC tall tower network provides the measurement backbone for quantifying UK GHG emissions. Current technology for making in situ GHG concentrations measurements is able to collect high frequency and continuous measurements with minimal intervention or maintenance requirements.

Relevant tracer measurements for more detailed and improved source apportionment; likely future capability in the medium-term (i.e., next five years) and long-term

Improved source apportionment of GHG emissions is possible using additional atmospheric measurements, for example, 1) stable isotope ratios, 2) halogenated GHGs, 3) radiocarbon, and 4) reactive trace gases. Offline isotope ratio mass spectrometry is the current ‘gold standard’ for high precision measurement of $\delta^{13}C$ and $\delta^{2}H$ in CH_4. Measurements from laser spectrometers that have lower maintenance and provide high frequency in situ analysis should become possible over the next five years. Measurements of halogenated GHGs are likely to continue requiring specialised equipment for the foreseeable future, however, improvements in robustness and reliability of hardware should allow these measurements to be scaled up under sufficient support. Radiocarbon measurements ($\Delta^{14}CO_2$) are likely to remain a highly valuable measurement and high-throughput analysis is possible. The challenge over the next five to ten years will be to improve the high-frequency capability. Techniques for laser spectrometers capable of radiocarbon measurements are also in development. Trace gases co-emitted with GHG, including carbon monoxide, ethane, and O_2, can be measured alongside GHGs at tall towers, but ethane typically they require more specialised equipment. Scaling up measurements of ethane and O_2 into a larger regional network is possible with sufficient supporting infrastructure.

Complementary measurements and platforms

Mobile airborne and ground-based measurement platforms could be used to focus on specific emissions by utilising advances made in laser spectrometry for onboard deployment. Lower cost sensors for measurement of CO_2 are now being deployed across several cities. Although the precision of these devices is relatively low, the density of deployment and methods to network the measurements could allow for a useful understanding of emissions at the city scale.

Question 4: What role could remote sensing play in the verification of estimates of GHG emissions and removals, and for which GHGs/sources does remote sensing data already have the capacity to calibrate/inform emissions estimation methods?

For which GHGs/sources does remote sensing data already have the capacity to calibrate/inform emissions estimation methods?

The power of satellite observations lies in their ability to provide spatially and temporally resolved measurements of atmospheric CO_2 and CH_4 concentrations globally which provides a strong constraint on the net amount of each gas that is exchanged between the surface and the atmosphere by natural and anthropogenic processes. This is now well established thanks to the pioneering satellite missions SCIAMACHY, GOSAT and OCO-2. These data are being used already to successfully estimate emission from large power stations, and OCO-2 is being used to assess emission inventories for large cities. Observations from GOSAT, and more recently from TROPOMI, have been successfully used to quantify anthropogenic emissions for large countries and a pilot dataset of CH_4 emissions by sector and country-scale resolution has already been generated. Commercial satellites with very high spatial resolution (10s of metres) such as GHGSat or hyperspectral missions such as Worldview-3 and Sentinel-2 have improved capabilities to observe and quantify localised CH_4 emissions.

Future capabilities of remote sensing to support verification of GHG emissions and removals

A major advance in space-based observations of CO_2 and CH_4 will be achieved with the launch of the ESA CO2M mission in 2025, which has been designed specifically to provide remote sensing observations needed for monitoring of anthropogenic CO_2 and CH_4 emissions. Over the next five years, other technologies including active and geostationary missions will become available that will complement data obtained from CO2M, for example during high latitude winter. We will also see a substantial increase in commercial and hybrid missions over the next five to ten years which promise further advances in monitoring with more frequent observations and lower detection limits.

Question 5: Which areas of policy interest are best-served by bottom-up inventory approaches, and where might atmospheric measurements, in the longer term, be able to support emission estimates?

The bottom-up inventory is most uncertain in the areas of LULUCF, waste management, and agriculture. The LULUCF sector raises problems for the top-down approach for CO_2 because of the large gross CO_2 fluxes which dominate the atmospheric signal, which are largely unrelated to anthropogenic impacts in the LULUCF sector. The other sectors are all relatively well-served by the bottom-up inventory approaches, with low relative uncertainties (2-4%). The industrial process and public-sector emissions have the lowest absolute uncertainties. Given the magnitude of emissions from the energy (including mobile combustion (i.e., transport) and stationary combustion (i.e., business and residential) sectors, these represent larger absolute uncertainties.

The key intersection where the bottom-up approach is weak and atmospheric measurements have the most potential is the agriculture and waste management sectors. To a lesser degree, there is scope in the areas of transport and domestic emissions. To quantify emissions from point sources, which dominate the energy production and industrial sectors, more targeted measurement and modelling approaches are needed.

Bottom-up and top-down approaches need not be considered as distinct, but careful integration of the two is required. Consistency in the various nomenclatures used to classify emissions (NFR – “Nomenclature for Reporting”, SNAP – “Selected Nomenclature for sources of Air Pollution”, SIC – “Standard Industrial Classification”, CRF – “Common Reporting Format” etc.), and openness of data would be helpful here.

Question 6: Could atmospheric measurements enable tracking of the effectiveness of specific policies in near real time, and what are the levels of temporal, spatial and sectoral resolution required?

Using existing data from the tall tower network to estimate emissions from particular sectors at specific times or locations, in relation to tracking specific policies, is generally rather uncertain. To increase the time resolution with which we can make precise estimates, we need to add high-resolution measurements of some key atmospheric properties, e.g., boundary layer height.

Emission sectors for which atmospheric measurements have the most potential to help provide more rapid estimates of emissions include: N_2O from agriculture; CO_2 from road transport; CO_2 from energy production and industry; CH_4 from offshore facilities; CH_4 and N_2O from landfill sites; CO_2 from shipping. Monthly resolution with a short time lag would be a practicable target. The most accurate estimates will still require bottom-up activity data, and this may be the limiting factor on the lag time.

Point sources including industrial plants, large landfill sites, and power stations are not well sampled by the existing tower network, and require a more targeted approach, focussing on spatial variation around the point source. Using in-situ ground-based measurements, aircraft-based measurements and/or satellite data can yield high-resolution data for some key emissions.

While near-real-time (NRT) data with higher time resolution could provide faster evidence of change, because of the background natural variability and aleatoric uncertainty, longer term monitoring would still be needed for the wider context.

Question 7: What are the infrastructure requirements for increasing the role of measurements in tracking GHG emissions reductions?

To increase the role of measurements in tracking GHG emissions reductions, it is vital that infrastructure receives continuous support, covering both maintenance and innovation of the measurement networks, over periods of decades to provide the long-term context for any future changes in the UK's emissions. Further investment in measurement infrastructure is necessary to better target emissions from specific sectors and from cities, as well as provide emissions estimates at regional scales or better.

Specific infrastructure requirements to increase the role of measurements include expansion of the existing DECC tall tower network, establishment and maintenance of in situ measurements networks in cities, and implementation of complementary data infrastructure to support measurement infrastructure. Expansion of the existing DECC tall tower network is needed to address the current lack of coverage in Scotland, the North of England, and the Midlands. As a minimum, this would require the establishment of two new sites to replace the spatial footprints formerly covered by the Angus (Scotland) and Bilsdale (Yorkshire) sites. Capability to measure tracer gases for source attribution (e.g., anthropogenic vs. biogenic) should be included in new sites and added to existing sites where they are not currently in place.

Establishment and maintenance of in-situ measurement networks in cities is required to address the challenge of quantifying urban emissions and monitoring their trends. These should target the largest and most populous metropolitan areas that contribute the most emissions and can build on existing or previous projects (e.g., London, Glasgow).

Implementation of complementary data infrastructure to support measurement infrastructure, e.g., a dedicated open access repository of data with common standards, formats, would ensure that maximum value is derived from the UK's GHG measurement infrastructure. This should incorporate GHG emissions and fluxes calculated from the measured atmospheric concentrations.

0.4 Conclusions and recommendations

The UK was the first country in the world to establish a GHG measurement network to inform national GHG emission estimates reported annually to the UNFCCC. While the UK activity remains world-leading, it is no longer unique, with large-scale initiatives being developed across the world which take advantage of new technologies and techniques to build integrative measurement and modelling systems. The UK science and technology communities have the expertise to evolve and improve the current system, to expand the volume and type of atmospheric GHG measurements being collected, to improve source attribution of emission estimates, to exploit new data to improve the resolution of GHG inventories, and to improve the integration of cutting-edge atmospheric models and estimation methods for GHG emissions.

To increase the role of atmospheric measurements in tracking UK progress towards reducing GHG emissions, it is essential that the measurement/modelling infrastructure receives continuous financial support on decadal scales. This investment will ensure we maintain our current baseline measurement and analysis capability, and help evolve this capability by adopting new technologies. This also ensures that the UK remains at the forefront of using atmospheric data to inform their knowledge of national annual GHG emissions.

On this basis, six high-level, integrative recommendations have been collated. Each recommendation describes a priority action that will support the UK GHG inventory development in accuracy and completeness. The actions will help the UK maintain its position at the leading edge of research and development using atmospheric data to quantify national GHG emissions.

These recommendations are complemented by further suggestions concerning each individual research question presented in Section 5.2, Annex 2.

1. Maintain baseline monitoring capability for UK GHG emission estimates and nurture new instrument and computational technologies that will eventually improve the baseline capability.

2. Develop new and existing computational tools that are necessary to translate atmospheric data into emission estimates and uncertainties.

3. Improve UK colocation of GHG and air quality measurements to improve emission estimates for individual source sectors.

4. Improve the availability of higher temporal resolution inventory estimates to improve the interpretation of high-frequency atmospheric measurements that are used to infer annual emission estimates reported by the UK to the UNFCCC.
5. Extend the existing UK measurement/analysis system to integrate inventory compilation, different measurement types, and top-down emission estimation methods to improve posterior estimates and uncertainties.
6. Engage early with the private sector to collect and deliver baseline monitoring measurements and to establish an open and accessible data repository.

1. Introduction

1.1 Introduction and objective of the study

The consortium of Ricardo Energy & Environment, the National Centre for Earth Observation (NCEO), the National Centre for Atmospheric Science (NCAS) and the UK Centre for Ecology and Hydrology (UK CEH) has carried out a study to support the Department for Energy Security and Net Zero (DESNZ) in investigating the future role of measurements in tracking progress on greenhouse gas emissions reductions and targets. This project is part of the wider programme Climate Services for a Net Zero Resilient World (CS-N0W).

CS-N0W is a 4-year, £5 million research programme that will use the latest scientific knowledge to inform UK climate policy and help us meet global decarbonisation ambitions. The programme aims to enhance the scientific understanding of climate impacts, decarbonisation, and climate action, and improve accessibility to the UK ˎ s climate data. It will contribute to evidence-based climate policy in the UK and internationally, and strengthen the climate resilience of UK infrastructure, housing, and communities.

DESNZ is seeking to understand what the UK’s current monitoring, reporting and verification (MRV) needs are and how these might be met by current and emerging capabilities. The objective of this study is to explore the opportunities for atmospheric measurements to improve the MRV of UK GHG emissions estimates, particularly in relation to the UK’s pathway to net zero by 2050, and how these might be met by current and emerging capabilities and technologies.

There are seven key research questions which this study seeks to answer:

Key research questions:

1. What is the current landscape of activity on verification in the UK and internationally, and what has the impact of the activity been on understanding the accuracy of greenhouse gas (GHG) inventories and assessing whether emissions reductions are leading to the anticipated reductions in atmospheric concentrations? This should identify the leading organisations, governments, and academic researchers that the UK should be engaging with routinely to collate and share and enhance best practice.
2. To what extent could improving atmospheric monitoring capability fill important gaps in knowledge and help reduce uncertainties in the inventory, including in offshore oil, gas and shipping emissions, diffuse emissions from the waste, agriculture and LULUCF (land use, land-use change and forestry) sectors, and diffuse fugitive sources of CH_4 and H_2 from energy and industry?

3. What is the current technological capability, and what is the likely future capability in the medium-term (i.e., next five years) and long-term, for monitoring GHGs in line with policy needs?
4. What role could remote sensing play in the verification of estimates of GHG emissions and removals, and for which GHGs/sources does remote sensing data already have the capacity to calibrate/inform emissions estimation methods?
5. Which areas of policy interest are best-served by bottom-up inventory approaches, and where might atmospheric measurements, in the longer term, be able to support emission estimates?
6. Could atmospheric measurements enable tracking of the effectiveness of specific policies in near real time, and what are the levels of temporal, spatial and sectoral resolution required?
7. What are the infrastructure requirements for increasing the role of measurements in tracking GHG emissions reductions?

1.2 Summary of the methodology

This study has taken the approach of having two parallel workstreams that have fed into this final report:

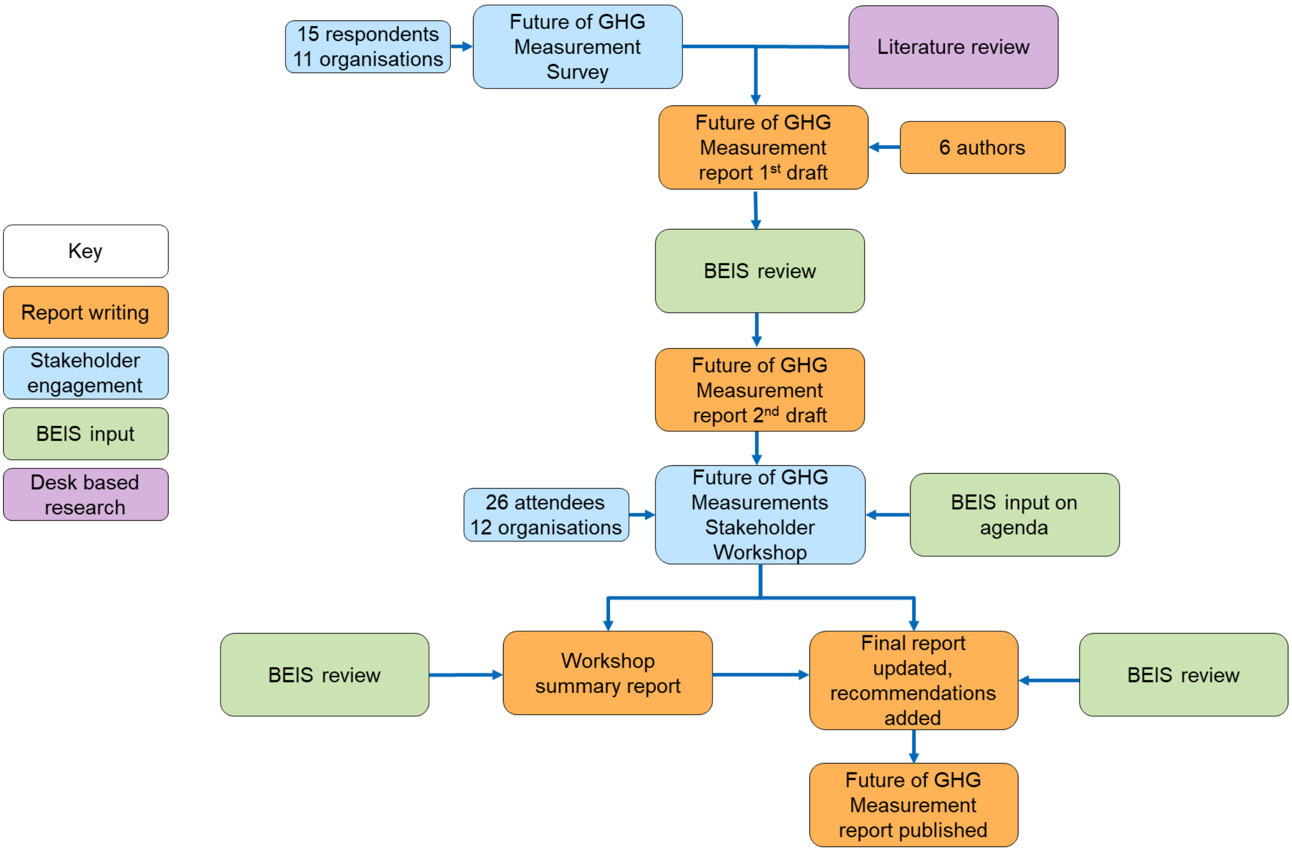
1. Desk based research, comprising a rapid situational review
2. Stakeholder engagement, included an online targeted survey and virtual stakeholder workshop.

Figure 1 shows the process followed. The development of this report followed a collaborative effort with the question authors, Ricardo, DESNZ, and a number of core stakeholders from a variety of institutions, both within academia and government.

The process started by gaining more insight into the key focus areas around the seven questions via a stakeholder survey and literature review. The survey questions were developed by the project team in collaboration with DESNZ and sought to gather information and views from a variety of different stakeholders (see Annex 1 for a list of stakeholder organisations engaged as part of the project) while a literature view led by the authors aimed to bring the latest research into the forefront of the report. Following the first draft of the report there was a comprehensive review from DESNZ to provide feedback for a second iteration.

The review of research and literature was shared with relevant stakeholder experts. Stakeholders were also invited to attend a workshop held on 17-18 March 2022 to further discuss the topics presented and consider what recommendations should be presented to DESNZ for them to consider. Section 5.1 Annex 1 lists the stakeholders consulted. During the workshop, the report authors, along with input from DESNZ, used this session to present their findings, shaping the discussion around key topic areas that needed further clarity. A key outcome from the workshop was that there was no dissent from the content presented or ideas discussed, i.e. a general consensus on the direction of travel and key opportunities. A range of different approaches were discussed. A separate workshop report has been developed by Ricardo to summarise the discussions which fed into the recommendations and final update provided by the report authors.

Figure 1. Report methodology



2. Review of latest research and expert insights

The following section provides an overview of the latest research and stakeholder insights focusing on the seven key research questions of this study.

2.1 Question 1: What is the current landscape of activity on verification in the UK and internationally, and what has the impact of the activity been on understanding the accuracy of greenhouse gas (GHG) inventories and assessing whether emissions reductions are leading to the anticipated reductions in atmospheric concentrations? This should identify the leading organisations, governments, and academic researchers that the UK should be engaging with routinely to collate and share and enhance best practice.

2.1.1 Summary

Verification activities are not designed to dispute the accuracy of a GHG inventory. Rather, they are designed to support the development of the inventory to enhance its accuracy and completeness.

Using atmospheric measurements to verify GHG inventories, within a Measurement Reporting and Verification (MRV) framework, requires high-quality and calibrated data *and* well-characterised mathematical methods to translate those data into emission estimates, including a rigorous uncertainty analysis.

There are a growing number of long-term measurement networks that have been (or are being) established with the purpose of eventually delivering data to inform national GHG emissions estimates. Currently, only the UK and Switzerland use data collected from atmospheric networks to report top-down emission estimates to the United Nations Framework Convention on Climate Change (UNFCCC). A few other countries report GHG estimates using only one or two sites, e.g., Australia and New Zealand.

There is also a growing body of work that uses (short-term) field campaign measurements of CO_2 and CH_4 in the UK and elsewhere to identify discrepancies between national to city-scale inventories and emissions inferred from atmospheric data.

The duration of measurement records for CO_2 and CH_4, collected as part of national networks, are beginning to be sufficiently long that they can be used to detect ongoing emission trends and to provide a test for national inventories. Currently, this is relevant to the UK and Switzerland.

Some of the best examples of atmospheric data being used to help with the verification of GHG inventories are those involving hydrofluorocarbons (HFCs). These compounds were subjected to emission controls a few decades ago as part of international efforts to minimise further human destruction of stratospheric ozone. Consequently, data records are typically much longer than for CO_2 and CH_4 and are more suitable for quantifying trends, and in some instances for identifying illegal usage.

There is growing interest in city-scale experiments (scales of less than a few kms) to verify GHG emissions, which are using a range of in situ and remote-sensing technologies to observe atmospheric GHGs. The next generation of satellite technology, with improved sensors and better spatial resolution, will play a larger role in estimating emissions on this spatial scale. This capability complements information that satellites already provide on (sub) national spatial scales.

Quantifying hotspot emissions includes point sources smaller than cities, e.g., oil and gas extraction, pipe leaks, and shipping. These require high spatially resolved data available via ground-based or airborne platforms, and via next-generation satellite instruments.

Leading researchers generally reside in universities and research institutes, funded primarily by public money. The private sector is beginning to contribute to this field, particularly focused on emission hotspots that are on the asset spatial scale, in response to regulations that are being introduced via recommendations made by the Task Force on Climate-Related Financial Disclosures.

Substantial expertise already exists in identifying best practice, but this is an ongoing activity. Stakeholder engagement is widely considered to be an important component of developing an effective MRV, including regional and national government agencies, inventory compilers, emission trading practitioners, and developers of downstream services.

2.1.2 The role of verification in the development of national GHG inventories

1. Before we start with the summary of the latest “landscape”, it is important to understand how verification activities are used to support the development of GHG inventories. The Intergovernmental Panel on Climate Change (IPCC) 2006 GHG Inventory Guidelines provide a clear explanation of the function of verification as shown in Box 1 below.

Box 1. IPCC 2006 GHG inventory Guidelines

IPCC 2006 Guidelines, Chapter 6: QA/QC and Verification

6.10 Verification*. “For the purposes of this guidance (the IPCC 2006 GLs), verification activities include comparisons with emission or removal estimates prepared by other bodies and comparisons with estimates derived from fully independent assessments, e.g., atmospheric concentration measurements. Verification activities provide information for countries to improve their inventories and are part of the overall QA/QC and verification system. Correspondence between the national inventory and independent estimates increases the confidence and reliability of the inventory estimates by confirming the results. Significant differences may indicate weaknesses in either or both of the datasets. Without knowing which dataset is better, it may be worthwhile to re-evaluate the inventory. This* *section (of the 2006 GLs) describes approaches that can be used to verify inventory estimates at both the source/sink category and inventory wide levels."*

***6.10.2 Comparisons with atmospheric measurements**. "An ideal condition for verification is the use of fully independent data as a basis for comparison. Measurements of atmospheric concentrations potentially provide such datasets, and recent scientific advances allow using such data as a basis for emission modelling. The approach is particularly valuable as it is independent of standard estimation method drivers, such as sector activity data and implied emission factors. The scale of such models can be designed around local, regional, or global boundaries and can provide information on either level or trends in emissions"*

2.1.3 Current landscape: UK

2. Currently, only the UK[1] (non-CO_2 GHGs) and Switzerland[2] (CH_4 and N_2O) submit top-down results (see glossary of terms in Section 6) with their GHG emission submissions to the UNFCCC, accompanying their inventory estimates. These top-down estimates are typically inferred from one or more tall towers (telecommunication masts) where air is collected and pumped downwards to the surface where it is analysed. Neither country has reported national emissions of CO_2 because bottom-up estimates of anthropogenic emissions of GHGs are generally considered to be sufficiently accurate to address policy requirements.
3. The UK MRV framework, established in 2012[3] by the University of Bristol and the Met Office, is primarily funded via DESNZ (formally by the Department of Energy and Climate Change) with contributions from Natural Environment Research Council (NERC)-funded research projects GAUGE (Greenhouse gAs Uk and Global Emissions) led by the University of Edinburgh (Palmer *et al.*, 2018) and DARE-UK (Detection and Attribution of Regional greenhouse gas Emissions in the UK) led by the University of Bristol, and from the National Measurement System by the National Physical Laboratory (NPL). The resulting network is entitled the Deriving Emissions relevant to Climate Change (DECC), (Stanley, Grant, O'Doherty, Young, *et al.*, 2018). The core DECC network includes atmospheric measurements collected at Angus (Scotland, until it was decommissioned in September 2015) Bilsdale (N. Yorkshire, until it was destroyed by a fire[4] in August 2021), Heathfield (East Sussex), Mace Head (Ireland), Ridgehill (Herefordshire), and Tacolneston (Norfolk). NERC have provided capital funding for a purpose-built tall tower to be established by March 2023[5], located in Angus, Scotland to be run by researchers from the University of Edinburgh and the James Hutton Institute, in collaboration with the current DECC network. Proposed measurements include CO_2, CH_4, carbon monoxide, radon, wind speed and

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[1] https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2106091119_ukghgi-90-19_Annex_Issue_2.pdf
[2] https://unfccc.int/sites/default/files/resource/CHE_BR4_2020.pdf
[3] Before this date the UK used emissions measures from Mace Head only to infer emissions. See section 1.4 below.
[4] https://www.bbc.co.uk/news/uk-england-tees-58821271
[5] https://blogs.ed.ac.uk/soar/

direction, relative humidity, and temperature. There are plans to include N_2O, but this is subject to funding.

4. As part of the NERC-funded projects DARE-UK project[6] led by University of Bristol researchers and the London GHG experiment[7] led by University of Cambridge researchers, and activities led by University of Leicester researchers and funded by the NERC National Centre for Earth Observation (NCEO)[8], London is being used as a testbed to quantify urban fluxes of GHGs and air pollutants. Since late April 2021 ground-based remote sensing instruments have been collecting CO_2 and CH_4 data at three sites across London (National Physical Laboratory in Teddington, the University College London Engineering Building on Torrington Place, and Highfields Tower in North-East London), which will be used to compare against satellite data. These are accompanied by a range of air quality measurements to help interpret the GHG measurements (carbon monoxide, nitrogen dioxide, ozone, formaldehyde, sulphur dioxide, and aerosols). This expands the scope of GHG data that has been collected by UK Centre for Ecology and Hydrology (UK CEH) researchers on the BT Tower[9] since 2011; NERC National Centre for Atmospheric Science (NCAS) also collect a small number of relevant air pollutants at this site (Lee *et al.*, 2015). At this central London site, CO_2 flux estimates were consistent with London inventory estimates, but CH_4 emissions were twice those reported by the inventory (Helfter *et al.*, 2016).
5. UK researchers have used an aircraft to survey CH_4 emissions from UK and Dutch offshore oil and gas installations (France *et al.*, 2021). They also collected a range of trace gases and CH_4 isotopologues to help attribute observed CH_4 to the oil and gas sector (e.g., (Wilde *et al.*, 2021)). The purpose of these data collected during two campaigns in 2018 and 2019 was to understand how to use atmospheric data to infer offshore CH_4 emissions. The combined analyses demonstrate the ability of non-methane hydrocarbon to identify emission sources within the oil and gas industry (Wilde *et al.*, 2021), but emphasised that aircraft sampling of emission plumes is difficult due to the irregularity of flights and uncertainties in meteorology (France *et al.*, 2021). A coordinated measurement programme that included other platforms, e.g., drones and ships, would help provide a more representative assessment of emissions from this sector (France *et al.*, 2021). Some of this material is also discussed in Section 2.2.4.

2.1.4 Current landscape: international

6. Switzerland has a GHG observation network that includes the high-altitude research station Jungfraujoch, a high-precision atmospheric tower GHG network (Oney *et al.*, 2015; Henne *et al.*, 2016), and low/mid-cost CO_2 sensor network[10] that includes 200 low-cost and 14 mid-cost CO_2 sensors

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[6] https://dareuk.blogs.bristol.ac.uk/

[7] https://gtr.ukri.org/projects?ref=NE%2FR000921%2F1

[8] https://www.nceo.ac.uk/article/setting-up-the-london-remote-sensing-observatory-for-carbon-and-air-quality/

[9] https://www.ceh.ac.uk/our-science/projects/bt-tower-london-uk-urban-atmospheric-pollution-observatory

[10] http://carbosense.wikidot.com/

across Switzerland, with a focus on Zurich as part of ICOS-Cities. These activities are mostly coordinated by the Swiss Federal Laboratories for Materials Science and Technology (EMPA). The Swiss tower sites form the basis of annually reported CH_4 and N_2O emission estimates reported to the UNFCCC. Top-down estimates typically provide additional temporal granularity to officially reported bottom-up estimates provided every five years by Meteotest.

7. Australia uses one measurement site (Cape Grim, Tasmania) to infer emission estimates of synthetic GHGs and ozone depleting substances, e.g., 2021 report[11]. These emissions are estimated either using the InTEM inverse method or via correlation with carbon monoxide measurements from Melbourne, from the Greater Melbourne area and then upscaled based on population. For several years, Australian reports to the UNFCCC have been based on these atmospheric data, e.g., 2020 report[12].
8. Brazil, in cooperation with the National Oceanic and Atmospheric Administration (NOAA) in the US, has a GHG laboratory in which they use aircraft to collect vertical profiles of CO_2 collected at four sites within Brazil. These data form the basis of a number of high-profile papers, e.g., (Gatti *et al.*, 2021) focused on the carbon balance of the Amazon basin. They are not currently used in official government statistics[13].
9. Canada maintains a nationwide network of GHG measurements[14] but these are not used directly to inform national inventories. Provincial level measurement campaigns help to identify gaps or inconsistencies in CH_4 inventory estimates, particularly the oil and gas sector (Chan *et al.*, 2020) including oil sands (Liggio *et al.*, 2019). The Canadian Government is addressing the Global Methane Pledge with a pledge to reduce CH_4 emissions from the oil and gas sector[15] by 75% by 2030, representing an ideal test for their atmospheric measurement networks. Canada is also investing in ground-based networks to quantify GHG emissions of cities, e.g., Toronto[16] (involving University of Toronto and Environment and Climate Change Canada).
10. China maintains a network of seven background GHG measurements sites. While these data have not been used to inform the UNFCCC, they have been used to study the Chinese carbon budget (Wang *et al.*, 2020) and subsequently used to inform Chinese net zero plans. China has a range of urban experiments, but the biggest one is the Beijing, Tianjin, and Hebei (BTH) megacity carbon emission project. This involves a range of science-grade in situ and remotely sensed instruments, which will soon be supplemented by a dense network of low-cost sensors. The China National Environmental

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[11] https://www.awe.gov.au/environment/protection/ozone/publications/csiro-report-australian-global-sgg-emissions-2021

[12] https://unfccc.int/documents/228017

[13] http://seeg.eco.br/

[14] https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/Climate-change/pdf/CCCR_FULLREPORT-EN-FINAL.pdf

[15] https://liberal.ca/our-platform/cutting-methane-emissions/

[16] http://www.chasing-greenhouse-gases.org/toronto-ghg/

Monitoring Centre has just announced a further 16 urban pilot projects, including Tangshan, Jinan, and Shanghai.

11. France has several activities focused on developing a capability to use ground-based and satellite observations to infer GHG emissions. The ARGONAUT project[17] is the main current project at the national scale. They are developing a prototype analysis system to combine air quality pollutants that are co-emitted during combustion (nitrogen oxides, carbon monoxide, and non-methane hydrocarbons) with GHG measurements (CO_2), in preparation for the European CO_2 Monitoring (CO2M) satellite constellation, ultimately to refine national inventories that describe anthropogenic emissions of GHGs. As part of ARGONAUT, French researchers are developing the design of an operational assimilation system that will also have the capability to zoom into cities and individual industries. Ground-based city-wide networks are being established for Marseille[18] and Reims.
12. Germany has a mature plan[19] (see Action 8) reported by the science ministry to deliver top-down estimates to the UNFCCC. The first phase of the Integrated GHG Monitoring system for Germany (ITMS) was due to start in December 2021. It will eventually combine measurements and modelling systems to deliver top-down GHG emission/flux estimates.
13. Japan has several regional measurement sites as part of the Global Atmospheric Watch (GAW). The Ministry of Environment established in 2021, a project[20] to use data to estimate nationwide GHG emissions of CO_2, CH_4, and N_2O in support of the 2023 Global Stocktake, taking advantage of a wide range of data. To accompany this project, they will publish an annual report summarising Japanese and wider Asian GHG emission estimates.
14. The Ruisdael Observatory[21] is a national atmospheric network for the Netherlands. It is currently focused on weather and air quality measurements. While there is a growing interest in incorporating measurements of CH_4 and N_2O there are no firm plans. The Netherlands (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, TNO) play a key role in developing emission inventories for anthropogenic emissions of CO_2 and CH_4 and of associated air pollutants co-emitted with these GHGs.
15. Atmospheric measurements of CO_2 and CH_4 collected at Lauder (South Island) and Baring Head (North Island) form the basis of the New Zealand atmospheric GHG measurement network. Top-down CH_4 emission estimates inferred from those data have already been used as independent verification of

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[17] https://anr.fr/Project-ANR-19-CE01-0007

[18] https://anr.fr/Project-ANR-19-CE03-0008

[19] https://www.bmbf.de/SharedDocs/Publikationen/de/bmbf/FS/31648_Forschung_fuer_Nachhaltigkeit_en.pdf

[20] https://esd.nies.go.jp/cop26/pdf/presentation-slides/1_COP26_JPseminar_Ito_20211102_v5.pdf

[21] https://ruisdael-observatory.nl/

agricultural emissions in the New Zealand Greenhouse Gas Inventory[22]. CO_2 flux estimates are under development.

16. South Korea is establishing an integrated observation-modelling system (INVERSE-KOREA) to help them realise their carbon neutral vision for 2050. Their national measurement network currently includes seven in situ sites, one tall tower, and one Total Carbon Column Observing Network (TCCON) ground-based remote sensing site (see below). These will be accompanied in 2022 by a range of mobile sensors, regular aircraft measurements, and an urban network focused on Seoul. Continuous (resolution of 1 hour or less) and weekly measurements in CO_2, CH_4, N_2O, sulphur hexafluoride, chlorofluorocarbons (CFCs), and since 2014 a range of CO_2 and CH_4 isotopes.
17. There are also substantial research activities that are focused on developing a pan-Europe MVS (Measurement Verification Support), driven by funding from H2020 and Horizon Europe. These include the CO_2 Human Emission project[23] (CHE), VERIFY[24], and CoCO2[25]. These are being followed up by research-driven Horizon Europe projects: AVENGERS, EYE-CLIMA, PARIS.
18. The CoCO2 project is building prototype systems for a European MRV system. This is partly driven by a new CO_2 service under the European Commission Copernicus program, which will include a three-satellite constellation (CO2M) and an associated ground-based network. Collectively, these activities will underpin an Operational Anthropogenic CO_2 Emissions MVS Capacity (Commission *et al.*, 2017, 2019; Janssens-Maenhout *et al.*, 2020). The European Space Agency (ESA) have also invested in projects focussed on using ground-based remote sensing instrument to help validate satellite instruments, e.g., FRM4GHG[26]. The Joint Research Centre provides independent science advice and support to the European Commission. It maintains the Emissions Database for Global Atmospheric Research (EDGAR), including inventories for CO_2, CH_4, and a range of co-emitted air pollutants.
19. Within Europe, there have been a number of city-scale experiments, e.g., CO2-MEGAPARIS. Most recently, Horizon 2020 funded the ICOS Cities project[27]. This project will form a testbed for city pilot studies, including Paris (large city), Munich (medium city), and Zurich (small city). Other, smaller cities will join the network to understand best practice. These cities include Antwerp, Athens, Barcelona, Basel, Brno, Copenhagen, Heidelberg, Helsinki, Krakow, Porto, Rome, and Rotterdam.
20. National US activities include the United States Carbon Cycle Program[28] that coordinates carbon cycle activities across fourteen federal agencies and departments. The NASA Carbon Monitoring Service[29] is

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[22] https://environment.govt.nz/assets/Publications/New-Zealands-Greenhouse-Gas-Inventory-1990-2019-Volume-1-Chapters-1-15.pdf
[23] https://www.che-project.eu/
[24] https://verify.lsce.ipsl.fr/
[25] https://www.coco2-project.eu/
[26] https://frm4ghg.aeronomie.be/
[27] https://www.icos-cp.eu/projects/icos-cities-project
[28] https://www.carboncyclescience.us/
[29] https://carbon.nasa.gov/

the closest to a US MRV, bringing together data and models but it does not currently influence the US GHG emission submission to the UNFCCC. There are also a substantial number of activities led by the University sector focused on estimating national emission inventories, e.g., (Xu *et al.*, 2021) for N_2O; (Hu *et al.*, 2017) for HFCs; (Vaughn *et al.*, 2018) for natural gas emissions of CH_4, (Rutherford *et al.*, 2021) for oil and gas emissions of CH_4; sector-based inventory (Cusworth, Bloom, *et al.*, 2021). One of the largest activities is the state-funded California Methane Survey[30]. In late January 2022, the President's Council of Advisors on Science and Technology hosted a meeting[31] on "Improving efforts to measure and monitor greenhouse gas emission," that included a number of presentations[32] relevant to the development of a future US MRV system. This has been followed up with an activity[33] led by the US National Academies to "develop a framework for evaluating global anthropogenic greenhouse information to support decision making."

21. The US has helped to pioneer urban GHG measurement networks. The 2010 Indianapolis Flux Experiment (INFLUX, (Davis *et al.*, 2017)) was one of the first coordinated experiments to understand how to quantify urban GHG emissions. This experiment had the advantage of a well-defined urban emission core. INFLUX was followed in 2013 by the LA Megacities_Project[34] (e.g., (Verhulst *et al.*, 2017) and in 2014 by the Northeast Corridor Experiment[35] (incorporating Washington, D.C. Baltimore, and Maryland urban regions). In situ tower networks formed the measurement backbone for all these experiments. Aircraft and ground-based remote sensing instruments provided additional information. Smaller-scale experiments are also being conducted across the US, e.g., Boston (Sargent *et al.*, 2018), Salt Lake City (Mallia *et al.*, 2020), Berkeley (Delaria *et al.*, 2021). High resolution emission inventories (e.g., Hestia[36]) are being developed to support high-resolution measurement networks. Except for a few experiments, many of the city-wide networks are run for short periods and therefore cannot be used to study emission trends.

22. US investigators have reported a range of large CH_4 emitting facilities using airborne remote sensing instruments. These include emissions from the Four Corners region (Frankenberg *et al.*, 2016), where there is extensive oil and gas extraction. They were able to detect hundreds of individual CH_4 plumes (scales of a few metres) from gas processing, storage stakes, pipeline leaks, and coal mine venting. Similar results are found over the Permian Basin (Cusworth, Duren, *et al.*, 2021), another oil and gas producing region. Generally, satellites are less sensitive to these smaller plumes but catastrophic CH_4

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[30] https://www.energy.ca.gov/publications/2020/california-methane-survey
[31] https://www.whitehouse.gov/pcast/meetings/2022-meetings/
[32] https://www.youtube.com/watch?v=t47gXx5fb3o
[33] https://www.nationalacademies.org/our-work/development-of-a-framework-for-evaluating-global-greenhouse-gas-emissions-information-for-decision-making
[34] https://www.nist.gov/greenhouse-gas-measurements/los-angeles-megacity-carbon-project
[35] https://www.nist.gov/northeast-corridor-urban-test-bed
[36] https://hestia.rc.nau.edu/

leakage from point sources (Pandey *et al.*, 2019) are clearly observable from space (Lauvaux *et al.*, 2022).

23. Satellites that include sufficient across track coverage can effectively map GHG gradients across cities. Examples are OCO-3 (Kiel *et al.*, 2021) aboard the International Space Station, and some orbit tracks from OCO-2 (Zheng *et al.*, 2020). The French/UK MicroCarb satellite mission, due for launch in 2024, will include a specific city-sweep observing mode. The geostationary GeoCarb satellite will also provide CH_4 data throughout the sunlit day.
24. Open or underground coal mines can release substantial (but diffuse) CH_4 emissions. Airborne (Krautwurst *et al.*, 2021) and satellite remote sensing (Palmer *et al.*, 2021) have the capability to observe these emissions, with top-down values inferred from atmosphere data consistent with inventory values.
25. Recent work has highlighted the ability of satellite and ground-based remote sensing to observe CH_4 emissions from waste disposal (Tu *et al.*, 2021), which found larger emission rates than currently assumed by the official Spanish emission inventory. This complements UK work that has used unmanned aerial systems[37] to infer landfill CH_4 emissions.
26. Mobile sensors and collection systems have proved to be extremely useful in spatially mapping CH_4 leaks within UK and international cities, e.g., pipelines, sewage, historical landfills, and via manhole covers. These include collecting bag samples at discrete locations (Xueref-Remy *et al.*, 2020) to analyse CH_4 and its isotopologues, to mobile sensors atop of Google Street View cars (Von Fischer *et al.*, 2017) and installed on regular passenger cars (e.g., (Ars *et al.*, 2020; Maazallahi *et al.*, 2020; Defratyka *et al.*, 2021)). Deploying these sensors can deliver data in near-real time to help companies identify and mend costly leaks. There are also examples of best practice of researchers working closely with energy providers so they can plug leaks that are reported, e.g., Énergir and McGill University. Some of this material is also discussed in Section 2.2.2.

2.1.5 The impact of GHG emission changes on atmospheric measurements

27. Before the advent of the UK network, top-down estimates of UK CH_4 emissions were inferred exclusively from measurements at Mace Head, Ireland (Manning *et al.*, 2003, 2011). (Manning *et al.*, 2011) reported CH_4 emissions trends from the early 1990s (1990-1992) to mid-2000s (2005-2007), with smaller reductions inferred from the measurements (24%) than those suggested by inventory estimates (50%); although baseline values were higher than inventory estimates. Reductions in inventory estimates were dominated by reductions to emissions from landfills and coal mine emissions. More recent work that used the larger DECC measurement network (Lunt *et al.*, 2021) reported a consistent

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[37] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/684501/Validation_of_landfill_methane_measurements_from_an_unmanned_aerial_system_-_report.pdf

CH_4 emission annual decrease of 2-3% from 2013 to 2020, compared with a more modest 1% annual decrease reported by UK inventory estimates. This study found no evidence in the measurements to suggest an elevated decrease due to the Covid-19 lockdown. (Lunt *et al.*, 2021) also highlighted the gap in measurements over Scotland, resulting in uncertain regional estimates. During an earlier period (2015-2017) ferry-borne measurements of CH_4, collected regularly between Rosyth in Scotland and Zeebrugge, were consistent with emissions reported by the UK to the UNFCCC (Helfter *et al.*, 2019). The NERC-funded GAUGE project reported value in using high-density regional measurement networks[38] (e.g., East Anglia) that helped to improve spatial distribution of CH_4 emission estimates from landfills and agriculture. Some of this material is also discussed in Section 2.2.3.

28. Similar to CH_4, UK emissions of N_2O were inferred from measurements collected at Mace Head from 1990 (Manning *et al.*, 2003, 2011). Annual reductions in top-down estimates inferred from measurements are consistent with inventory estimates (driven by emission from agricultural soils, fuel combustion, and in the late 1990s from the chemistry industry), but baseline values are lower than inventory estimates. Analysis reported by Manning *et al.*, 2011 was consistent with the UK meeting its Kyoto Protocol commitment but by a smaller margin than reported by inventory estimates.
29. HFCs are potent GHGs that were first subjected to emission reductions in the Montreal Protocol because of their role in stratospheric ozone depletion. (Brunner *et al.*, 2017) report emission of HFC-125, HFC-134a and sulphur hexafluoride across Europe, including the UK, for 2011. More recent work (Manning *et al.*, 2021) extended this analysis to incorporate a wider range of HFCs and three further rural sites (Ireland, England, and Germany). This study reported that top-down emission estimates, typically substantially lower than inventory estimate, have dropped by 35% from 2009-2012 to 2020, suggesting that EU regulations of HFC emissions, imposed in the UK, that focused on mobile air conditioning and F-gas regulation have had a positive impact.
30. A recent UK study (White *et al.*, 2019), using two years of CO_2 data collected during the GAUGE project, reported that measurements were consistent with a larger net release of CO_2 than prior CO_2 inventories, including a more pronounced uptake during summer months, likely due to uncertainties in the natural biosphere. A follow-up study (Palmer et al, 2022, in preparation) emphasises the need to include measurements in nearby countries across mainland Europe to overcome the uneven distribution (and the seasonal change in the regional sensitivity) of UK measurement sites. Some of this material is discussed in Section 2.2.3.
31. A number of research groups used the lockdowns associated with the Covid-19 pandemic as a natural experiment. Some focused on developing proxies for changes in sectoral emissions, which were available much quicker than more established sources of information. High profile papers using these proxies reported large changes in CO_2 emissions (e.g., (Le Quéré *et al.*, 2020; Liu *et al.*, 2020)) but

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[38] https://www.repository.cam.ac.uk/handle/1810/264146

subsequent analysis showed that the temporary changes were too small to be verified using in situ or remotely sensed atmospheric measurements. In April 2021, NOAA reported an uptick[39] in the global growth rate of CO_2 and CH_4 during 2020 although some researchers believe the CH_4 signal might be driven by changes in oxidant chemistry (Laughner *et al.*, 2021) rather than increased emissions. Record increases in CO_2 and CH_4 growth rates[40] were also observed in 2021.

32. Analysis of the Jungfraujoch measurements of HFC-23 revealed large point emissions from a Teflon producing factory in Italy (Keller *et al.*, 2011). Most recently, a previously unreported source of N_2O (from the production of Niacin) in Valais was undetected by the network because it is not sensitive to the Alpine Valley where the factory is located. Measurement gaps over Switzerland are exacerbated by topography.
33. Looking forward, based on stakeholder input, there is consensus that better resolved emission estimates will be necessary to help understand the UK Net Zero trajectory. Ideally, the spatial and temporal resolution of these emissions is improved in tandem, but also keeping in mind that better resolution could also focus on sectors that may require a bespoke measurement system, e.g., agriculture. The balance between spatial and sector resolution has implications for the distribution of measurements across urban, peri-urban, rural, and offshore sites, and for the ability of models to interpret the data being collected.

2.1.6 Uncertainties and best practice

34. Well quantified emission uncertainties still exist in all methods used to infer GHG fluxes, and currently there is no agreed procedure to track or account for these uncertainties. Posterior flux errors, associated with top-down emission estimates, tend to be dominated by model errors (land-atmosphere, transport) and by methods used to attribute net fluxes to emission from human activity (e.g., combustion of fossil and bio- fuels, land use change). This is an area of active research. As GHG verification science evolves from being predominantly basic research to operational delivery of flux estimates to support regulatory frameworks, transparency in reported emissions and their uncertainties will become paramount.
35. Except for NOAA, most ground-based networks are based on a federal model that relies on decadal-scale national funding. This current model of funding national and international networks is widely acknowledged[41] as a risk to a continuous record of atmospheric GHGs. Without redundancy, even intermittent breaks in data compromise the fidelity of a measurement network to support nationwide GHG emission estimates.

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[39] https://research.noaa.gov/article/ArtMID/587/ArticleID/2742/Despite-pandemic-shutdowns-carbon-dioxide-and-methane-surged-in-2020

[40] https://www.noaa.gov/news-release/increase-in-atmospheric-methane-set-another-record-during-2021

[41] https://www.copernicus.eu/sites/default/files/2019-09/CO2_Green_Report_2019.pdf

36. A key weakness in the design of an effective MRV that has been identified early on in all recent projects has been stakeholder engagement, including national and regional government agencies, and potential providers of downstream services. These are a critical element to the design and execution of any trusted and transparent MRV.
37. There is recognition from the stakeholder inputs of the value of private sector to help develop MRVs, particularly in terms of providing additional data, however the importance of quality assurance of such data and the independence and veracity of private companies is a key consideration. These should go hand in hand.
38. In addition to individual research projects, there are a number of coordinated activities that are helping to understand more broadly how to engage with stakeholders: World Meteorological Organization (WMO)-coordinated Integrated Global Greenhouse Gas Information System[42] (IG^{3}IS); the European Commission CO_2 Task Force blue[43], red[44], and green[39] reports; and the Committee on Earth Observation Satellites[45].

2.2 Question 2: To what extent could improving atmospheric monitoring capability fill important gaps in knowledge and help reduce uncertainties in the inventory, including in offshore oil, gas and shipping emissions, diffuse emissions from the waste, agriculture and LULUCF (land use, land-use change and forestry) sectors, and diffuse fugitive sources of CH_4 and H_2 from energy and industry?

2.2.1 Summary

Different measurement platforms are best positioned to address different components of uncertainty in the UK National Atmospheric Emissions Inventory (NAEI). The in situ UK DESNZ funded DECC measurement network has been used to successfully quantify emissions at the national scale for a variety of GHGs including CH_4 and HFCs. The network has been used to quantify CH_4 emissions from diffuse agriculture and waste sources, as well as the net biosphere CO_2 flux from the UK.

The current surface network is heavily biased towards southern England, meaning emissions from diffuse source sectors in Scotland (which account for around 10% diffuse source UK GHG emissions) estimated from atmospheric data have larger relative uncertainties.

Increasing the number of sites of the long-term continuous monitoring provided by the surface network would allow better quantification of diffuse emissions. Incorporating frequent or continuous CH_4 isotopologue (e.g., $\delta^{13}CH_4$) or ethane measurements into the UK DECC network could further improve

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[42] https://ig3is.wmo.int/en/welcome
[43] https://www.copernicus.eu/sites/default/files/2019-09/CO2_Blue_report_2015.pdf
[44] https://www.copernicus.eu/sites/default/files/2019-09/CO2_Red_Report_2017.pdf
[45] https://ceos.org/

the differentiation of individual CH_4 source sectors, particularly diffuse fugitive sources from energy and industry.

Emissions of CH_4 from offshore oil and gas platforms have been detected and quantified in small-scale limited time campaigns using measurements on-board ships or aircraft. Future campaigns require longer time-sampling windows to increase the chances of favourable weather conditions. More work is needed to establish the ability of onshore sites to monitor offshore CH_4 emissions.

Current monitoring of atmospheric H_2 is limited but measurements are available that could be used to define the current global background level and estimate global or hemispheric emissions before the hydrogen economy takes off. Modelling studies would be needed to establish what further measurements are necessary to estimate future H_2 emissions at the national scale and account for the significant soil sink of atmospheric H_2.

2.2.2 Background

1. As detailed in Section 2.5, independent emission estimates derived from atmospheric measurements may reduce inventory uncertainties most from sources that involve complex biological processes such as waste, agriculture and Land Use, Land Use Change and Forestry (LULUCF) or from sources that are the result of unintentional leaks.
2. H_2 is not currently included in the UK's inventory. Although not a direct GHG, H_2 has an indirect global warming potential[46] due to impacts on atmospheric CH_4, ozone and stratospheric water vapour. Increased production and use of H_2 is part of the UK's net-zero strategy and as such emissions are expected to increase in the future.

2.2.3 Recent studies on UK GHG emissions

3. As mentioned in Section 2.1, there have been various studies examining UK emissions of CH_4, HFCs and biosphere CO_2 using data from the UK DECC network. These studies have shown how the data can be used to estimate the total national emissions, but have not focussed on individual sector emissions.
4. An evaluation of emissions of all GHGs except CO_2 is provided in Annex 6 of the UK's annual submission to the UNFCCC[47]. This evaluation is based on atmospheric surface measurements of each GHG. However, at present, this only considers total emissions of each GHG, without providing an analysis of individual sectors.
5. In situ measurement sites also provide measurements of atmospheric H_2. Measurements are currently taken at the Mace Head station in Ireland and provide a record of the current Northern hemisphere

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[46] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760538/Hydrogen_atmospheric_impact_report.pdf

[47] https://uk-air.defra.gov.uk/reports/cat09/2106091119_ukghgi-90-19_Annex_Issue_2.pdf

baseline (Grant *et al.*, 2010). Further measurements are available at Weybourne in North Norfolk (Forster *et al.*, 2012).

6. Data from mobile sources have been used to quantify emissions from individual sources, with particular relevance for offshore oil and gas platforms. For example, (Riddick *et al.*, 2019) used measurements of CH_4 taken on-board fishing boats to quantify CH_4 emissions from oil and gas platforms in the North Sea. CH_4 enhancements were detected downwind of platforms during normal operations, suggesting a continuous leakage source, as opposed to CH_4 released during flaring. Emission rates ranged between 98-1928 kg CH_4 day^{-1}, and were consistent with the NAEI, although NAEI emissions are dominated by flaring which did not occur during this measurement campaign.
7. Emissions from offshore oil and gas platforms in the North Sea have also been detected and quantified using aircraft-based measurements. (Wilde *et al.*, 2021) used ethane/methane enhancement ratios to identify sources from oil and gas platforms. Different CH_4 emission ratios were detected for deep water oil extraction compared to gas extraction in shallow waters.
8. Mobile measurements have also been used to characterise more diffuse sources of CH_4 in urban settings. (Zazzeri *et al.*, 2017) conducted a mobile measurement survey in London to assess the accuracy of the spatial distribution of sources within the UK inventory. Using $\delta^{13}CH_4$ isotope measurements, the survey identified a greater contribution from diffuse gas leaks than the mapping of the UK inventory for London suggests.

2.2.4 Potential improvements to reduce uncertainties in key sectors of the inventory

Agriculture

9. Agriculture emissions of GHGs mainly include CH_4 and N_2O and are widely distributed diffuse area sources. For CH_4, agriculture is estimated to account for around 50% of emissions, with emissions mostly distributed in South West England, North West England, Wales, Northern Ireland and Scotland. However, at present the network is heavily biased to the south of the UK with no measurement sites north of Norwich within the UK. Lunt *et al.*, 2021 found that although estimates of CH_4 emissions from England were constrained to within ±5% by the current data, emissions from Scotland were strongly dependent on prior estimates, due to a lack of measurement coverage. Additional measurement sites in Scotland (a new site is planned, see Q1) and Northern England are obvious improvements that would help reduce uncertainties on agriculture CH_4 estimates.
10. Isotope measurements of $\delta^{13}CH_4$ (and CH_3D, see Section 2.3) can potentially help differentiate between source sectors of CH_4, such as microbial and fossil fuel sources. Continuous isotopic measurements made alongside CH_4 at UK DECC sites may allow for pollution events to be more easily attributed to particular source sectors. However, there can be considerable variation in isotopic source signatures within individual source sectors (Zazzeri *et al.*, 2015), and careful interpretation may be needed where

isotopic source signatures overlap. As such, isotope measurements are likely to be most useful for differentiating between microbial and fossil fuel CH_4 sources, and a similar effect may be had through the use of ethane measurements. The development of modelling methods to incorporate these isotope or ethane measurements and account for uncertainties and spatio-temporal variability in source signatures would be required to maximise their usefulness.

11. For N_2O, agriculture sources accounted for almost 70% of emissions in 2019 within the UK NAEI. Improved monitoring of these emissions is feasible using the UK DECC network and the development of modelling methods. N_2O emissions exhibit complex temporal variability in response to environmental variables such as precipitation, and human management such as the timing of fertiliser application. In addition to increasing measurement coverage, incorporating ancillary observational data such as temperature and precipitation into inverse modelling frameworks could help better isolate and quantify agriculture sources of N_2O. Localised studies of areas of known agricultural sources to quantify N_2O and CH_4 emissions may be the best approach to isolate agriculture emissions in atmospheric data and evaluate inventory emission factors.

Waste

12. Increasing the density and coverage of the UK DECC network alongside modelling developments may allow better isolation of diffuse waste sector emissions. Incorporating more isotope measurements of $\delta^{13}CH_4$, particularly continuous measurements, would further enable better isolation of waste sector emissions from diffuse energy sources.
13. Targeted monitoring of individual landfills and wastewater treatment plants can be achieved through mobile sampling, particularly from vehicles (e.g., (Bakkaloglu *et al.*, 2021)). These can provide better quantification of the isotopic CH_4 source signatures of individual landfills, which could be combined with longer-term monitoring of the fixed location surface network.

LULUCF

14. There are emissions and removals of CO_2 in the LULUCF sector, and these fluxes are sometimes very large. Net emissions of CO_2 are the sum of these emissions and removals. Expressed as a mass of gas, there are relatively small emissions of CH_4 and N_2O. The main source of CH_4 is from drainage and re-wetting in grasslands and wetlands. Emissions of N_2O also occur from these activities, in addition to being emitted from mineralisation. GHG emissions from the LULUCF sector therefore mainly include CO_2 and CH_4. For CH_4, accurate knowledge of the spatial distribution of grassland and wetland emissions is required in order to partition emissions to these sources. Transparency and availability of the datasets (e.g., spatial distribution of wetland land cover) that form the basis of CH_4 LULUCF estimates in the NAEI would aid atmospheric inverse modelling to quantify emissions from this source.

Within the NAEI all land in the UK is considered managed, which avoids any inconsistencies between definitions for inverse modelling and reported emissions for both CO_2 and CH_4.

15. Whilst atmospheric data has been used to estimate the net biogenic CO_2 flux of the UK (White *et al.*, 2019), the LULUCF flux is only a small part of this total biosphere flux. Therefore, resolving the explicit LULUCF signal is very difficult and unlikely to be covered by any existing measurement or modelling methods.
16. Localised studies on areas of managed land may offer the best approach to investigate assumptions underpinning LULUCF CO_2 fluxes in the inventory and their consistency with atmospheric data.
17. For estimating both the net biogenic CO_2 flux and CH_4 wetland emissions, greater spatial coverage of the UK DECC network is key to reducing uncertainties on estimated emissions, particularly from Scotland.

Offshore oil and gas

18. There are a range of activities that cause GHG emissions in the offshore oil and gas sector. Fugitive emissions of CH_4 and CO_2 occur, as well as emissions from flaring. Emissions of CO_2 from venting and flaring are relatively large. On a mass basis, emissions of N_2O are very small.
19. Long-term monitoring of offshore oil and gas emissions may be difficult to establish due to the offshore location, weak signal at existing DECC network sites, and difficulty in isolating emissions from the UK or other nations' sections of the North Sea. A strong CH_4 signal at the Weybourne atmospheric observatory has been noted during northerly winds but has not been investigated in the peer-reviewed literature.
20. Network design modelling studies to establish the influence of North Sea oil and gas CH_4 emissions at locations on the east coast of Britain could be carried out to establish the ability of onshore sites to quantify emissions using CH_4 data (as well as ethane and isotope measurements).
21. Satellite data offer the potential for long-term monitoring of individual platforms (see section 2.4), but due to low reflectivity over water, and requirements for cloud free conditions the use of these data may be challenging. This may be further complicated by relatively small emissions of individual facilities. The development of high-resolution retrievals that perform well in sun-glint mode with low detection limits would allow satellites to be used for this purpose. A private sector research effort using data from GHGSat[48] is underway to investigate the feasibility of using satellites to monitor offshore oil and gas CH_4 emissions, including from platforms in the North Sea.
22. Mobile platform measurements from ships and aircraft can both sample upwind and downwind of individual platforms, allowing emissions to be quantified. France *et al.*, 2021 highlighted the need for

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[48] https://www.ghgsat.com/en/newsroom/ghgsat-announces-research-project-to-demonstrate-satellite-based-measurement-of-methane-emissions-from-offshore-sources

accurate measurement of local winds and/or more accurate modelling of meteorological conditions, and the inclusion of co-emitted gas measurements such as ethane. For aircraft campaigns, long-term measurement windows, rather than single day sampling campaigns would be needed to exploit the best meteorological conditions.

23. The cooperation of the oil and gas industry is crucial to enable accurate comparisons to reported emission rates. For example, measurement campaigns need to be provided with relevant information on the operational status of individual platforms during the limited time window of the campaigns. Previous examples include NCAS flight surveys[49] supporting the TOTAL response to the Elgin rig leak and the industry has been involved in measurement-based report of CH_4 emissions through the UNEP O&G Methane Partnerships (OGMP) v2.0 framework. A recent partnership[50] between Neptune Energy and the Environmental Defense Fund using drones to measure facility level CH_4 emissions from the Cygnus platform in the North Sea highlights how researchers and industry might work together.

Shipping

24. Satellite data can potentially be used to identify and quantify emission sources from shipping. Satellite measurements of NO_2 from the TROPOMI instrument have been used to detect pollution plumes from individual ships in the Mediterranean (Georgoulias *et al.*, 2020). The satellite NO_2 columns were combined with Automatic Identification Systems (AIS) to attribute plumes to individual ships. AIS data are already used within the UK inventory for shipping emissions and allow for differentiation between domestic shipping (which are included in the national inventory totals) and international shipping (which are reported as a memo item). Finch, Palmer and Zhang, 2022 have demonstrated how NO_2 plumes in TROPOMI data can be automatically identified using image recognition techniques. Multiple NO_2 plumes were identified in the English Channel and North Sea.
25. Gronholm *et al.*, 2021 used in situ measurements from a remote island in the Baltic Sea to quantify CO_2 and CH_4 emissions from ships passing 600 metres away. Krause *et al.*, 2021 used a remote sensing technique to measure SO_2 and NO_X emissions from ships in the river Elbe, Germany. The study used an artificial light source and reflectors on the opposite bank to measure ship plumes, a method which could be expanded to include CO_2 and CH_4.

Diffuse fugitive emissions of CH_4 and H_2 from energy and industry

26. Co-located measurements of ethane (see Section 2.3) in addition to CH_4 at the UK DECC network sites will reduce uncertainties in diffuse energy sector estimates of CH_4 emissions. Ramsden *et al.*, 2022 reported an average 15% reduction of estimated uncertainty in emissions of CH_4 from the energy sector

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[49] http://homepages.see.leeds.ac.uk/~lecrrb/10-final_report_v3.pdf

[50] https://www.neptuneenergy.com/media/press-releases/year/2021/neptune-energy-and-edf-complete-first-its-kind-methane-study-uk

when incorporating ethane measurements at two sites of the UK DECC network, Mace Head and Tacolneston. Further measurements at other sites would help to reduce this uncertainty further. Further mobile sampling and measurement of the isotopic CH_4 composition would help to quantify the relative contributions of different source sectors to emissions in urban areas which contain energy, industry and waste sources (e.g., (Zazzeri *et al.*, 2017), (Saboya *et al.*, 2022)).

27. H_2 is an indirect GHG, and so a transition to a more hydrogen-based economy is likely to result in radiative forcing from fugitive releases (Derwent *et al.*, 2006). Careful attention must be given to reduce to a minimum the leakage of H_2 from the synthesis, storage and use of H_2 in a future global H_2 economy if the full climate benefits are to be realised.
28. There are currently very few atmospheric measurements of H_2, limited to in situ measurement sites. Data from the Advanced Global Atmospheric Gases Experiment (AGAGE) network[51] provide a long-term record of global background levels before the hydrogen economy takes off. These data could be used to establish the global H_2 background and update estimates of global and regional sources and sinks (e.g., Xiao *et al.*, 2007). Studies of the global budget of H_2 have highlighted the importance of the northern hemisphere soil sink and photochemical production (e.g., Rhee, Brenninkmeijer and Röckmann, 2006). 3D atmospheric modelling work is needed to explore what benefits additional measurements would bring for estimating regional H_2 sources and sinks.

2.3 Question 3: What is the current technological capability, and what is the likely future capability in the medium-term (i.e., next five years) and long-term, for monitoring GHGs in line with policy needs?

2.3.1 Summary

This section reviews measurement technology available for in situ, mainly ground-based, analysis of GHGs in ambient air samples. A high-quality multi-site tall tower network of sufficient accuracy and precision allows trends in emissions to be quantified and spatially resolved across a region.

The successful development of a network is constrained by the calibration, maintenance and quality assessment infrastructure that is necessary to support it. This needs to be a strong consideration in the scaling up of measurements or the investment in deployment of new technology.

Deviations in the stable isotopic building blocks of molecules can serve as quantitative tracers to study processes or as fingerprints for the source of addition or removal to the atmosphere. Isotope ratio mass spectrometry is the current ‘gold standard’ for high precision measurement of $\delta^{13}C$ and $\delta^{2}H$ in CH_4, however, use of laser spectrometers for lower maintenance, high-frequency in situ analysis should become possible over the next five years.

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[51] https://agage.mit.edu/data/agage-data

Measurement of the suite of halogenated GHGs is likely to continue requiring specialised equipment for the foreseeable future, however, improvements in robustness and reliability of hardware should allow these measurements to be scaled up under sufficient support.

Radiocarbon measurements of CO_2 ($\Delta^{14}CO_2$) to partition out the fossil fuel derived portion are challenging to make, requiring offline sample processing and expensive analysis by specialised mass spectrometry laboratories. However, $\Delta^{14}CO_2$ is likely to be a highly valuable measurement and high-throughput analysis is possible. The techniques for making $\Delta^{14}CH_4$ measurements also exists, however, the challenge over the next five to ten years will be in bringing this to a higher-frequency capability. The techniques for laser spectrometers capable of radiocarbon measurements is in development.

The co-emitting tracers carbon monoxide, ethane and oxygen (O_2) can be measured in situ alongside the GHGs at tall towers but ethane and O_2 require more specialised equipment. Scaling up measurements of ethane and O_2 into a larger regional network is possible with sufficient supporting infrastructure.

Radon can be used as an independent tracer to understand atmospheric mixing and how well models are simulating concentrations. Very precise radon measurements can be made; however, significant data processing is required for direct comparison of these measurements against the GHGs, which currently hampers data useability.

Other platforms include mobile (ground and air) measurements to focus on specific area emissions by utilising advances made in laser spectrometry for onboard deployment. Deployment of ground-based total column instrumentation is now possible owing to automated weather enclosures. Lower cost sensors for measurement of CO_2 are now being deployed across several cities. Although the precision of these devices is relatively low, the density of deployment and novel methods to network the measurements could allow for a useful understanding of emissions at the city scale.

2.3.2 Measurements of The Major GHG Gases (CO2, CH4 and N2O)

1. The choice of measurement location is crucial in developing an in situ measurement network. A site should capture the integrated signal from the area/source of interest; not be too close to individual emission sources where the signal is difficult to interpret and not too far to ensure a signal can be reliably quantified.[52] Use of tall towers by the UK DECC network has enabled limited interference from local sources and therefore continuous detection and quantification of pollution representative of emissions from a large area (Ganesan *et al.*, 2015; Palmer *et al.*, 2018; Stanley, Grant, O'Doherty, Di. Young, *et al.*, 2018; Stavert *et al.*, 2019).

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[52] https://library.wmo.int/doc_num.php?explnum_id=10034

2. This type of measurement infrastructure is only served through the use of technology capable of detecting small deviations in the atmospheric signal that are comparable across multiple locations. The GAW Programme of the WMO sets out ‘network compatibility goals’ as a benchmark for maximum allowable measurement bias aimed at use in global and regional carbon cycle and emissions modelling activities.[53]
3. Current technology for making in situ GHG concentrations measurements largely now exists around the use of laser spectrometers that are able to make high frequency and continuous measurements with minimal intervention or maintenance requirements. Networks (e.g., Integrated Carbon Observing System – ICOS[54] (e.g., Yver-Kwok *et al.*, 2021) and UK DECC e.g., (Stanley, Grant, O’Doherty, Young, *et al.*, 2018) work on development of standardised operating and calibration procedures of these spectrometers to meet the needs of high-precision GHG monitoring. Drying the sample before delivery to the spectrometer has reduced inaccuracies associated with different water content between samples and standard without use of any additional operational consumables (based on the developments in Welp *et al.*, 2013).
4. Knowledge of the composition of the air coming into the study region is an important aspect of accurate emissions estimation. Calibration on international scales allows measurements made by global networks to be used for this purpose. To accomplish this requires production and sharing of compressed air cylinders that have been assigned values for GHG concentration traceable through a measurement chain to the international scale. The NOAA Global Monitoring Laboratory (GML)[55] serves as the WMO Global Atmosphere Watch (WMO/GAW) Central Calibration Laboratory (CCL) for CO_2, CH_4, N_2O and is responsible for maintaining the WMO/GAW international scale. Other important international scales are maintained, and reference materials disseminated by the AGAGE[56], Scripps CO2 programme[57] and others.
5. As a network expands, more reference materials for in situ instrument calibration are required (as well as standard protocols for operation and data analysis). Measurements of reference materials can generally be handled by WMO/GAW regional World Calibration Centres that take ad hoc requests for measurement, however, ICOS has set up its own calibration laboratory that centrally serves their growing network. Any national expansion of a network needs to carefully consider the best route for calibration.

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[53] https://library.wmo.int/doc_num.php?explnum_id=10353
[54] https://www.icos-cp.eu/observations/atmosphere
[55] https://gml.noaa.gov/
[56] https://agage.mit.edu/
[57] https://scrippsco2.ucsd.edu/

2.3.3 Measurement of Halogenated GHGs

6. Measurements of the halogenated GHGs (chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, sulphur hexafluoride and nitrogen trifluoride) are challenging owing to their relatively low abundance (<300 ppt). Their high radiative efficiencies, however, mean that together their climate impact and source identification is vital to track (Rigby *et al.*, 2014; Manning *et al.*, 2021).
7. Major in situ methods for measurement of these species include gas chromatography-electron capture detector (GC-ECD) and GC-mass spectrometry (GC-MS) and these methods have been very successfully utilised by the global in situ networks of NOAA, AGAGE and others (Miller *et al.*, 2008; Arnold *et al.*, 2012). For the lower abundance species preconcentration of the analyte has been necessary for measurement at the required level of precision. This extra technological challenge has led to only a few regional and global capabilities to measure the full suite of gases. Incremental improvements continue to be made to these systems to improve reliability and useability; however, traceability issues (as explained above) and availability of standard gases are more acute for these species relative to the major GHGs.
8. New developments in the mass spectrometer used in these automated preconcentration GC-MS systems are possible (Hoker *et al.*, 2015; Guillevic *et al.*, 2021). These developments will likely lead to continued improvements to possible sensitivity and precision, however, their potential to make a significant improvement for routine in situ analysis needs to be examined.

2.3.4 Relevant Tracer Measurements for More Detailed and Improved Source Apportionment

Stable isotope ratios

9. Deviations in isotopic ratios can serve as quantitative tracers to study processes or as fingerprints for the source of addition or removal to the atmosphere. For the major stable isotope ratios for CO_2 and CH_4 ($^{13}C/^{12}C$, $^{18}O/^{16}O$, D/H) these are reported in δ-notation, e.g. $\delta^{13}C = (^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{standard} - 1$, where $(^{13}C/^{12}C)_{sample}$ is the calibrated isotope ratio of the sample and $(^{13}C/^{12}C)_{standard}$ is the isotope ratio of an international standard. Over the last decades isotope ratios of GHGs have been made using mass spectrometry, typically requiring collection of a sample in a flask and analysis by a specialist laboratory.
10. Networks making high precision routine measurements of $\delta^{13}C$ and $\delta^{18}O$ in CO_2 from flasks samples include ICOS, NOAA/INSTAAR (Institute of Arctic and Alpine Research) and Scripps stable isotope programme, with impacts mainly on understanding global and continental carbon cycles (e.g. Welp *et al.*, 2011; Peters *et al.*, 2018). These networked measurements continue to be maintained with improvements in calibration and access to standard gases (Wendeberg *et al.*, 2013).

11. Laser spectrometry for in situ measurement of isotope ratios is gaining maturity. As with the concentration measurements, laser spectrometers allow direct high frequency measurement with minimal sample processing, which allows for a more accurate understanding of the variability within a given modelling time window.
12. The current ‘gold standard’ for high precision measurement of $\delta^{13}C$ and $\delta^{2}H$ in CH_4 also begins with isotope ratio mass spectrometry and several global networks (NOAA/INSTAAR; Royal Holloway University of London (RHUL); and National Institute of Water and Atmospheric Research (NIWA)) exist making independent measurements of the trend in $\delta^{13}C$ (Nisbet *et al.*, 2016). Although $\delta^{2}H$ datasets are available and measurements by individual groups are maintained, no continuous operational network exists for measurement of $\delta^{2}H$. Multiple recent efforts by Utrecht University have been made to deploy isotope-ratio mass spectrometer (IRMS) instrumentation for in situ measurement (Röckmann *et al.*, 2016; Menoud *et al.*, 2020, 2021), demonstrating the potential for this to become a more routine approach in the near future.
13. Laser spectrometry for $\delta^{13}C$ measurements of CH_4 exists and successful attempts have been made to improve precision beyond those stated by instrument manufacturers (Miles *et al.*, 2018). To be competitive in precision with IRMS, preconcentration is a proven option before delivery of the sample into the laser spectrometer (Eyer *et al.*, 2016; Rennick *et al.*, 2021). Dual laser spectrometers are uniquely able to measure both $\delta^{13}C$ and $\delta^{2}H$ simultaneously from the same sample (Rennick *et al.*, 2021).
14. Improvement in the sensitivity and deployability of laser spectrometers will improve over the medium and long term, however, bringing these advances to fruition also requires continued data gathering of the source signature information. This area of work is gathering pace (Sherwood *et al.*, 2017; Zazzeri *et al.*, 2017), with several projects planned over the coming years to fill in gaps in knowledge, which could have a significant impact in differentiating emissions from key sectors (Section 2.2.4).
15. Measurement of deviations from random (stochastic) distributions of isotopes within the suite of isotopologues (termed ‘clumping’) and deviations from mass-dependent fractionation relationships are at an early stage of development and interpretation (>5-year time frame) (Koren *et al.*, 2019; Chung and Arnold, 2021).

Radiocarbon

16. Purely fossil fuel derived CO_2 is largely devoid of carbon-14 and therefore the degree to which it is absent in a sample acts as an excellent tracer as to the origins of the CO_2, however, quantifying the difference in amount of carbon-14 between samples is very challenging owing to the very low natural abundance of carbon-14. As with the stable isotope ratios, all measurements are reported as a ratio to $^{12}CO_2$ and against an international isotope ratio scale reference point using notation of $\Delta^{14}CO_2$.

Measurements of $\Delta^{14}CO_2$ are made using an accelerator mass spectrometer (AMS). Prior to analysis, offline graphitisation of the CO_2 sample is necessary along with separate measurement of CO_2 total amount fraction and stable isotope composition of CO_2. Making measurements of $\Delta^{14}CO_2$ is therefore a highly specialised activity, however, given automated sampling procedures and sufficient laboratory time is available for analysis, measurements can be scaled up (Graven *et al.*, 2018; Wenger *et al.*, 2019). The possibility to combine these specialised in situ analyses with space-based observations is possible (Section 2.5.3).

17. Several laboratories are working on laser spectrometry for $\Delta^{14}CO_2$ with the aim to generate higher throughput and cheaper measurement (Genoud *et al.*, 2019), however, operational measurement of ambient air is likely still a long term rather than medium term goal.
18. The same approach can be applied to make measurements of $\Delta^{14}CH_4$ to interpret the fossil content of CH_4 pollution (Graven, Hocking and Zazzeri, 2019), however, given the abundance of CH_4 relative to CO_2 significantly more air sample needs to be processed. Measurements have a been made in a few samples and efforts are underway to develop in situ sampling methodologies that might lead to the necessary higher sample-throughput for local/regional scale analysis (>5-year time frame) (Townsend-Small *et al.*, 2012; Zazzeri, Xu and Graven, 2021).

Carbon monoxide

19. Carbon monoxide has been used to interpret the origin of CO_2 and CH_4 emissions, mainly in the urban setting where co-emission is dominated by anthropogenic combustion sources (Lopez *et al.*, 2013; O'Shea *et al.*, 2014; Newman *et al.*, 2016; Pitt *et al.*, 2019). Carbon monoxide measurements are made alongside CO_2, CH_4 and N_2O using off-the-shelf laser spectrometer systems. Thus, there is not necessarily an additional hardware cost in making these measurements. Maintaining comparability of measurements over time and space, however, is more challenging. Carbon monoxide is known to drift significantly within working standard cylinders, which can impact the accuracy of calibration procedures if this drift is not fully characterised. As an air quality pollutant, Carbon monoxide is also measured under Defra's Automatic Urban and Rural Network (AURN).[58]

Ethane

20. Ethane is emitted through fossil fuel production, so can be used to help quantify fossil fuel derived CH_4 emissions which are also emitted from the waste and agricultural sectors (Ramsden *et al.*, 2022). Optical techniques exist for the measurement of ethane alongside CH_4, however, these are yet to be demonstrated in routine long-term operation (Defratyka et al., 2021). Gas chromatography techniques coupled to either a flame ionisation detector (FID) or MS, however, have allowed for measurements

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[58] https://uk-air.defra.gov.uk/networks/network-info?view=aurn

to be made continuously over several decades at several locations at very high precision and frequency as discussed in Section 2.2.4 (Ramsden *et al.*, 2022).[59]

Oxygen

21. Precise measurements of atmospheric O_2 have the theoretical potential to be used to quantify the fossil fuel component of atmospheric CO_2 ($ffCO_2$) because there is a different O_2:CO_2 exchange ratio for fossil fuel combustion than for terrestrial biosphere exchange. The most recently developed analytical techniques for measuring atmospheric $\delta(O_2/N_2)$ ratios are a GC technique, which measures the $\delta(O_2/N_2)$ ratio directly using a thermal conductivity detector (Tohjima, 2000), a differential fuel cell technique (Stephens *et al.*, 2007), whereby changes in O_2 mole fraction are detected via an electrochemical reaction of O_2 with a lead electrolyte solution and no change in N_2 is assumed (similar to the paramagnetic and vacuum ultraviolet (VUV) techniques), and a commercially available cavity ring-down spectroscopy technology (CRDS) technique (Berhanu *et al.*, 2019).
22. The differential fuel cell technique is more precise than the CRDS technique and is currently deployed at two tall tower locations under the NERC DARE-UK project. The success in networking these two instruments will be apparent over the coming two years as measurements are incorporated into a regional inversion framework.

Radon

23. Radon-222 (radon) is the first volatile decay product of the uranium-238 decay chain and has a half-life of 3.8 days (radioactive decay). Given sufficient knowledge on emission rates, radon has potential to be used to understand the influence of atmospheric mixing that might not be well represented in atmospheric transport models. Several techniques exist to measure radon, however, the ANSTO (Australian Nuclear Science and Technology) monitor has been well characterised, been widely deployed world-wide, and requires minimal maintenance for high precision measurements (Schmithüsen *et al.*, 2017). The raw measurements made by the ANSTO monitors require a signal deconvolution routine to be applied to enable direct comparison against the GHG measurements with a time resolution on the order of 30-60 minutes. A European metrology project traceRadon is underway and should provide the standard protocols for analysis and data processing within the next 18 months for instruments within ICOS and DECC, as well as bring improvements to the emission maps for Europe through a process-based model.

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[59] https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2006240803_Non_Methane_Volatile_Organic_Compounds_in_the_UK.pdf

2.3.5 Hydrogen

24. Increased utilisation of H_2 for transport and residential and commercial heating systems increases the importance of monitoring to assess the magnitude of leaks. High frequency, high precision in situ measurements of H_2 have been made by global networks for several years using a GC reduction gas analyser technique, with long term records at the Mace Head and Weybourne observatory (Novelli, 1999; Grant *et al.*, 2010; Jordan and Steinberg, 2011; Forster *et al.*, 2012; Schmidt *et al.*, 2014). Other techniques (but still requiring in line GC) include the pulse discharge detector (PDD), which has potential to offer improved sensitivity for continuous in situ analysis (Novelli, Crotwell and Hall, 2009). IRMS has been used for δ^2H measurements (see Section 2.2.4).

2.3.6 Complementary Measurements and Platforms

25. For improving the use of tracers in GHG emissions quantification, greater confidence is required for the source tracer:GHG ratios. This is particularly the case for improving the confidence in the use of $\delta^{13}C$ and δ^2H for CH_4 source apportionment. Several campaigns are ongoing or planned for CH_4's $\delta^{13}C$ and δ^2H, however, a scaling up of this effort is likely to be needed to adequately account for spatial and temporal isotopic inhomogeneity in sources.
26. The robustness of equipment detailed in section 2.1, particularly the laser spectrometers, allows for instruments to be readily deployed on mobile campaigns including use of vehicle surveys and aircraft platforms provide useful snapshots of emissions or source signature estimates (Hoheisel *et al.*, 2019; Pitt *et al.*, 2019; France *et al.*, 2021; Al-Shalan *et al.*, 2022), highlighting potential issues that would not be detected through a stationary network.
27. The technology now exists for ground-based, total column measurements of CO_2, CH_4 using a solar tracking Fourier transform spectrometer as is implemented in the TCCON network (Wunch *et al.*, 2011). TCCON has an accuracy of better than 0.25% for CO_2 when calibrated against aircraft in situ profiles. TCCON is a vital dataset for satellite validation and for linking the satellite measurements to the ground-based in situ network. A site of the TCCON network is located at Harwell operated jointly by RAL Space and NCEO.
28. Total column measurements are also possible from compact and portable instruments which form the COllaborative Carbon Column Observing Network (COCCON) (Frey *et al.*, 2019). These instruments, once equipped with an automatic weather enclosure, can be used in a flexible manner to supplement TCCON sites, for example around cities (Dietrich *et al.*, 2021). Three spectrometers have been deployed across London via NERC Field Spectroscopy Facility.
29. Lower cost sensors targeted at developing a higher spatial coverage of CO_2 measurements across urban environments are in use (Arzoumanian *et al.*, 2019; Müller *et al.*, 2020; Delaria *et al.*, 2021). In the

BEACO2N network[60] off-the-shelf multiple NDIR sensors have been successfully deployed across multiple urban settings (the small units containing the sensors can be placed on any accessible roof with a power source). The uncertainties on these sensors for city scale analysis are ~ 2 ppm for CO_2, which can be compared to the minimum compatibility goals of 0.2 ppm under the WMO/GAW framework. How to calibrate, network and integrate these sensors and understanding their value for city-scale analysis is likely to be a growing area of research over the next five to ten years.

2.4 Question 4: What role could remote sensing play in the verification of estimates of GHG emissions and removals, and for which GHGs/sources does remote sensing data already have the capacity to calibrate/inform emissions estimation methods?

2.4.1 Summary

We have reviewed the capabilities of remote sensing measurements from current and future satellites for providing the data needed for verification approaches of emission of GHGs. We focus on total column observations of CO_2 and CH_4 from satellites as the key technology to inform on emissions of both gases. Remote sensing of CO_2 and CH_4 can in principle also support GHG removals through nature-based solutions, but this is less well studied so far in the scientific community.

The power of satellite observations lies in their ability to provide spatially and temporally resolved measurements of atmospheric CO_2 and CH_4 concentrations globally which provides a strong constraint on the net amount of each gas that is exchanged between the surface and the atmosphere by natural and anthropogenic processes. This is now well established thanks to the pioneering satellite missions SCIAMACHY, GOSAT and OCO-2. Although these missions have not been designed to track anthropogenic sources and sinks, these missions and their successors have provided already a multitude of successfully demonstrations for space-based observation and estimation of CO_2 and CH_4 emission sources.

Using data from OCO-2 and GOSAT, it has been shown that CO_2 emission plumes related to large power stations can be observed and that their CO_2 emission strength can be estimated. CO_2 data from OCO-2 is also used to assess emission inventories for cities which is now further advanced with the OCO-3 mission with its city mapping mode and similarly by the French/UK MicroCarb mission to be launched in 2022/2023.

CH4 observations from GOSAT and now also from TROPOMI have been successfully used to investigate anthropogenic emissions for large countries and a pilot dataset of CH_4 emissions by sector and country-scale resolution in support of the global stocktake has already been generated. TROPOMI has also

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[60] http://beacon.berkeley.edu/about/

added the capability to identify and estimate emissions from large, often unknown CH4 point sources such as well blowouts, large oil/gas production sites, coal mines and even large landfills but this is limited to very large sources due to the coarse spatial resolution of TROPOMI.

Improved capabilities to observe and quantify localised CH_4 emission is provided by commercial satellites with very high spatial resolution such as GHGSat or hyperspectral missions such as Worldview-3 and Sentinel-2 that have successfully been used to observe and quantify weaker CH_4 point sources compared to TROPOMI, including a range of oil and gas facilitates and landfills, with emissions as low as 100kg/h.

A major advance in space-based observations of CO_2 and CH_4 will be achieved with the launch of the ESA CO2M mission in 2025. CO2M has been specifically designed to provide remote sensing observations needed for monitoring of anthropogenic CO_2 and CH_4 emissions. CO2M will form the space-based element of the European MVS which will provide operational information on emitting hot spots, monitor their trends, assess emission changes against local reduction targets and assess national emissions and changes to inform the global stocktake.

In next five years, other technologies including active and geostationary missions will become available that will complement data obtained from CO2M, for example during high latitude winter.

We will also see a substantial increase in commercial and hybrid missions over the next five to ten years, which promise further advances in monitoring of CH_4 and CO_2 point sources with more frequent observations and lower detection limits.

2.4.2 Role Remote Sensing Could Play in The Verification of Estimates of GHG Emissions

CO_2 Monitoring and Verification Support Capacity

1. As a response to this need for independent verification, systems for a global CO_2 MVS capacity making use of independent, observation-based atmospheric data to complement the bottom-up transparency framework and to support climate policymakers are now developed. Most prominent is the European anthropogenic CO_2 emissions monitoring and verification support capacity (CO2MVS) implemented within the Copernicus programme[61] (see Commission, Centre and Ciais, 2016; Janssens-Maenhout *et al.*, 2020). This system will also form an essential element of the Integrated Global Greenhouse Gas Information System[62] (IG^3IS) coordinated by the WMO.[63]
2. Such a MVS will be based on a top-down (or inversion) approach that takes advantage of variations in atmospheric CO_2 concentrations or columns that reflect changes in surface emissions and uptake and

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[61] https://www.copernicus.eu/en
[62] https://ig3is.wmo.int/en/welcome
[63] https://public.wmo.int/en/resources/bulletin/integrated-global-greenhouse-gas-information-system-ig3is

atmospheric transport (e.g., Feng *et al.*, 2009). An atmospheric transport model is used to understand the relationship between surface fluxes (emissions minus uptake) and atmospheric concentrations or columns.

3. Variations in atmospheric CO_2 reflect the superimposition of anthropogenic emissions and active natural carbon cycle, whose variability is driven primarily by photosynthesis and respiration by the land biosphere (Beer *et al.*, 2010) and by the solubility of CO_2 in the ocean (Ciais *et al.*, 2014). Fluxes from these natural processes at a given time can be much larger than those from anthropogenic emissions. Thus, atmospheric inversions (e.g., from the CarbonTracker[64] system) are traditionally used for large-scale carbon cycle research with the goal of quantifying surface-atmosphere fluxes from natural systems, while prescribing fossil CO_2 emissions from bottom-up inventories.
4. Until recently, atmospheric inversion work has been driven by atmospheric measurements of CO_2 and CH_4 and other GHGs provided by a global network of surface-based stations managed by the WMO/GAW[65] programme. These ground-based in situ measurements are very accurate and well calibrated, but they do not have the spatial resolution and coverage needed everywhere on Earth to identify or quantify the sources emitting CO_2 and CH_4 into the atmosphere or the natural sinks that remove these gases on regional or national scales.
5. Achieving the overarching goal of monitoring anthropogenic CO_2 emissions crucially depends on a substantial increase in available worldwide atmospheric CO_2 observations. As highlighted in a recent whitepaper by the Committee on Earth Observation Satellites (CEOS)[66], this will require global satellite observations of column integrated CO_2 (XCO_2) with the revisit and spatial resolution needed to resolve both natural and anthropogenic emissions.[67]

Copernicus CO2M

6. The Copernicus CO_2 Monitoring[68] (CO2M) mission is a space-based system specifically developed to provide an operational capacity that contributes to the global monitoring of anthropogenic CO_2. CO2M forms the space-based component of the European MVS.
7. The mission objectives of CO2M are to provide the observations needed to:
    a. detect emitting hot spots, such as large urban areas and power plants;
    b. monitor trends in hot spot emissions to assess emission reductions and increases;
    c. assess emission changes against local reduction targets to monitor impacts of NDCs; and
    d. assess national emissions and changes in 5-year time steps to inform the global stocktake.

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[64] https://gml.noaa.gov/ccgg/carbontracker/
[65] https://public.wmo.int/en/programmes/global-atmosphere-watch-programme
[66] https://ceos.org/
[67] http://hdl.handle.net/2014/52009
[68] https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v3.0_20201001_Issued.pdf

8. To achieve these goals, CO2M will provide a CO_2 imaging capability with a spatial resolution on the order of 4 km^2 to resolve emission plumes from large point sources, and a XCO_2 precision better than 0.7 ppm for individual samples with systematic biases less than 0.5 ppm to quantify the emissions from these sources. The mission will use an across-track swath of 250 km to cover the full size of densely populated regions where intense emissions occur. To achieve global coverage every two to three days, CO2M will deploy a constellation of satellites with targeted launch date of 2025 (CO2M MRD[69]; Sierk *et al.*, 2021a).
9. Top-down methods using ground- or space-based observations alone, are not capable of providing process or sector-specific information or information across the full range of spatial and temporal scales required. To quantify anthropogenic CO_2 emissions and their trends at the scale of large urban areas, industrial sites, nations, and globally, the planned operational system will integrate atmospheric data together with other complementary components (Commission *et al.*, 2019):
    a. Atmospheric CO_2 measurements obtained from dedicated space-borne sensors, complemented by in situ surface networks and ancillary observations such as NO_2 and carbon monoxide;
    b. Operational and frequently updated bottom-up fossil fuel CO_2 emission maps and other anthropogenic emission maps with high spatial and temporal resolution;
    c. An operational data-assimilation system, which will integrate atmospheric measurements with bottom-up information into consistent and accurate estimates of anthropogenic CO_2 emissions and their trends.
10. In such a system, satellite CO_2 data can be combined with complementary tracers of fossil fuel emissions that can help to distinguish CO_2 added by fossil fuel combustion from the effects of natural CO_2 fluxes. This includes carbon monoxide, and nitrogen oxides (NO_x), that are produced during fossil fuel combustion and that are observed by satellites (Kuhlmann *et al.*, 2019). Satellite CO_2 data could also be combined with ground-based tracer observations such as radiocarbon (^{14}C) in CO_2 which is the best approach identified so far for separating fossil fuel CO_2 emissions from natural fluxes because fossil fuels do not contain ^{14}C (Levin *et al.*, 2003; Turnbull *et al.*, 2006). Is it worth noting that this cannot be equated to anthropogenic vs. non-anthropogenic emissions, as LULUCF is an anthropogenic but non-fossil source. This also links back to Section 2.3.4.
11. The coverage and repeat frequency that these systems provide will still be limited by optically thick clouds and the need for sunlight which can bias results towards conditions without clouds. The expected constellation with three satellites will provide 30 to 60 days with useful observations over major cities which can be exploited to infer emissions and for monitoring emission trends.[70] The ability of CO2M to estimate emissions from power station plumes has been studied by Kuhlmann *et al.*, 2021.

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[69] https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v3.0_20201001_Issued.pdf
[70] Ibid.

They found that emissions for power stations with a source strength >10 Mt yr^{-1} can be inferred with an uncertainty of 18–65% on an annual basis for a constellation of three satellites.

Other Space-based Systems

12. Some limitations of space-based column sensors using reflected sunlight can be partly compensated by establishing a virtual constellation of different space-based systems.[71] Active sensors (lidars), such as the MERLIN (Methane Remote sensing Lidar mission)[72] XCH_4 mission planned for launch in 2025 by the French (CNES) and German (DLR) space agencies, do not rely on sunlight so can provide measurements during polar night and they can provide high accuracy reference measurements to cross-validate measurements from passive CO_2 imagers. Geo-stationary missions such as NASA GeoCarb[73] scheduled for launch in 2022 offer revisits multiple times a day within their field of view.
13. Data collected by satellite instruments that have sensitivity to thermal-IR wavelengths, such as the current IASI[74] and future IASI-NG[75] missions will also provide data in the absence of sunlight. CH_4 data from both missions is generated by Science and Technology Facilities Council/Rutherford Appleton Laboratory (STFC RAL) and is available from the UK Centre for Environmental Data Analysis (CEDA)[76]. These missions provide long-term data until at least 2040 with a peak sensitivity in the upper tropospheric and thus provide a less effective constraint on regional surface fluxes. There is good potential for combined use of data from thermal-IR sounders with total column sensors which can enhance their value for source and sink estimation. This is investigated in the ongoing ESA Methane+ study[77].
14. The French/UK MicroCarb[78] mission is the first dedicated CO_2 mission from Europe and will be launched in 2023/2024. MicroCarb is designed to map CO_2 emissions and uptake, following an approach used by NASA's OCO-2 mission. MicroCarb has a narrow swath of 13.5 km and a ground resolution of 4.5 x 9 km^2. Thanks to an onboard pointing system, MicroCarb can modify its observing pattern along its orbit and facilitate a city-observing mode with higher resolution of 2x2 km^2.
15. The Japanese space agency plans to launch GOSAT-GW[79] (Global Observing SATellite for Greenhouse gases and Water cycle) in 2023. GOSAT-GW is aimed at anthropogenic and natural emissions mapping of CO_2 and CH_4. It will provide global coverage every three days with a flexible resolution ranging from 1 x1 km^2 to 10x10 km^2.

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[71] Ibid.
[72] https://www.dlr.de/pa/en/desktopdefault.aspx/tabid-4619/7601_read-42427/
[73] https://eospso.nasa.gov/missions/geostationary-carbon-cycle-observatory-evm-2
[74] https://www.eumetsat.int/iasi
[75] https://www.eumetsat.int/eps-sg-iasi-ng
[76] https://catalogue.ceda.ac.uk/uuid/f717a8ea622f495397f4e76f777349d1
[77] https://methaneplus.eu/
[78] http://www.space4climate.com/microcarb-satellite/
[79] https://gosat-gw.global-atmos-chem-lab.jp/en/

16. A constellation of satellites aimed at monitoring anthropogenic CO_2 and CH_4 emissions is also planned by China. This is called Tansat-2[80] and would consist of a constellation of three satellites with a proposed launch date of 2022.
17. In the case of CH_4, operational data products with daily global coverage and spatial resolution of 7x7 km^2 with an expected performance similar to Sentinel 5P (Lorente *et al.*, 2021) will be acquired by the Sentinel 5[81] mission planned for launch in 2024.[82]
18. These operational, public missions for CO_2 and CH_4 monitoring will be augmented by a large number of often private or hybrid satellite missions that target CH_4 and CO_2 emissions on a much finer spatial scale often of tens to hundreds of meters resolution. Here, hybrid missions refer to missions partly funded by philanthropic organisations. These missions typically target only specific emission locations. The Canadian GHGSat[83] has already three instruments in space that provide 50 x 50m^2 resolution data over a 12 x 12 km^2 area to target industrial CH_4 emissions (mostly from the oil and gas sector) with a detection threshold of 100 kg CH_4/h. GHGSat is expected to launch further satellites in the future. The US Environmental Defense Fund[84] MethaneSat[85] is scheduled for launch in 2022 and it will measure CH_4 with very high precision of 2-3 part per billion (ppb) with a 200km wide swath and a spatial resolution as small as 100m. The US Carbonmapper[86] is planned as a constellation to target CO_2 and CH_4 from point sources with a spectrometer concept that allows a swath of 18 km and spatial resolution of 30-35 m. A pushbroom mapping capability allows to cover larger areas. They can detect emissions of up to 200,000 kg CO_2/hr which allows coverage of 90% of the world's coal power plants. An overview over missions with capabilities to measures CO_2 and/or CH_4 is given in the joint report by the Group on Earth Observations (GEO), Climate TRACE and the World Geospatial Industry Council (WGIC).[87] UK-based mission concepts for CH_4 and CO_2 are being developed with Her Majesty's Government funding but are three to four years from being launched into an Earth orbit.
19. Complementary satellite observations are also available to help understand the functioning of the terrestrial biosphere. The most promising observation is Solar Induced Fluorescence (SIF), which reflects the small amount of excess energy emitted by vegetation during photosynthesis. SIF therefore provides information about gross primary. SIF can be inferred from a narrow band in the near infrared observed by most existing CO_2 spectrometers and thus a SIF product is available alongside satellite observations of CO_2. SIF measurements are valuable, for example, for discriminating the contribution

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[80] http://database.eohandbook.com/database/missionsummary.aspx?missionID=957
[81] https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/copernicus-sentinel-5
[82] https://space.oscar.wmo.int/instruments/view/sentinel_5
[83] https://www.ghgsat.com/en/
[84] https://www.edf.org/
[85] https://www.methanesat.org/
[86] https://carbonmapper.org/
[87] https://earthobservations.org/documents/articles_ext/GHG%20Monitoring%20from%20Space_report%20final_Nov2021.pdf

of green spaces, agricultural and wooded areas within and around cities to XCO_2 (e.g., (Lan *et al.*, 2020). The ESA FLEX[88] (FLuorescence EXplorer) satellite mission, due for launch in 2022, is dedicated to SIF observations. Above ground biomass gives the standing dry mass of live or dead matter from trees or shrubs and is inferred from Radar and Lidar instrument. ESA's Climate Change Initiative[89] will produce global biomass datasets for multiple years which can then inform on biomass changes. This initiative is led by a UK university and involves four more UK universities. A dedicated mission for biomass mapping called BIOMASS[90] will be launched in 2023. BIOMASS, with science lead from a UK university, will be the first spaceborne P-Band radar mission to determine the worldwide distribution of forest above-ground biomass and its changes with high accuracy.

2.4.3 Examples of satellite remote sensing data being used to calibrate/inform bottom-up emissions

20. Satellite observations of XCO_2 and XCH_4 first became available with the launch of the SCIAMACHY instrument in 2002 followed by GOSAT in 2009, NASA's OCO-2 in 2014, Chinese Academy of Science Tansat in 2016 and NASA OCO-3 in 2019.
21. The missions have demonstrated an excellent performance with XCO_2 single sounding random errors between 0.1 and 0.3% (0.4 to 1.2 ppm) and systematic biases between 0.25 and 0.5% (1 to 2 ppm) over most of the globe (e.g., Wunch *et al.*, 2017) and for XCH_4, single sounding random errors are near 13 ppb and systematic biases are between 0.2 and 0.4% (4 and 7 ppb; (Buchwitz *et al.*, 2017; Parker *et al.*, 2020)), thus fulfilling or being close to fulfilling the stringent requirements for climate variables set by Global Climate Observing System (GCOS)[91].
22. Current satellite sensors were not designed with the spatial and temporal resolution and coverage needed to track anthropogenic sources and sinks on urban to national scales, or with the accuracy and precision needed to improve national CO_2 and CH_4 emission inventories. However, these missions have already successfully demonstrated the capabilities of space-based observations to inform on emissions of CO_2 and CH_4 giving confidence in the value of dedicated future satellite systems for operational monitoring and verification of anthropogenic emissions.

Carbon Dioxide

23. Data from the NASA OCO-2 instrument has been used to detect CO_2 gradients of a few ppm in CO_2 between cities and their background which can be attributed to emissions (Schwandner *et al.*, 2017). Using a high-resolution atmospheric transport model in conjunction with OCO-2 data, Yang *et al.*, 2020

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[88] https://earth.esa.int/eogateway/missions/flex
[89] https://climate.esa.int/en/projects/biomass/
[90] https://www.esa.int/Applications/Observing_the_Earth/Biomass
[91] https://gcos.wmo.int/en/home

investigated five Middle Eastern cities and they found that emission inventories need to be scaled by a factor of two. Similarly, (Janardanan *et al.*, 2016) has used CO_2 observations from the GOSAT missions to diagnose emissions from large sources such as megacities and power plants and they found discrepancies of tens of percent. Weir *et al.*, 2021 has found that OCO-2 data taken over the World's largest emitting regions is consistent with a reduction of 3-13% of annual global emissions as a result of Covid-19 restrictions.

24. The mapping mode of NASA OCO-3 mission captures about three times as much of the city emissions compared to single-swath overpasses. This has been demonstrated for a case study over Los Angeles in Kiel *et al.*, 2021.
25. Although the swath width of OCO-2 is only 10km, it occasionally captures parts of emission plumes from power stations which can then be used to quantify emissions from large coal-fired power plants. This has been first reported by Nassar *et al.*, 2017 for US power stations with well-known CO_2 emission values. They found that space-based estimates agree with reported values within 1–17%. Similar results have been found by Reuter et al. 2019 and Nassar et al., 2021.
26. CO_2 from OCO-2 in combination with surface in situ data has also been used to analyse the impact of large-scale reforestation in China (Wang *et al.*, 2020). They found a land sink equivalent to about 45% of estimated annual Chinese anthropogenic emissions over the period 2010 to 2016 likely reflecting fast-growing plantation forests in southwest China.

Methane

27. CH_4 data from GOSAT generated by NCEO and now also from TROPOMI have been successfully used to investigate anthropogenic emissions for large countries. For example, Turner *et al.*, 2015 found that emissions reported in the bottom-up inventory EDGAR are 50% smaller than estimated with GOSAT while Ganesan *et al.*, 2017 found for India, CH_4 emissions from GOSAT that are 30% smaller compared to EDGAR, highlighting potentially significant uncertainties in bottom-up inventories. Furthermore, Sheng *et al.*, 2021 diagnosed CH_4 emissions from China and they found a significant positive trend that has slowed down in recent years which they attributed to a decline in China's coal production.
28. Recently, a pilot dataset of CH_4 emissions and uncertainties, by sector, at 1-degree and country-scale resolution for the Global Stock Take was derived from GOSAT and TROPOMI observations (Worden *et al.*, 2021).
29. Owing to its mapping capability, although coarse ($7x7km^2$), TROPOMI data allows observation of major CH_4 emission plumes, often from previously unobserved sources such as a major well blowout in Ohio with an emission rate of 120 ± 32 metric tons per hour (Pandey *et al.*, 2019) or anomalously large CH_4 point sources from oil and gas production in Turkmenistan releasing 142 ± 34 metric kilotonnes of CH_4 between February 2018 through January 2019 (Varon *et al.*, 2019).

30. In a recent study on the use of satellites for regulatory activities conducted by the Environment Agency, it has been assessed whether TROPOMI can observe the CH_4 emission signal from UK landfills and it was concluded that their emission strength is too low to be observable with TROPOMI.[92] However, landfill CH_4 emissions have been recently observed with TROPOMI for a landfill near Madrid.[93]
31. A strength of TROPOMI is that it can place strong point source emissions in a regional context which can then be used to target other satellite instruments with finer spatial resolution such as GHGSat (Varon *et al.*, 2019) or hyperspectral/multispectral missions like Worldview-3 (Sánchez-García *et al.*, 2021) or PRISMA (Guanter *et al.*, 2021). However, such hyperspectral/multispectral missions have not been developed for spectroscopic CH_4 measurements and they can only detect sources with emission rates of the order of several hundred kg/h.
32. Recently CH_4 detection from hotspot emissions has also been reported from operational hyperspectral/multispectral sensors including Sentinel-2 (Varon *et al.*, 2021). They have the advantage that data is freely available, and they acquire data routinely, thus providing a valuable dataset for global identification of strong CH_4 point sources. A theoretical analysis of CH_4 detection capabilities from hyperspectral satellites is given in Cusworth *et al.*, 2019.

2.5 Question 5: Which areas of policy interest are best-served by bottom-up inventory approaches, and where might atmospheric measurements, in the longer term, be able to support emission estimates?

2.5.1 Summary

The bottom-up inventory approach is most effective when the activity data and emission factors are well known. This is generally where:

a. emissions are closely related to trading of commodities, such as the buying and selling of fossil fuels, so that the activity data is well quantified; and
b. the emission process is chemical or physical rather than biological.

The top-down approach, based on current atmospheric measurements and modelling, is most effective when:

a. the emission sources are diffuse, rather than from point sources;
b. the instrument technology allows for reliable high-precision measurements, comparable across sites; and

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[92] https://www.gov.uk/government/publications/satellite-measurements-of-air-quality-and-greenhouse-gases-application-to-regulatory-activities

[93] https://www.esa.int/Applications/Observing_the_Earth/Satellites_detect_large_methane_emissions_from_Madrid_landfills

c. the interpretation of the atmospheric signal is straightforward with respect to the reported inventory (this is less straightforward for LULUCF and biogenic fluxes).

The bottom-up inventory is weakest (most uncertain) in the areas of LULUCF and waste management, and also agriculture.

The other sectors are all relatively well-served by the bottom-up inventory approaches, with low relative uncertainties (2-4%). The industrial process and public-sector emissions have the lowest absolute uncertainties. Given the magnitude of emissions from the energy, including mobile combustion (i.e., transport) and stationary combustion (i.e., business and residential) sectors, these represent larger absolute uncertainties.

We attempt to identify the intersection where the bottom-up approach is weak and atmospheric measurements have the most potential. Currently, we consider this to be the agriculture and waste management sectors. To a lesser degree, there is scope in the areas of transport and domestic emissions.

To quantify emissions from point sources (which dominate the energy production and industrial sectors), more targeted measurement and modelling approaches are needed, and these show potential.

Bottom-up and top-down approaches need not be considered as distinct, but careful integration of the two is required. Consistency in the various systems used to classify emissions (NFR, GNFR, SNAP, SIC etc.), and openness of data would be helpful here.

The LULUCF sector raises particular problems for the top-down approach for CO_2 because of the large gross CO_2 fluxes which dominate the atmospheric signal, which are largely unrelated to LULUCF.

2.5.2 Bottom-up versus top-down approaches

1. The bottom-up inventory can be seen as a collection of methodologies and models which predict the national-scale GHG flux (emissions) as a function of parameters (such as "emission factors") and input variables ("activity data" of various kinds).[94] The methodologies that must be used are defined by the IPCC and adopted under the UNFCCC. There are several sets of IPCC Guidance, augmented with the 2019 Refinement.

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[94] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/349618/IntroToTheGHGI_2014_Final.pdf

2. By contrast, atmospheric measurements are used in a top-down approach, based on a model which predicts the mixing ratio of a GHG as a function of the GHG flux and atmospheric transport.[95]
3. The bottom-up approach is a forward model in which the flux is predicted, whereas the top-down approach is an inverse model in which the flux is inferred. We can see the two approaches as distinct exercises and compare the two sets of results and interpret differences. More commonly nowadays, a Bayesian perspective is used, with the bottom-up inventory providing the prior distribution of emissions, and the atmospheric measurements providing additional data with which these are updated to produce a posterior distribution of emissions. In principle, we can combine the two models, and thereby make inferences about the bottom-up model parameters using atmospheric measurements, and in this respect, the approaches need not be seen as distinct. This is a topic of current research (e.g., in the NERC DARE-UK project[96]). Practical limitations come about because of the potentially large number of parameters, with respect to the constraint provided by the atmospheric data.

2.5.3 Precision of bottom-up versus top-down approaches

4. In deciding which areas of policy interest would benefit most from using atmospheric measurements to support estimates of emissions, the factors to consider are the precision and accuracy of the emissions estimated by the bottom-up and top-down approaches. Some emission estimates are poorly constrained by bottom-up inventories (and so are estimated with low precision and accuracy) and would benefit from additional constraints given by atmospheric measurements (e.g., Skiba *et al.*, 2012). Some emissions are difficult to quantify using atmospheric measurements, because of their spatial and temporal distribution or because the technology for measuring some GHGs (such as N_2O) is less well-developed (and so are estimated with low precision). The precision will always be increased by adding new data, so to prioritise areas of policy interest, the questions are:
   a. where does the precision on the bottom-up estimate most need to be increased?
      - i.e., which bottom-up estimates are most uncertain, in absolute terms?
   b. where does the precision on the top-down estimates significantly help this?
5. In terms of optimisation, we want the greatest increase in overall precision and accuracy with the least additional effort, and this should be a guide to prioritising where atmospheric measurements should be improved.

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[95] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/683369/Methodology_Report_20Sept2017.pdf

[96] https://dareuk.blogs.bristol.ac.uk/

2.5.4 Areas of policy interest best-served by bottom-up inventory approaches

6. In general, the bottom-up inventory approach works best when GHG emissions are closely related to commodities that are traded financially or subject to taxation, such as the buying and selling of fossil fuels or fertilisers. This is because there are clear economic needs to accurately record the activity, and financial transactions provide quantitative data, closely related to the activity data required by the bottom-up model. The activity data are therefore known with high precision and accuracy. The link between financial transactions and the activity data may not be exact; for example, the amount of fuel purchased on a given date may be known, but the timing and location of its use (and resulting emission) may be unknown. Similarly, the bottom-up approach works best when emission factors are well understood and well-known. Again, combustion of fuel is a relatively simple chemical process, and the amount of GHG produced per unit of fuel can be estimated with high precision and accuracy.
7. The bottom-up approach is less successful where the GHG emission is not directly related to an economic activity, but an unintended consequence of some other action. The emissions may be physical (gas leakage), chemical (release of CO_2 from lime applied to soil), or biological (waste decomposition, forest growth, soil carbon change) in nature. These emissions are much less well characterised in terms of activity data and emission factors and scaling up to the national scale is challenging (Levy *et al.*, 2021), so precision on estimates is much lower.

2.5.5 Uncertainty in the current inventory

8. Figure 2 below shows the contribution from each sector to the total uncertainty in the national inventory[97], weighting the different GHGs by their global warming potentials and expressed in terms of CO_2 equivalents.

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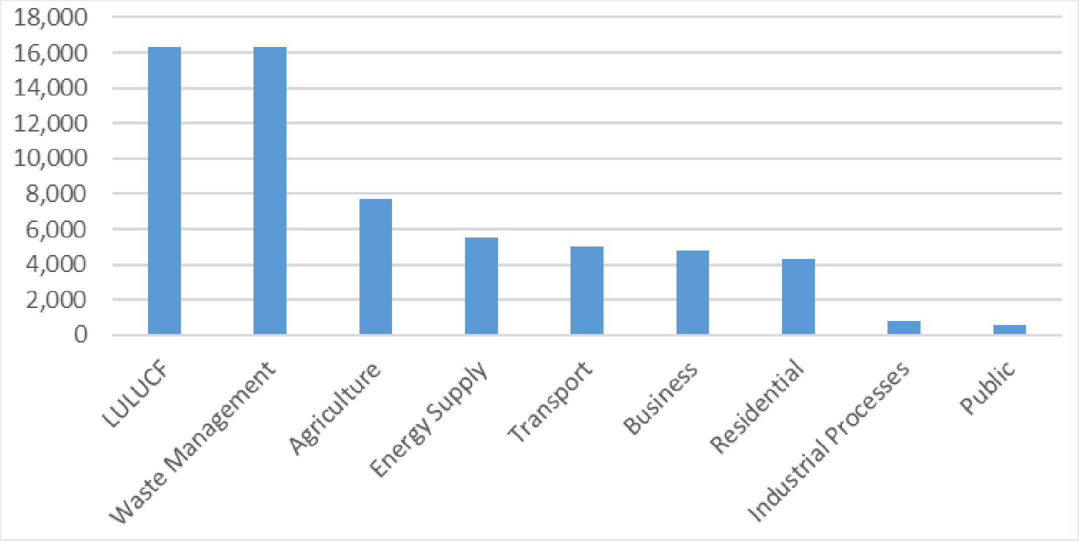
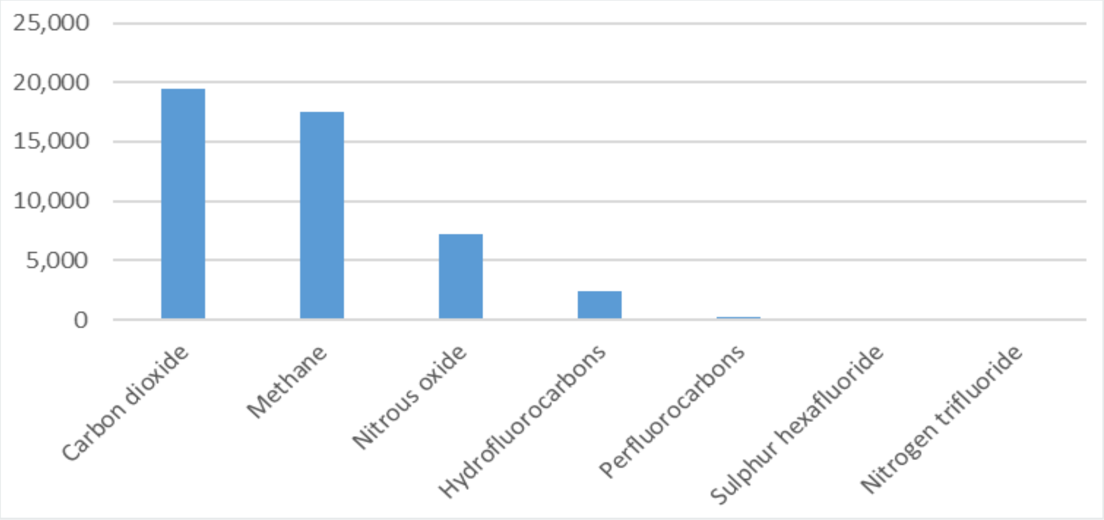
[97] https://naei.beis.gov.uk/resources/Sector_Summary_Factsheet_2020-v2.html#5_uncertainties

Figure 2. Uncertainty in Inventory by Sector (Tg CO_2-eq/y)



9. This shows that LULUCF and waste management have substantially larger uncertainties than the other sectors, followed by agriculture. Energy, transport, business, and residential combustion all have rather similar uncertainty, at around a quarter of that of LULUCF. Industrial processes and public sector emissions have very low uncertainty.
10. Figure 3 below shows the same analysis by gas and shows that the highest absolute uncertainty is for CO_2, but CH_4 is very close. The uncertainty contributed by N_2O is around 40% of these values. Uncertainty in the fluorinated gases is relatively low by comparison.

Figure 3. Uncertainty in Inventory by Gas (Tg CO_2-eq/y)



11. So, in terms of the priorities for reducing uncertainty in the bottom-up inventory, we can identify: CO_2 from LULUCF; CH_4 from waste management; CH_4 from agriculture; N_2O from agriculture; CO_2 from

energy; CO_2 from transport. (Uncertainty in CH_4 emissions from LULUCF is not included here, but its estimation is in progress.)

12. Meeting the Net Zero target implies that gross emissions will be greatly reduced and balanced by gross uptake in carbon capture and storage (CCS) and LULUCF by 2050. The relative contribution from the different sectors will thus change radically. The uncertainties in LULUCF and CCS will become more critical as the other emissions decline. Depending on the nature of future CCS developments (e.g., the location of stored CO_2 reservoirs), this may affect future measurement network design.

2.5.6 Scope with current atmospheric measurements

13. The current DECC network consists of three sites in the UK, all in southern England, with additional measurement sites at Mace Head in Ireland and Weybourne on the coast of East Anglia (Stanley, Grant, O'Doherty, Young, *et al.*, 2018; Stavert *et al.*, 2019). The footprint of the measurements – the upwind area over which they are sensitive to the surface emissions – can be estimated with an atmospheric transport model. This shows an approximately exponential decline with distance, so most sensitivity within a few tens of kilometres, much less so over hundreds of kilometres, weighted towards the prevailing wind direction. Shipping and aviation are particularly awkward to sample with the current terrestrial network (though see Helfter *et al.*, 2019), given that a large fraction of the emissions occur offshore, at high altitude, from a small number of point sources (ships / aircraft / airports). Remote sensing of atmospheric GHG mixing ratios is becoming more feasible with advances in satellite instrumentation, and this has enabled the estimation of point sources (e.g., Reuter *et al.*, 2019; Varon *et al.*, 2019; Irakulis-Loitxate *et al.*, 2021). However, cloud cover over the UK presents particular problems. Although satellite-inferred GHG data products are now available on an operational basis, their interpretation and use are still at a research stage, though with future potential (see also Sections 2.4 and 2.6).

2.5.7 Spatial distribution of UK emissions

14. In relation to the current measurement sites, we can consider the spatial distribution of emissions of the different GHGs and from different sectors. A key consideration is the extent to which emissions are spatially restricted into a small number of highly emitting point sources (power stations, industrial plants, waste facilities etc.), as opposed to diffuse sources such as agriculture, which are more uniformly spread over a large area. The former will be very hard to pick up unless they happen to coincide with the footprint of one of the towers and require more detailed high-resolution modelling (involving stack heights and more detailed turbulence data) to predict the movement of molecules from one point (the source) to another (the sensor on a tower). Diffuse sources are more likely to be sampled across the network.

15. **CO_2**: Considering the spatial distribution of the different GHGs, CO_2 is dominated by point source emissions: 80% of the emissions is concentrated in only 6% of the UK area (based on analysis of NAEI data). 30% of the total emissions comes from only 100 point sources - mainly power stations, steel works and cement production. In terms of sectors – around 43% is emitted from sectors dominated by point sources (energy production and industry). 56% comes from transport and domestic combustion, and these are somewhat intermediate between point and diffuse sources, being distributed roughly in line with the population distribution and the set of linear features making up the transport network.
16. **CH_4**: Emissions of CH_4 are much more diffuse than CO_2: 80% of emissions come from 35% of the area, and only 3.5% of the total emissions comes from the top 100 point sources. By sector, around 85% is emitted from sectors dominated by diffuse sources (agriculture and waste).
17. **N_2O**: As agriculture contributes 70% of the emissions, N_2O is largely a diffuse source, with 80% of the emissions coming from 50% of the UK area. Around 100 point sources (in the energy, industrial and waste sectors) contribute 4% of the emission. Around 80% is emitted from sectors dominated by diffuse sources (agriculture and waste).

2.5.8 Intersection: emissions with high uncertainty in bottom-up estimates and low uncertainty in top-down approach

18. The GHG emissions which have high uncertainty in bottom-up estimates and are most tractable with the current network and modelling framework are CH_4 and N_2O emissions from agriculture and waste. In the case of both CH_4 and N_2O, these two sectors account for approximately 80% of the emissions of these gases. The spatial distribution of emissions is diffuse, such that current modelling methods are applicable.
19. In the case of N_2O, the bulk of the emissions is from a single sector, which makes interpretation simpler. However, ground-based measurement of N_2O is more difficult than for CH_4. Gas chromatography is still widely used for N_2O, and while this is a well-established technology, it is awkward to automate and run unattended on a continuous basis. Laser-based spectroscopic methods for N_2O are still in their early stages (e.g., Pitt *et al.*, 2016; Haszpra *et al.*, 2018; Cowan *et al.*, 2020). There are also significant problems in reconciling calibration standards across different networks. By contrast, laser-based spectroscopic methods for CH_4 are relatively mature and reliable.
20. In the case of CO_2, there is potential to estimate emissions from the transport and domestic combustion sectors, given that these are at least partially diffuse sources, and the associated activity data is relatively well constrained.
21. The LULUCF sector has the highest uncertainty compared to the other sectors, mostly concerning CO_2, but this is particularly difficult to address via atmospheric measurements. Firstly, there are large gross fluxes which occur on diurnal and seasonal time scales - photosynthetic assimilation during the day

and respiration during the night, and analogously, the growth of the vegetation in the spring and summer, and its subsequent respiration. These large gross fluxes dominate the atmospheric signal but balance out to near zero over the diurnal and seasonal cycles. Secondly, on a year-to-year timescale, there are variations in weather – heat waves, droughts, cold and dull summers etc., which mean that some years show net CO_2 uptake and others show net CO_2 emission. Thirdly, on a longer timescale, there may be net CO_2 flux because of longer-term changes in the environment such as elevated CO_2, climate change, nitrogen deposition, recovery from acidification etc. All the above are real fluxes but excluded from the accounting methods for LULUCF. LULUCF accounts for land management activities which are known to produce emissions, and changes in land use (e.g., afforestation of grassland, conversion of cropland to grassland (Levy *et al.*, 2018), which cause a subsequent change in carbon stock (i.e., a flux). However, this is a relatively small component of the gross fluxes reflected in the atmospheric mixing ratio and disentangling the two is very challenging.

22. The current atmospheric modelling framework does not disaggregate emissions by sector, which makes interpretation of the output difficult in terms of specific activities or policy measures. However, work in the NERC DARE-UK project is addressing this, using the atmospheric measurements to update the sector-specific parameters of a temporally resolved model of the inventory (ukghg[98]), as opposed to updating emission maps. Sector-specific tracers, such as ethane and isotopes of CH_4 have limited scope in distinguishing between biological sources (such as CH_4 and N_2O from agriculture and waste).

2.6 Question 6: Could atmospheric measurements enable tracking of the effectiveness of specific policies in near real time, and what are the levels of temporal, spatial and sectoral resolution required?

2.6.1 Summary

The bottom-up approach necessarily has a time delay between emissions occurring and official inventory of GHG emissions being reported of around 18 months. By contrast, the atmospheric mixing ratios of the major GHGs are measured in near-real-time on the current DECC tall-tower network, and these respond to changes very quickly. Here we explore the potential for using these and other data to assess changes in emissions more rapidly, and to detect the effect of particular policies.

Observations of atmospheric mixing ratios are not used in isolation, but as part of a modelling framework which depends on other aspects of the atmosphere to be quantified appropriately. Although GHG mixing ratios can be measured on an hourly basis, to produce corresponding estimates of GHG emissions requires that other atmospheric variables are better characterised at high resolution. Most critically, high-resolution measurements are needed of boundary layer growth and

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[98] https://github.com/NERC-CEH/ukghg

the vertical profile of GHG mixing ratios. Ground-based upwards-looking remote sensing instrumentation provides potential in this respect, such as ceilometers, Fourier-Transform infrared spectroscopy (FTIR), and differential absorption lidar (DIAL) lidar systems.

Other air pollutants are co-emitted tracers with GHGs, and some of these are measured more widely (e.g., CO, NO_2, ammonia), either by ground-based networks or satellite instruments. By incorporating these in the modelling framework, we can infer the temporal and spatial variation in GHG emissions with greater precision, and these may also yield sector-specific information. High-resolution bottom-up activity data, where it is available, may be used in a similar way. This may require a more sophisticated modelling process, incorporating sector-specific parameters of the inventory (see Section 2.5.8, para.22).

Point sources such as industrial plants, waste-water-treatment sites, large landfill sites, gas distribution sites, biogas plants and power stations are not well sampled by the existing tower network, and require a more targeted approach, focussing on spatial variation around the point source. Using in situ ground-based measurements, aircraft-based measurements and/or satellite data can yield high-resolution data for some key emissions.

Emission sectors for which atmospheric measurements have the most potential to help provide more rapid estimates of emissions include: N_2O from agriculture; CO_2 from road transport; CO_2 from energy production and industry; CH_4 from offshore facilities; CH_4 and N_2O from landfill sites; CO_2 from shipping. Monthly resolution with a short time lag would be a practicable target. The most accurate estimates will still require bottom-up activity data, and this may be the limiting factor on the lag time.

In summary, using existing data from the tall tower network to estimate emissions from particular sectors at specific times or locations are generally rather uncertain. To increase the time resolution with which we can make precise estimates, we need to add high-resolution measurements of some key atmospheric properties, e.g., boundary layer height. In addition, an improved emission estimation framework would benefit from higher-resolution activity data and atmospheric measurement of trace gases co-emitted with GHGs, which are increasingly available from satellites. While near-real-time data with higher time resolution could provide faster evidence of change, because of the background natural variability and aleatoric uncertainty, longer term monitoring over a number of years would still be needed for the wider context.

2.6.2 Background

1. The requirement under the UNFCCC and the Kyoto Protocol is to report a national GHG inventory annually. This is done with a time lag close to two years, because of the time needed to retrospectively collate data, complete and carefully check the calculations and produce the reports.
2. The time between updates of GHG inventories is typically controlled by the time needed to update key statistical data – such as energy statistics. This means that there is a time delay between emissions occurring and official emission statistics being reported of approximately 18 months. Energy statistics are often released every year, and then the inventory has to be updated, which takes a few months, in part to allow for careful quality control and quality assurance checks. This duration of update can be reduced by using proxy data and modelling, and the UK has in the past generated an estimated set of emissions approximately every 3 months.
3. As well as the time delay, another important factor is the responsiveness of the methods that are used to generate estimates of emissions. The inventory will only reflect the impacts of mitigation policies if the methodologies used in the inventory are able to reflect the impact of those policies. This means that the inventory needs to use higher-tier methods and country-specific emission factors that will be able to handle the effects of mitigation actions.
4. This makes it a rather slow and inflexible process for monitoring change. However, atmospheric measurements are available with much higher time resolution, and in near-real-time. Here, we consider the potential for using atmospheric measurements and modelling to update or constrain the bottom-up inventory at higher time resolution, to provide evidence of change in particular sectors, and to verify the effect of particular policies.

2.6.3 Using atmospheric measurements in a top-down approach

5. Atmospheric measurements can be made from a range of platforms including terrestrial towers, aircraft, ships or satellites. A common basis for using these measurements to estimate regional-scale emissions is within an inverse modelling framework, wherein the emissions are inferred from the atmospheric data using a computational model that describes land-surface exchange of a GHG and the subsequent atmospheric transport. A common estimation approach is Bayesian inference that combines prior and measurement information to produce a posterior estimate, which is better than either the prior or measurement. Prior probability represents what is originally believed before new evidence is introduced, and posterior probability takes this new information into account. Some spatial or temporal pattern in the emissions is required in order to do this, as this drives the observed atmospheric signal at a particular location and time. Similarly, detecting the effect of a specific policy on the atmosphere needs a distinctive spatial or temporal pattern to provide a signal which we can attribute to that particular policy or sector. In a Bayesian inference framework, our understanding of

the effect of a specific policy in terms of this spatial or temporal pattern is important, as this forms part of our prior probability distribution.

2.6.4 Hourly variation / diurnal timescale

6. Many atmospheric measurements are available on an hourly basis, and this is the highest temporal resolution we might consider for estimating emissions. However, the relationship between measured mixing ratios and the surface emission on any given day is complicated by several factors. The mixing ratio measured on a tower is influenced not only by the surface emission, but also by the flux at the top of the boundary layer – the entrainment of air from the free troposphere as the boundary layer grows and via synoptic-scale subsidence. Firstly, this means that the growth of the boundary layer over the day needs to be measured or accurately modelled. Currently in the UK, boundary layer measurements are very few, and most inverse modelling attempts rely on numerical weather prediction models. These models may get the average behaviour of the boundary layer correct but are probably not reliable for a specific hour at a specific location (e.g., Banks *et al.*, 2015; Harvey, Hogan and Dacre, 2015). Secondly, the mixing ratio of the tropospheric air is poorly known, but often quite variable because of residual layers (air which was previously influenced by the surface and then separated above a nocturnal boundary layer). In the absence of direct measurements, a background mean mixing ratio is often assumed for the entrained air, and this assumption adds considerable uncertainty to hourly emission estimates. Thirdly, there are considerable time lags in the atmospheric transport between upwind emission sources and the arrival of the emitted gas at the sensor. This can be modelled but depends on a statistical representation of turbulence, and the stochastic nature means that we cannot interpret the spatial variation in the surface emissions on very short timescales. For tower-based measurements, the above factors limit the temporal and spatial resolution of top-down emission estimates. Many of these problems can be minimised with aircraft-based measurements, where vertical profiles and horizontal transects can be sampled, and the uncertain terms directly measured. However, because of the expense and logistics, such measurements are usually restricted to localised campaigns of only a few days, which leaves the problem of extrapolating in time and to the wider region.

2.6.5 Monthly variation / seasonal timescale

7. Over longer timescales, the random variability in the entrainment flux and atmospheric transport tends to average out and analysing monthly variation over the seasonal timescale is a more tractable proposition. However, many of the same systematic errors are also present at the seasonal timescale, particularly for CO_2, where the problem is referred to as the "rectifier effect" (Potosnak *et al.*, 1999) - the systematic covariation between the surface flux and boundary layer dynamics, which occurs at

both diurnal and seasonal timescales. In the daytime/summertime, there are large negative CO_2 fluxes (i.e., uptake) but their effect on the mixing ratio is diluted within a deep boundary layer; in the night-time/wintertime, there are large positive CO_2 fluxes (i.e., emission) and their effect on the mixing ratio is amplified within a shallow boundary layer. Failure to take accurate account of this covariation leads to systematic error in estimates of emissions, which can be sizeable (Stephens *et al.*, 1999). The issue is greatest with CO_2 but is present for any gas emission which shows significant diurnal or seasonal variation. The upshot is that accurate measurement or modelling of the boundary layer (and atmospheric transport) is required for higher-resolution emission estimates to be accurate (Lloyd *et al.*, 2001).

2.6.6 Approaches to near-real-time emission estimates

8. In light of the above considerations, several approaches are possible for improving the temporal resolution of emission estimates for verifying the effect of policies. These are described below, and include constraining models with high-resolution atmospheric data, using measurements of co-emitted tracers, using high-resolution bottom-up activity data as an additional constraint, and targeted measurements on key point sources. These can be considered as additional, complementary measures to the current tall-tower network, or as stand-alone measurements.

Constraining models with high-resolution atmospheric data

9. Some of the limiting factors in providing accurate estimates of emissions from atmospheric measurements lie in the representation of atmospheric dynamics. If some key atmospheric variables were better quantified on a routine basis with appropriate time resolution, the associated estimates of surface emissions would be significantly improved. This would provide better accuracy and reliability on the short time scales relevant to producing near-real-time emissions.
10. **Boundary layer dynamics** are very important for the interpretation of the time series of GHG mixing ratio observations. Alternatives to the traditional radiosonde approach now exist, including ceilometers, sodar, and radar. These are upwards-looking remote-sensing instruments, using laser, sound or radio waves to determine vertical structure, based on backscattering from the atmosphere above. With developments in laser technology, ceilometers show the most cost-effective potential for operational monitoring of boundary layer dynamics (Lotteraner and Piringer, 2016). If co-located with the tall-tower network, these instruments would help interpret hourly-resolution data by constraining terms that are currently poorly known, and this can have a substantial effect on estimates of emissions and their uncertainty (Levy *et al.*, 1999). These instruments are designed to be run continuously, and are for example, routinely run at airports. Beyond capital costs, some significant time is required for the interpretation and integration of the data.

11. **Vertical profiling of mixing ratio:** the current tower-based network uses measurements at one or more heights on the tower and assumes this represents the well-mixed boundary layer. A key uncertainty is the GHG mixing ratio in the air being entrained at the top of the boundary layer. To address this uncertainty, ground-based remote sensing techniques show considerable potential in providing measurements of the vertical profile of several GHGs. The main technologies are FTIR and DIAL. The former is a more mature technology, currently adopted by the established TCCON[99] and COCCON projects and shows potential for resolving profiles as well as measuring whole-column averaged GHG concentrations (Shan *et al.*, 2021). DIAL measurements are more explicitly focused on retrieving height-resolved mixing ratios but are at an earlier stage of development. Again, co-location of these instruments with the tall-tower network would provide considerable synergy, adding observations well beyond the height of the tower (Collier *et al.*, 2005). These are technologically demanding instruments to run, but expertise exists in the UK, for example at NPL, NERC FSF, Uni. Leicester, and STFC RAL. Aircraft platforms provide more direct in situ measurements (e.g., Polson *et al.*, 2011; Pitt *et al.*, 2019), and the capacity exists in the UK, for example at the NERC FAAM.[100] However the logistics limit operations to a campaign basis, unless commercial aircraft are used, and this has shown potential, for example, in Europe[101] and Japan[102].

Co-emitted tracers

12. A different approach to take is to measure one or more co-emitted gases and use their temporal or spatial variation to infer emissions of the GHG of interest. Examples of this include using carbon monoxide as a tracer anthropogenic carbon dioxide emission from combustion (Gamnitzer *et al.*, 2006), and using ethane as a tracer for anthropogenic CH_4 emissions (Ramsden *et al.*, 2022). There is considerable scope to extend this approach, using multiple tracers as constraints, and this may yield the high spatial and temporal resolution that we lack in the GHG measurements. For example, the TROPOMI instrument on-board the Sentinel satellite is now providing measurements of NO_2 and carbon monoxide at approximately 5-km resolution every few days. Both NO_2 and carbon monoxide act as tracers for CO_2 emission, the former particularly from the transport sector, the latter more generally from combustion. By estimating the ratios in which these are emitted from different sectors, we can infer CO_2 emissions at this higher spatial and temporal resolution.

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[99] http://www.tccon.caltech.edu/
[100] https://www.faam.ac.uk/
[101] https://www.iagos.org/
[102] http://www.cger.nies.go.jp/contrail/

High-resolution bottom-up activity data

13. By a similar logic, we can directly use bottom-up activity data where this is available with high spatial or temporal resolution. While atmospheric data lack detail about contributions from specific regions or sectors, they can be combined with prior emission data within a Bayesian framework, which allows us to combine these data and make inferences beyond those solely based on the atmospheric observations. Examples are in the energy and transport sectors, where we have high-resolution near-real-time activity data, but the emission factors are less well constrained. The combination of the bottom-up estimates and atmospheric measurements gives us greater precision and higher resolution on emissions from these sectors. This is on-going work in the NERC DARE-UK project.

Targeted measurements on point sources and urban areas

14. Another approach is to focus on spatial variations around a point source by using targeted measurements. These data can take the form of in situ ground-based measurements, aircraft-based measurements or satellite data. This approach makes use of the spatial variation in the GHG mixing ratio created by the point source, which typically takes the form of a Gaussian plume spreading downwind. If mixing ratio measurements can be made with appropriate spatial resolution, and some assumptions about the atmospheric transport, the source strength of the emission can be estimated (e.g., Super *et al.*, 2017). With improved portability of laser-based spectroscopic instruments and satellite data such as that from the TROPOMI instrument, this approach is becoming more widely used. Recent examples of this include CH_4 emissions from mines[103], landfill sites in the UK[104] and elsewhere in Europe[105], and offshore oil and gas platforms[106].
15. The more direct flux measurement method, eddy covariance, is not well-suited to measuring point sources, but has been shown to work successfully in urban environments. The potential sensitivity of this method has been demonstrated using the Covid-19 lockdown period in London and other cities across Europe.[107]

2.6.7 Policy areas with potential for near-real-time assessment using atmospheric measurements

16. Based on the above discussion, we consider the following policy areas, set out in the sections below, to have scope for using atmospheric data to inform progress and provide evidence of change more quickly than the current two-year inventory cycle. While these data could provide short-term evidence indicative of change, because of the background natural variability and aleatoric uncertainty, longer

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[103] https://meetingorganizer.copernicus.org/EGU21/EGU21-15693.html
[104] https://meetingorganizer.copernicus.org/EGU21/EGU21-8192.html
[105] https://meetingorganizer.copernicus.org/EGU21/EGU21-12518.html
[106] https://meetingorganizer.copernicus.org/EGU21/EGU21-9536.html
[107] https://www.icos-cp.eu/event/933

term monitoring over a number of years would still be required before drawing firm conclusions. Monthly resolution with a short time lag would be a practicable target in most cases. However, the most accurate estimates will still require bottom-up activity data, and this may be the limiting factor on the lag time and vary among sectors.

N_2O from agriculture

17. Variation in N_2O emissions from agriculture can be addressed at a monthly timescale. This is the topic of work ongoing in the UK NERC DARE project, which uses monthly resolution activity data on fertiliser and farm management practice. In combination with this, researchers are using atmospheric measurements of ammonia, which is co-emitted by many of the same processes as produce N_2O. Ammonia is measured on a country-wide network with monthly time resolution, providing much greater spatial coverage and detail than the N_2O measurements from the tall-tower network.
18. We can use this higher-resolution data to make inferences about the timing and location of N_2O emissions. This potentially allows us to infer spatiotemporal patterns i.e., how the temporal variation varies in space. In terms of specific policies, these observations could be used to examine the effectiveness of attempts to reduce fertiliser use and the efficacy of moving to different fertiliser types (e.g., from ammonium nitrate to urea), and the use of urease inhibitors. Recently, fertiliser prices have doubled since May 2020, and the ongoing effect of this strong incentive to optimise fertiliser use may be discernible in the data.

CO_2 from road transport

19. For several reasons, the road transport sector is well-suited to achieving higher levels of temporal resolution. Variations in CO_2 emissions from road transport can potentially be addressed at the monthly, weekly, and hourly timescales. The sector has a very well-defined spatial pattern (the road network), and a relatively well-quantified temporal pattern in activity data (from road traffic statistics and automated traffic counting data). Information from co-emitted tracers is available – NO_2 and carbon monoxide, and potentially other tracers, and these are measured both on the ground and by the TROPOMI satellite instrument. Although there are still some vagaries of the TROPOMI data, these species are some of the more reliable ones, and are available at high spatial and temporal resolution. Again, the combined data provides information over a much wider area than the tall-tower network, and potentially allows us to infer spatiotemporal patterns. In terms of specific policies, the ongoing move to electrification of road transport should become apparent in the data as its effect becomes more significant over time.

CO_2 from energy production and industry; CH_4 from offshore facilities

20. These areas are predominantly point source emissions, and therefore amenable to the targeted approach described above. The very large magnitude of emissions from power stations and major industrial plants (such as steelworks) makes these obvious targets, as they provide a large signal for measurement. This can potentially be combined with high-temporal resolution activity data in the energy sector. Offshore facilities present particular logistic challenges and are better suited to aircraft and satellite measurements.

CH_4 and N_2O from waste (landfill sites)

21. Landfill sites are not precisely point sources, given their typical areas, but are still amenable to the targeted approach described above. Given the smaller magnitude of emissions, these are less likely to be detectable by aircraft and satellite measurements, and more suited to higher precision ground-based measurements. There has been a strong policy move to capping landfill sites to prevent CH_4 release, and to harness the gas for bioenergy production where possible. The data would be suitable for assessing the efficacy of these measures at specific sites.

CO_2 from other transport - shipping

22. A recent study has demonstrated the potential to detect individual ships based on the NO_2 plumes in seen in TROPOMI data (Georgoulias *et al.*, 2020). Combined with high-resolution activity data from the AIS data, this can be used to constrain the spatial and temporal missions from a sector which is otherwise logistically awkward to measure. See also Section 2.2.4.

2.7 Question 7: What are the infrastructure requirements for increasing the role of measurements in tracking GHG emissions reductions?

2.7.1 Summary

We have reviewed the existing infrastructure for measuring atmospheric GHG concentrations in the UK. Long-term measurements of GHGs made by the DECC network[108] were established and subsequently supported by DESNZ. Further measurements and analysis have been developed and supported through the NERC projects GAUGE (Palmer et al., 2018) and DARE-UK.[109] The measurement infrastructure can be categorised as follows:

a. Long-term in-situ observations at remote locations on tall telecommunications towers;

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[108] http://www.bris.ac.uk/chemistry/research/acrg/current/decc.html

[109] https://dareuk.blogs.bristol.ac.uk/

b. Networks of in situ observations focusing on the local and urban scales;

c. Short term field campaigns targeting specific sources with mobile measurements (aircraft, uncrewed aerial vehicles (UAVs), ships, cars/vans);

d. Isotopic analysis of air samples to attribute emissions sources;

e. Ground-based remote sensing of total atmospheric column concentrations;

f. Space-borne observations of column concentrations (see Section 2.4 for more details).

To obtain emissions estimates at a regional to national scale these measurements are used in conjunction with atmospheric transport models that describe meteorology and atmospheric chemistry, and inverse methods. Emissions at a local or facility level derived from mobile measurements make use of dispersion models (e.g., the UK Met Office NAME model[110]) to map measured concentrations downwind of a source to the rate at which gases are emitted. These 'top-down' approaches are currently used to verify the UK's submissions to the UNFCCC, which are calculated using a 'bottom-up' method (Section 2.7.3, para 10). A sufficient spatial distribution of high-quality measurements, with a measurement footprint capturing most of the UK's emissions, is an essential component in the production of reliable emissions estimates.

To increase the role of measurements in tracking GHG emissions reductions, it is vital that this infrastructure receives continuous support, covering both maintenance and innovation of the measurement networks, over periods of decades to provide the long-term context for any future changes in the UK's emissions. A lot of the UK's GHG emissions verification is currently supported by relatively short-term research grants; this introduces the risk of introducing inconsistencies in the coverage and quality of the emissions verification networks, which would undermine the conclusions drawn from the observed long-term trends. Further investment in measurement infrastructure is necessary to better target emissions from specific sectors and from cities, as well as provide emissions estimates at regional scales or better.

Specific infrastructure requirements to increase the role of measurements:

a. Expansion of the existing DECC tall tower network to address the current lack of coverage in Scotland, the North of England, and the Midlands. As a minimum, this would require the establishment of two new sites to replace the spatial footprints formerly covered by the Angus (Scotland) and Bilsdale (Yorkshire) sites. Capability to measure tracer gases for source attribution (e.g., anthropogenic vs. biogenic) should be included in new sites and added to existing sites where they are not currently in place.

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[110] https://www.metoffice.gov.uk/research/approach/modelling-systems/dispersion-model

b. Establishment and maintenance of in situ measurement networks in cities to address the challenge of quantifying urban emissions and monitoring their trends. These should target the largest and most populous metropolitan areas that contribute the most emissions and can build on existing or previous projects (e.g., London, Glasgow).

c. In addition to improving our measurement infrastructure, it will be essential to implement data infrastructure to support this. A dedicated open access repository of data with common standards, formats, would ensure that maximum value is derived from the UK's GHG measurement infrastructure. This should incorporate GHG emissions and fluxes calculated from the measured atmospheric concentrations. Data should be made available on the repository in as timely a manner as possible and on a regular basis (at least annually for continuous emissions, up to daily for more sporadic emissions such as natural gas venting), to allow users to quickly identify changes in GHG concentration and emissions trends.

2.7.2 Existing measurement infrastructure in the UK

1. At the UK DESNZ funded DECC network sites (see Figure 4) (Stanley, Grant, O'Doherty, Young, *et al.*, 2018; Stavert *et al.*, 2019), high temporal frequency measurements of all major GHGs (CO_2, CH_4, N_2O, sulphur hexafluoride and a range of halocarbons) are made and these are situated in remote locations. This makes them highly suitable for determining background concentrations and inferring integrated emissions on a regional scale.
2. A number of research groups are making measurements of GHGs targeting specific sources, either by using portable gas analysers (e.g., those made by Los Gatos Research[111] and Picarro[112]) or by collecting air samples and analysing them for composition in a laboratory. To investigate city scale emissions, the NERC London GHG project lead by the University of Cambridge (Hoare *et al.*, 2020) is currently establishing a network of around 10 Picarro G2401 cavity ringdown spectrometers, which will provide high precision measurements of CO_2 and CH_4 concentrations across the city. A similar network was set up in Glasgow to coincide with COP26 (see the OpenGHG greenhouse gas data dashboard[113] for details).

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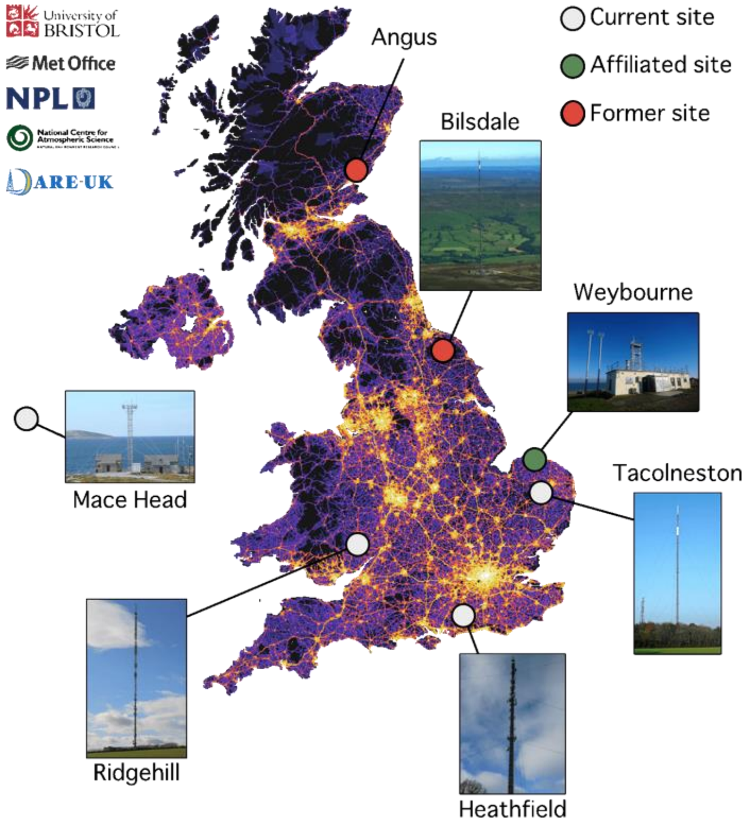
[111] http://www.lgrinc.com/analyzers/ultraportable-greenhouse-gas-analyzer/
[112] https://www.picarro.com/g2401_gas_concentration_analyzer
[113] https://openghg.github.io/dashboard/#/

Figure 4. Locations of the measurement sites that comprise the DECC network[114]



3. Portable gas analysers are also used on mobile platforms on a campaign basis to target specific emissions sources with spatially dense measurements on local to national scales. Platforms used for these targeted measurements include aircraft such as the Facility for Airborne Atmospheric Measurements[115] managed by NCAS (Pitt *et al.*, 2019), UAVs, (Shaw *et al.*, 2021), ships (Helfter *et al.*, 2019), and cars or vans (Maazallahi *et al.*, 2020).
4. Laboratory analysis of air samples for isotopic ratios helps to attribute emissions to sources. Observations of $\Delta^{14}CO_2$ can be used to estimate the contribution of fossil fuel emissions to atmospheric CO_2 concentrations, since emissions from fossil fuels do not contain $\Delta\,^{14}CO_2$ (Wenger *et al.*, 2019). Radiocarbon analysis of air samples has been performed during DARE-UK at the University of Bristol School of Chemistry[116]. Similarly, CH_4 sources are characterised by specific $\delta^{13}C\text{-}CH_4$ and $\delta D\text{-}CH_4$ signatures (Fisher *et al.*, 2017; Zazzeri *et al.*, 2017; Menoud *et al.*, 2022), so sufficiently high precision analysis of the stable isotopes of CH_4 (carried out in the UK by the Royal Holloway, University of London Greenhouse Gas Laboratory[117]) can be used to help improve our understanding of different source

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[114] http://www.bris.ac.uk/chemistry/research/acrg/current/decc.html
[115] https://www.faam.ac.uk/
[116] http://www.bristol.ac.uk/chemistry/facilities/brams/
[117] https://www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/earth-sciences/research/research-laboratories/greenhouse-gas-laboratory/

contributions to observed emissions (Rigby, Manning and Prinn, 2012; Röckmann *et al.*, 2016). In situ, high frequency, simultaneous high precision measurements of $\delta^{13}C$-CH_4 and $\delta^{2}H$-CH_4 are on the horizon (Rennick *et al.*, 2021).

5. Eddy covariance flux measurements have been made by the UK CEH from a site on top of the BT tower in Central London[118] since 2011 (Helfter *et al.*, 2016).
6. Measurements made by the DECC network and other instruments used throughout the GAUGE project are linked to a common calibration scale, to ensure comparability of these measurements with one another whilst also linking them with ongoing international GHG measurement activities (Palmer *et al.*, 2018), e.g., the NOAA / Earth System Research Laboratory GHG reference network, ICOS. All CO_2 and CH_4 measurements are linked to the appropriate WMO reference scale, through regular sampling of calibration standard gases as described in Stanley, Grant, O'Doherty, Di. Young, *et al.*, 2018.
7. As part of DARE-UK[119], a network of ground-based remote sensing instruments (Bruker EM27/SUNs, (Frey *et al.*, 2019)) which observe total atmospheric column GHG concentrations has been operational at three sites across London since April 2021 (sites operated by the NERC Field Spectroscopy Facility, FSF[120]). These instruments, which were funded and contributed towards the project by the NCEO[121], are less affected by very local sources than in situ sensors, so can be regarded as complementary to the in situ sensor networks and measurements described above. Their use in estimating urban emissions has been demonstrated for the cities of Munich (Dietrich *et al.*, 2021) and St. Petersburg (V. Makarova *et al.*, 2021), whilst they have proved to be useful for validating satellite observations and atmospheric reanalysis model outputs (e.g., (Tu *et al.*, 2020)).
8. More detail on currently operational satellite instruments which provide GHG total column concentrations over the UK is provided in Section 2.4.

2.7.3 Current role of measurements in tracking emissions reductions

9. Measurements of concentrations of GHGs in the atmosphere can be used in a 'top-down' approach to estimate emissions through regional scale inverse atmospheric modelling, which maps the relationship between the measured concentrations and the estimated emissions (the Inversion Technique for Emission Modelling: e.g., Ganesan *et al.*, 2015; White *et al.*, 2019; Lunt *et al.*, 2021; Manning *et al.*, 2021). Much of the measurement and data analysis framework that underpins these top-down emissions estimates for the UK was established during the NERC GAUGE project (Palmer *et al.*, 2018), and is being continued and expanded on through DARE-UK. The technique is used to provide

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[118] https://www.ceh.ac.uk/our-science/projects/bt-tower-london-uk-urban-atmospheric-pollution-observatory
[119] https://dareuk.blogs.bristol.ac.uk/
[120] https://fsf.nerc.ac.uk/
[121] https://www.nceo.ac.uk/

verification of UK GHG emissions, as described in the 'Long-Term Atmospheric Measurement and Interpretation of Radiatively Active Trace Gases' report to DESNZ.[122]

10. The 'bottom-up inventory' is referred to in more detail in Section 2.5.

2.7.4 Infrastructure requirements needed for increased role of measurements

11. To allow operational emissions tracking on regional scales or smaller, the existing DECC network of tall tower sites should be expanded with particular focus on Scotland, the North of England, and the Midlands. In the case of CH_4, Lunt *et al.*, 2021 have already shown that the current network has insufficient sensitivity to the northernmost parts of the UK when these measurements are used to estimate emissions at the level of the devolved administrations. This study also demonstrates the value of continuing support for the existing sites, in addition to continuing support for calibration efforts which allow the measurements from these sites to be used collectively in emissions estimates.
12. Breaking down emissions in cities by sector, region etc. would require the establishment of urban in situ measurement networks (e.g., Hoare et al., 2020) to provide the spatially resolved information required. An increased focus on urban emissions will also benefit from future satellite missions (CNES/UKSA MicroCarb[123] and Copernicus CO2M (Sierk *et al.*, 2021b)), which have been designed to make observations of GHG column concentrations at higher spatial resolutions than those achievable using existing satellite capability to address this requirement. Examples of similar networks and initiatives include BEACO2N[124] (Delaria *et al.*, 2021), which consists of a large number of low-cost sensors distributed across the San Francisco Bay area with 1km spacing between measurement locations, and the ICOS Cities project[125], which will initially focus on developing city-wide measurement networks in Paris, Munich and Zurich. These networks will incorporate a combination of tall tower sites, roof- and street-level in situ sensors, ground-based remote sensing and eddy covariance measurements. The project will tie in with the WMO Integrated Global Greenhouse Gas Information System (IG^3IS) organisation, which is currently developing a Best Research Practices document on Urban GHG Emission Observation.[126] The document, scheduled for release later in 2022, aims to provide technical guidance on current state of the art technologies in urban GHG information systems, along with some considerations for infrastructure requirements for each measurement system.

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[122] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/890579/verification-uk-greenhouse-gas-emissions-atmospheric-observations-annual-report-2018.pdf

[123] https://microcarb.cnes.fr/en/home-11

[124] https://beacon.berkeley.edu/about/

[125] https://www.icos-cp.eu/projects/icos-cities-project

[126] https://ig3is.wmo.int/en/events/ig3is-urban-greenhouse-gas-emission-observation-and-monitoring-best-research-practices

13. At present, estimates of GHG emissions from offshore oil and natural gas facilities are not routinely verified by measurement of atmospheric concentrations. This gap could be addressed through campaign-based measurements from aircraft (e.g., (France *et al.*, 2021), UAVs, or ships (e.g. Riddick *et al.*, 2019).
14. Measurement data delivered via NERC funded projects is currently archived by the CEDA[127], and in the case of the DECC tall tower network open access data is available for measurements taken up to the end of August 2020. To maximise the utility of GHG measurements made in the UK, regardless of method or platform, a dedicated open access repository of data with common standards and formats would save the effort needed to collate data from the range of sources discussed above. Data should also be made available in as timely a manner as possible and on a regular basis (at least annually for continuous emissions, up to daily for more sporadic emissions such as natural gas venting), to allow users to quickly identify changes in GHG concentration and emissions trends.
15. As discussed in Section 8, estimating or inferring GHG emissions from atmospheric concentration data also requires knowledge of the wind fields above and surrounding the region of interest. This is normally achieved by using an inversion model to revise emissions inventories based on observed atmospheric conditions, or by back trajectory analysis to determine origins of sampled air masses. Outputs from these analyses (GHG fluxes, ideally by sector) are of greater value to policymakers and other stakeholders than the measured concentrations. A platform for communicating and accessing the results of emissions estimates and analyses based on the observations (with traceability back to the original concentration data and clear, reproducible methodology) would ensure that maximum value is obtained from the investment in measurement infrastructure.
16. Evaluation of GHG emissions estimates is currently carried out by multiple bodies across the UK, who often have different priorities. As well as having a central platform for communicating estimated GHG fluxes, it is important that a consistent evaluation methodology and standard is applied to all estimates, along with equivalent standards applied to the measurements and models used to produce them.
17. Measurements of other gases which can act as tracers for different emissions sources should be added to existing sites (where they are not already in place) and included in any new sites, to aid with source attribution. Examples of these include atmospheric oxygen[128], carbon monoxide, nitrogen dioxide, ethane, and radon, all of which help distinguish anthropogenic from biogenic emissions.
18. Attribution of emissions to specific sectors can be improved by spatially targeted measurements close to a sample of sources within that sector. These could either be permanent sites, or temporarily set up on a regular (e.g., annual) campaign basis. There is also an opportunity for collaboration with

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[127] https://www.ceda.ac.uk/

[128] https://ueaeprints.uea.ac.uk/id/eprint/61979/1/Pickers_Penelope_2016_final_thesis.pdf

industry here where measurement campaigns are tied to mitigation efforts (for example, estimation of CH_4 emissions from natural gas infrastructure before and after a programme of pipeline repair and upgrade).

19. There is a further specific need to introduce measurement and modelling efforts to perform the challenging task of identifying emissions caused by land use change alongside those of other sectors resulting in direct emissions. For example, forest expansion and wetland restoration are two of the main means available to us for the removal of carbon dioxide from the atmosphere, so we need to be able to quantify the impact of these and similar mitigation measures.
20. The gap between the spatiotemporal scales covered by surface in situ measurements and satellite remote sensing could be filled by remote sensing instruments deployed on High Altitude Platforms (HAPS). Once tested and demonstrated, this new technology could enable continuous monitoring of GHGs and many other atmospheric and surface variables at a spatial and temporal resolutions on the order of metres and minutes. More relaxed restrictions on payload size and mass compared with satellite instruments mean that these sensors could offer comparable or superior spectral resolution to the conventional TIR and SWIR spectrometers deployed in space, therefore adding an accuracy benefit in addition to the improved spatial and temporal resolution compared with satellites.

3. Conclusions and recommendations

3.1 Overview

The UK was the first country in the world to establish a GHG measurement network to inform national GHG emission estimates reported annually to the UNFCCC. While the UK activity remains world-leading, it is no longer unique, with large-scale initiatives being developed across the world which take advantage of new technologies and techniques to build integrative measurement and modelling systems.

The UK science and technology communities have the expertise to evolve and improve the current system, to expand the volume and type of atmospheric GHG measurements being collected, to improve source attribution of emission estimates, to exploit new data to improve the resolution of GHG inventories, and to improve the integration of cutting-edge atmospheric models and estimation methods for GHG emissions.

To increase the role of atmospheric measurements in tracking UK progress towards reducing GHG emissions, it is essential that the measurement/modelling infrastructure receives continuous financial support on decadal scales. This investment will ensure the UK maintains its current baseline measurement and analysis capability, and help evolve this capability by adopting new technologies. This also ensures that the UK remains at the forefront of using atmospheric data to inform their knowledge of national annual GHG emissions.

The following list of immediate challenges and opportunities (within one to two years) are based on the literature review and inputs from stakeholder experts.

3.2 Immediate challenges

There are a number of immediate challenges associated with the compilation of the inventories, measurements, and analysis tools.

The bottom-up inventory is weakest (most uncertain) in the areas of LULUCF, waste management, and agriculture. The LULUCF sector raises problems for the top-down approach for CO_2 because of the large gross CO_2 fluxes which dominate the atmospheric signal, which are largely unrelated to anthropogenic impacts in the LULUCF sector. Before we begin the transition to the hydrogen economy as an approach to decarbonising the UK, there is a need to include molecular H_2 into the UK National Atmospheric Emission Inventory. While H_2 is not a direct GHG, it indirectly affects the lifetimes of atmospheric CH_4 and ozone.

The current surface measurement network is biased towards southern England, so that inferred emissions originating from northern England and from Scotland have larger relative uncertainties. The successful development of a network is constrained by the calibration, maintenance, and quality assessment infrastructure. Consequently, expanding the existing network will also require investment to ensure it meets world-class data quality standards. Measurement of the suite of halogenated GHGs is likely to continue requiring specialised equipment for the foreseeable future. However, improvements in robustness and reliability of hardware should allow these measurements to be scaled up under sufficient support.

Models of atmospheric transport are necessary for translating the atmospheric data into the flux estimates needed for the UNFCCC, and should be considered an integral part of the overall measurement system. These models effectively limit our ability to reduce uncertainties in posterior emission estimates. Development of inventories and expansion of the measurement network must be linked with a programme of model development to maximise the scientific return from the measurements.

3.3 Immediate opportunities

The key intersection where the bottom-up approach is weakest and atmospheric measurements have the most potential is the agriculture and waste management sectors. To a lesser degree, there is also scope to address emission uncertainties associated with the transport and domestic sectors. Improved emission estimates from point sources, which dominate the energy production and industrial sectors, requires targeted measurement and dedicated modelling.

In terms of the emission sectors for which atmospheric measurements have the most potential to immediately improve the temporal resolution of emission estimates, these include: N_2O from agriculture; CO_2 from road transport; CO_2 from energy production and industry; CH_4 from offshore facilities; CH_4 and N_2O from landfill sites; and CO_2 from shipping. A practical target would be monthly resolution with a short time lag, but this will still require knowledge of bottom-up inventory data for accurate source attribution, and that may be the limiting factor on the time lag.

Overall, different measurement platforms are best positioned to address different components of uncertainty in the UK NAEI. Here we collect the key points from the literature and stakeholder reports.

- Generally, the duration of measurement records for CO_2 and CH_4, collected as part of national networks, are beginning to be sufficiently long that they can be used to detect ongoing emission trends and to provide a test for national inventories. Consequently, it is essential the data records from the tall towers continue, eventually being enhanced by data collected at different locations and using different technologies.

- Current monitoring of atmospheric H_2 is limited, but UK measurements are needed to define the current UK background level, in the context of regional/global values, as we begin to enter the transitional period towards a hydrogen economy.
- Expanding the geographical coverage of the surface measurement network would allow better quantification of regional emissions across the UK, particularly over northern England and Scotland.
- Incorporating frequent or continuous CH_4 isotopologues measurements (e.g., $\delta^{13}CH_4$) and/or measurements of trace gases co-emitted with CH_4 from individual sectors (e.g., ethane) into the UK DECC network would further improve the differentiation of individual CH_4 source sectors, particularly diffuse fugitive sources from energy and industry.
- Generally, co-locating measurements of atmospheric GHGs and air quality trace gases co-emitted with GHGs, such as carbon monoxide, ethane, and O_2, will improve source attribution of atmospheric GHGs. Some of these additional gases will require more specialised measurements but scaling-up measurements across the network is possible with sufficient supporting infrastructure.
- Ground-based remote sensing represents a new technology that provides complementary information to the tall tower measurements. Deployment of this technology is now possible due to the UK development of an automated weather-proof enclosure. Establishing a network of these sensors will help unlock the information collected by Earth-orbiting satellites, which use a similar measurement technique.
- Lower cost sensors for atmospheric CO_2 are already being deployed across several cities. Although the precision of these devices is relatively low, the density of deployment and novel methods to network the measurements could allow for a useful understanding of emissions at the city scale.
- The power of satellite observations lies in their ability to provide spatially and temporally resolved measurements of atmospheric CO_2 and CH_4 concentrations globally which provide a strong constraint on the net exchange between the surface and the atmosphere determined by natural and anthropogenic processes. The next generation of satellite technology, with improved sensors and better spatial resolution, is anticipated to play a larger role in estimating emissions on spatial scales less than 100 m. This capability complements information that satellites already provide on (sub) national spatial scales.
- Long-term monitoring of offshore oil and gas emissions may be difficult to establish due to the offshore location, weak signal at existing DECC network sites, and difficulty in isolating

emissions from the UK or other nations' sections of the North Sea. A network design modelling study is needed to develop onshore measurement sites along the eastern coast of the UK that are routinely sensitive to North Sea oil and gas CH_4 emissions.

3.4 Recommendations on next steps

Based on evidence gathered during the desk-based research exercise reported here, feedback shared by key stakeholders during a targeted survey and workshops in late 2021, early 2022, and via feedback received from DESNZ, a series of high-level overarching recommendations are made below highlighting six key areas in which action should be prioritised. They represent high-level recommendations that integrate individual points raised throughout the study. These areas will support the UK Government to further enhance the accuracy and completeness of the UK's GHG inventory. This will help ensure the inventory maintains its position at the leading edge of research in using atmospheric data to verify and quantify GHG emissions.

These key overarching recommendations are complemented by further guidance with respect to each of the seven key questions answered within this study provided in Section 5.2, Annex 2.

1. **Maintain baseline monitoring capability for UK GHG emission estimates and nurture new instrument and computational technologies that will eventually improve the baseline capability.**

    - Enable the UK to remain at the forefront of reporting GHG emissions by establishing an R&D programme of periodic review and updates of measurement and computational technologies, focused on demonstrable improvements to emissions estimates and uncertainties.
    - Expand the measurement network of GHG isotopologues to improve our ability to quantify GHG emissions from individual sectors. Online measurement systems for GHG isotopologues, currently in various stages of development will improve the frequency of measurements, speed up analysis, and reduce human overhead.
    - Unlock the information collected by Earth-orbiting satellites by establishing a network of ground based GHG (CO_2 and CH_4) remote sensing technologies that complement information to traditional in situ data collected by the UK DECC network.
    - Prepare for next-generation satellite GHG (CH_4 and eventually CO_2) remote sensing technologies that provide sufficient sensitivity on spatial scales (<100s metres) comparable to emission inventories. Except for private satellites, most of these data will be freely available to use, e.g., Copernicus.

- Develop a coordinated activity to harmonise GHG information collected by different measurement technologies, including calibration and uncertainties. This will ensure that the UK takes advantage of baseline and emerging technologies that helps to future-proof the resulting Measurement Reporting and Verification (MRV) scheme.

2. **Develop new and existing computational tools that are necessary to translate atmospheric data into emission estimates and uncertainties.**
    - Agree a set of atmospheric model performance metrics suitable for core UK reporting activities associated with the UNFCCC and inter-compare performance of candidate model tools.
    - Develop a quality assurance framework to enable transparent reporting of emission estimates and uncertainties and agree on a set of uncertainty metrics that are most useful for core reporting activities.
    - Improve atmospheric transport models, which describe the relationship between emissions and atmospheric measurements. Currently, these tools effectively limit our ability to reduce uncertainties in posterior emission estimates. Deliberate release experiments (in which a gas is emitted at a known release rate and sampled at various downwind locations) is one approach to directly assess model transport errors but must be linked with a programme of model development to maximise the scientific return of the experiments. An international research programme is more appropriate than a UK-led activity.
3. **Improve UK colocation of GHG and air quality measurements to improve emission estimates for individual source sectors.**
    - Collocate air quality (AQ) and GHG measurements to take advantage of co-emission from different sectors, e.g., ammonia from agriculture, carbon monoxide and nitrogen dioxide from combustion. Consequently, interpretation of GHGs with AQ gases can help isolate the influence of a particular sector on observed atmospheric GHGs.
4. **Improve availability of higher temporal resolution inventory estimates to improve the interpretation of high-frequency atmospheric measurements that are used to infer annual emission estimates reported by the UK to the UNFCCC.**
    - Refinement of temporal and spatial scales of emissions inventories will improve the veracity of annual measurement-based GHG emission estimates. The focus of MRV schemes is primarily on reporting annual emissions but interpreting the corresponding atmospheric data (available on timescales < 1 hour) requires knowledge of emissions and meteorology on much finer spatial and temporal scales.

- Use proxy data (e.g., economic activity data, weather data, traffic flow data related to emission data) to help temporally disaggregate annual inventory estimates.

5. **Extend the existing UK measurement/analysis system to integrate inventory compilation, different measurement types, and top-down emission estimation methods to improve posterior estimates and uncertainties.**

    - Co-develop inventories and analysis schemes, particularly associated with characterising uncertainties, so the inventory data can be exploited more effectively by emission estimation methods.

    - Develop flexible (and scalable) emission estimation methods that can take advantage of new and emerging measurement technologies and their uncertainties.

6. **Engage early on with the private sector to collect and deliver baseline monitoring measurements and to establish an open and accessible data repository.**

    - Enable private sector vendors to collect and deliver baseline in situ observations and potentially to deliver core emissions data products. Similarly, explore the value of private sector satellite data to help further develop the baseline service. This approach evolves from the current *ad hoc* MRV that is being delivered by private, Government, and higher education sectors, and potentially frees up researchers to focus on R&D activities to eventually feed into the baseline service (see point 1). However, there would have to be a clear business case for what is essentially a public goods service, with perhaps the profitable business associated with developing and delivering downstream services.

    - Ensure a priority focus on reporting transparency and independence of commercial interests, with core data products freely available to government and public.

    - Establish an open and accessible data store (one-stop-shop) to improve transparency and information sharing. This is consistent with open and smarter Government initiatives. Storing all relevant (harmonised) data in one place helps to streamline GHG researcher activities, and also allows third parties to develop downstream services that contribute to the wider green economy.

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5. Annexes

5.1 Annex 1 List of stakeholder organisations consulted

Medium	Organisation
Survey only	GHGSat
	Rothamsted Research Sustainable Soils and Grassland Systems Department
Workshop only	Environmental Defense Fund & Royal Holloway University
Survey & Workshop	Defra
	Met Office
	NPL
	Space4Climate
	University of Bristol
	University of Manchester
	Cranfield University
	Royal Holloway, University of London
	UKRI-STFC / NCEO

In addition to the stakeholders in the table above, there were two survey respondents from universities and one from a research institute who requested to remain anonymous.

5.2 Annex 2 Supporting guidance for specific research questions

The following points were identified through the stakeholder workshop and research review as opportunities that can be taken forward in relation to each of the specific research questions.

Question 1: What is the current landscape of activity on verification in the UK and internationally, and what has the impact of the activity been on understanding the accuracy of greenhouse gas (GHG) inventories and assessing whether emissions reductions are leading to the anticipated reductions in atmospheric concentrations?

- Take steps to combine different measurement streams, making better use of what is already available.
- Define what outputs are needed from the inventory to inform measurements and modelling and vice versa to facilitate learning on both sides.
- Consider setting up a new umbrella organisation, e.g., Centre for GHG emissions measurements, that links everything together and support collaboration.
- A funding mechanism is needed to bridge the gap that is currently new uncertain science (but not innovation) that is currently neither funded by DESNZ nor NERC.
- Support private involvement to facilitate expansion of the network but with the understanding that this should be academically led / verified.

Question 2: To what extent could improving atmospheric monitoring capability fill important gaps in knowledge and help reduce uncertainties in the inventory, including in offshore oil, gas and shipping emissions, diffuse emissions from the waste, agriculture and LULUCF (land use, land-use change and forestry) sectors, and diffuse fugitive sources of CH_4 and H_2 from energy and industry?

- Further investigate the potential of inferring emissions onshore from offshore O&G emissions and/or explore measurements offshore, such as disused rigs and ferries – note that this should only be done following modelling work which could suggest what kind of data these locations could provide.
- Encourage buy-in from the O&G industry to progress towards measurement-based reporting, potentially under the UNEP O&G Methane Partnership (OGMP) v2.0 framework.
- Conduct more research into smaller scale measurement studies to aid with differentiating between CH_4 emissions from waste and agriculture or LULUCF CO_2 fluxes and evaluating associated emission factors.

- Develop and improve atmospheric chemistry transport models to better account for the sinks of H_2 to allow more accurate evaluation of H_2 sources in future.

Question 3: What is the current technological capability, and what is the likely future capability in the medium-term (i.e., next five years) and long-term, for monitoring GHGs in line with policy needs?

- Due to the high cost of purpose-built structures, the focus should be on repurposing existing sites
- There is a need for research into source signatures on tracers other than the ones that are already well-understood, such as ethane for CH_4.

Question 4: What role could remote sensing play in the verification of estimates of GHG emissions and removals, and for which GHGs/sources does remote sensing data already have the capacity to calibrate/inform emissions estimation methods?

- Look into upward looking systems to get around challenges of cloud cover preventing data resolution.
- Exploit multiple systems of satellite and in situ data to combine datasets and improve data quality.
- More research is required to establish methods of area mapping and point sources in the process of validation.
- More investment is needed to get tools that meet capabilities and requirements as well as demonstrating how to use these tools.
- Tools have been tested at the pilot stage, so more research should be conducted to establish them and make operational. Pulling a best practice depository could be useful.
- Look into the prospect of a different class of platform for remote sensing such as high-altitude platforms.

Question 5: Which areas of policy interest are best-served by bottom-up inventory approaches, and where might atmospheric measurements, in the longer term, be able to support emission estimates?

- If there is a policy to expand operations in the North Sea, including CCS CO_2 reservoirs, efforts focused on monitoring of leakage will be required.

- Reconciling different classification systems used in the inventory would help in resolving sector-specific emissions. (e.g., producing national totals and maps in the same classification system in the inventory data).
- More information about waste going to landfill and how the waste is managed would improve the accuracy of emissions estimates and support further mapping exercises within the waste sector.

Question 6: Could atmospheric measurements enable tracking of the effectiveness of specific policies in near real time, and what are the levels of temporal, spatial and sectoral resolution required?

- Higher-frequency (~hourly) bottom-up estimates are needed to interpret atmospheric measurements, even if not a policy requirement.
- The sector-specific temporal-spatial signals provide an under-utilised means of interpreting the data to achieve sectoral resolution.
- Seek to quantify uncertainties of emission estimates spatially and temporally to provide a inputs more useful to atmospheric modellers.
- Further work should be conducted to reduce transport model error.
- More research needs to be done both regarding the meteorological input to atmospheric transport model and the use of the meteorological data within the model.

Question 7: What are the infrastructure requirements for increasing the role of measurements in tracking GHG emissions reductions?

- Assistance from the Government in getting data and buy in from industries emitting measurable gases would be beneficial as this would allow for significant improvements to models in terms of distances and timescales.
- A one-stop-shop would be of value with respect to data provision, having a central repository for UK GHG measurements which are also accessible visually.

6. GLOSSARY OF TERMS

AGAGE	Advanced Global Atmospheric Gases Experiment. AGAGE measures the composition of the global atmosphere. It has the capability to measure most of the important gases in the Montreal Protocol (e.g., CFCs and HCFCs) and most of the non-CO_2 gases in the Kyoto Protocol (e.g., HFCs, CH_4, and N_2O) to protect the ozone layer and mitigate climate change.
AIS	Automatic Identification Systems. AIS use transceivers on ships for a variety of analytical uses, including to estimate GHG emissions of ships (NO_x, SO_x, and CO_2)
ANSTO	Australian Nuclear Science and Technology
ARGONAUT Project	Pollut**A**nts and g**R**eenhouse **G**ases emissi**O**ns mo**N**itoring from sp**A**ce at high Resol**UT**ion. AGRONAUT applies atmospheric inversion to provide a new estimate of anthropogenic emissions of the main air quality pollutants (NO_x, CO and NMVOCs) and CO_2 in France at 10 km resolution.
AURN	Automatic Urban and Rural Network (Defra). AURN is the largest automatic monitoring network in the UK and the main network used for Ambient Air Quality Directives compliance reporting. It includes automatic air quality monitoring stations measuring oxides of nitrogen (NO_x), sulphur dioxide (SO_2), ozone (O_3), carbon monoxide (CO) and particles (PM_{10}, $PM_{2.5}$).
$BEACO_2N$	Berkley Environmental Air-quality and CO_2 Network. $BEACO_2N$ uses a dense network of sensors ('nodes') which are located ~1 mile from each other. The sensors are less precise than traditional ones but create a detailed map of pollutants and CO_2 due to the dense sensor coverage.
DESNZ	Department for Energy Security and Net Zero
Biogenic	Produced or brought about by living organisms
BIOMASS	The first spaceborne P-Band radar mission to determine the worldwide distribution of above-ground forest biomass, changes in forest biomass, and the role they play in the carbon cycle. BIOMASS is a mission of the ESA.
Bottom-up emission estimate/ inventory	An approach utilising locally collected activity data and emission factors to estimate GHG emissions
BTH region	Region in China made up of Beijing, Tianjin and Hebei
C_2H_6	Ethane
Carbonmapper	Project monitoring CO_2 and CH_4 emissions using remote sensing technology. The data is then used to, for example, detect leaks in natural gas pipelines, inform landfill gas management, and move towards comprehensive carbon accounting.
CCL	Central Calibration Laboratory. The CCL is run by the WMO and GAW and provides calibration services for CO_2, CH_4, N_2O, SF_6, and CO.
CEDA	Centre for Environmental Data Analysis. The centre supports the environmental science community by providing the CEDA data archive, a supercomputer (JASMIN), and participation in a wide range of research projects.
CEOS	Committee on Earth Observation Satellites. CEOS promotes data exchange and supports the international coordination of civil space-based Earth observation programs. The working groups address a variety of topics such as capacity building, disaster management, climate, calibration, validation, and data processing standards.
CFC	Chlorofluorocarbon
CH_4	Methane
CHE	CO_2 Human Emissions project. CHE is a European initiative to separate the human impact from the natural carbon cycle. The project consortium consists of 22 European partners from the United Kingdom, Germany, Sweden, Norway, Italy, the Netherlands, France, and Switzerland.
CNES	Centre national d'études spatiales (French government space agency)

CNES/DLR MERLIN	MEthane Remote sensing LIdar mission by CNES (French Space Agency) and DLR (German Space Administration). MERLIN's key objective is to determine spatio-temporal gradients of atmospheric CH_4 columns.
CO	Carbon monoxide
CO_2	Carbon dioxide
CO2M	Copernicus Anthropogenic Carbon Dioxide Monitoring mission. CO2M is a satellite mission by the ESA in collaboration with the European Commission (EC) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) with the goal to measure the anthropogenically driven release of CO_2 into the atmosphere.
CO2-MEGAPARIS	Project with the aim to quantify the CO_2 emissions in Paris using a top-down approach.
CO2MVS	European anthropogenic CO_2 emissions Monitoring and Verification Support capacity. CO2MVS is part of the Copernicus Atmosphere Monitoring Service (CAMS) and coordinated by the European Centre for Medium-Range Weather Forecasts (ECMWF). The overarching objective of CO2MVS is to support the Paris Agreement's parties with measuring their progress towards their climate mitigation objectives by combining ground-based and satellite observations with computer modelling.
COCCON	COllaborative Carbon Column Observing Network. This network was established by the Karlsruhe Institute of Technology (KIT) from a need for a common standard for GHG measurements using the EM27/SUN spectrometer. More specifically, COCCON covers the definition and maintenance of instrumental standards, performance verification, a shared method of data processing, and data dissemination to the user community.
CoCO2	Project coordinated by the European Centre for Medium-Range Weather Forecasts (ECMWF) with the overarching objective to monitor the anthropogenic impact on CO_2. It further builds the prototype systems for CO2MVS and builds on the CHE and VERIFY projects.
COP21	UNFCCC Conference of the Parties 21, 2015 Paris
Copernicus Programme	EU's Earth Observation Programme. Its outputs draw from both satellite and in-situ data. The Copernicus Programme is managed by European Commission and implemented in partnership with the member states, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), EU Agencies, the ESA, the European Centre for Medium-Range Weather Forecasts (ECMWF), and Mercator Océan.
CRDS	Cavity Ring-Down Spectroscop
CRF	Common Reporting Format
DARE-UK	Detection and Attribution of Regional greenhouse gas Emissions in the UK. The key objective of DARE-UK is to "design and deliver a more coordinated national data research infrastructure for the UK". DARE-UK is funded by UKRI.
DECC	Deriving Emissions linked to Climate Change. DESNZ funded measurement network of four sites in the UK and Ireland measuring greenhouse and ozone depleting gases from tall telecommunication towers
DIAL	Differential Absorption Lidar
EDF	Environmental Defense Fund
EDGAR	Emissions Database for Global Atmospheric Research. A multipurpose, independent, global database of anthropogenic emissions of greenhouse gases and air pollution on Earth developed by the JRC, part of the EU
EMPA	Swiss Federal Laboratories for Materials Science and Technology
ESA	European Space Agency
ESA FLEX	European Space Agency FLuorescence Explorer mission, providing global maps of vegetation fluorescence. One key objective is to better understand how carbon moves between plants and the atmosphere and how carbon and water cycles are affected by
$ffCO_2$	fossil fuel component of atmospheric CO_2.
FID	Flame Ionisation Detector

FRM4GHG	Fiducial Reference Measurements for Ground-Based Infrared Greenhouse Gas Observations. Funded by the ESA, this project focuses on the intercomparison of instruments and harmonization of retrievals and products from collocated new and established GHG observation ground based Infrared instrumentations to get Fiducial Reference Measurements (FRMs) for GHGs.
FTIR	Fourier-Transform Infrared Spectroscopy
GAUGE	Greenhouse gAs UK and Global Emissions Project, funded by the Natural Environment Research Council (NERC) under the Greenhouse Gas Emissions and Feedback Programme. GAUGE's key objective was to provide improved GHG inventories and predictions for the UK, and for the globe at a regional scale.
GAW	Global Atmospheric Watch. A programme by the WMO that organises, participates in and coordinates global assessments of the chemical composition of the atmosphere.
GC	Gas Chromatography
GC-ECD	Gas Chromatography-Electron Capture Detector
GC-MS	Gas Chromatography-Mass Spectrometry
GCOS	Global Climate Observing System. Established in 1992, GCOS regularly assesses the global climate observations of the atmosphere, land, and ocean. GCSO is co-sponsored by the WMO, the United Nations Environment Programme (UN Environment), the International Science Council (ISC), and the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO).
GEO	Group on Earth Observations. GEO is a partnership of over 100 national governments and participating organisations, forming a global network to connect a variety of stakeholders (such as national governments, research institutions, businesses). The GEO community is creating the Global Earth Observation System of Systems (GEOSS) with the aim to improve the integration of observing systems and data sharing.
GHG	Greenhouse Gas
GHGSat	Aerospace company which specialises in the monitoring of GHG emissions using satellite data.
GML	Global Monitoring Laboratory, part of NOAA, conducts research on GHG and carbon cycle feedbacks, changes in clouds, aerosols, and surface radiation, and recovery of stratospheric ozone.
GOSAT	Greenhouse gases Observing SATellite. GOSAT was developed by Japan and monitors CO2, CH4, Ozone, and water vapor. Launched in 2009.
GOSAT-2	Greenhouse gases Observing SATellite 2. Monitors CO and NO2 in addition to what GOSAT monitors. Launched in 2018.
GOSAT-GW	Global Observing SATellite for Greenhouse gases and Water cycle
H_2	Hydrogen
H2020	Horizon 2020, EU's research and innovation funding programme from 2014-2020. Succeeded by Horizon Europe.
HFC-125	Pentafluoroethane, used as a refrigerant and as a fire suppression agent in fire suppression systems
HFC-134a	Tetrafluoroethane, used in refrigeration and air conditioning systems, as a blowing agent for polyurethane foams, and as a propellant for medical aerosols
HFC-23	Fluoroform, greenhouse gas with no ozone-depleting effects
HFCs	Hydrofluorocarbons are potent greenhouse gases that were first subjected to emission reductions in the Montreal Protocol because of their role in stratospheric ozone depletion.
HMG	Her Majesty's Government
Horizon Europe	The current EU research and innovation funding programme, replacing H2020.
IASI	Infrared Atmospheric Sounding Interferometer, a hyperspectral infrared sounder on the ESA's MetOp series of polar orbiting satellites. (Ended operations in 2021)

IASI-NG	Infrared Atmospheric Sounding Interferometer - Next Generation is a key payload element of the second generation of European meteorological polar-orbit satellites (METOP-SG) dedicated to operational meteorology, oceanography, atmospheric chemistry, and climate monitoring.
ICOS	Integrated Carbon Observation System. ICOS has over 140 measurement stations across 14 European countries which provide standardised, open data.
IG3IS	Integrated Global Greenhouse Gas Information System. IG3IS ascertains trends and distributions of GHGs in the atmosphere and analysis whether these are consistent with efforts to reduce GHG emissions.
INFLUX	The Indianapolis Flux Experiment. INFLUX aimed to develop and evaluate methods to measure and model urban CO_2 and CH_4 fluxes.
INSTAAR	Institute of Arctic and Alpine Research (Colorado, USA)
InTEM	Inversion Technique for Emission Modelling
INVERSE-KOREA	South Korea's integrated observation-modelling system
IPCC	Intergovernmental Panel on Climate Change
IRMS	Isotope Ratio Mass Spectrometry
Isotopologues	Chemical species that differ only in the isotopic composition of their molecules or ions
ITMS	Integrated GHG Monitoring system for Germany, aimed at improving the monitoring of CO_2, CH_4, and N_2O.
Lidar	Light Detection And Ranging, surveying method providing a 3D representation of the environment
LULUCF	Land Use, Land Use Change and Forestry
Meteotest	Swiss company in weather, climate, environment and computer science
MethaneSat	Satellite programme monitoring methane emissions from oil and gas operations around the world, with the target to provide regular monitoring of regions accounting for more than 80% of global oil and gas production.
MicroCarb	French-UK climate change satellite mission dedicated to measuring sources and sinks of carbon. MicroCarb is due to launch in December 2022.
MRV	Measurement, Reporting, and Verification
MS	mass spectrometry
MVS	Measurement Verification Support
N_2O	Nitrous oxide
NAEI	UK National Atmospheric Emissions Inventory
NASA GeoCarb	Geostationary Carbon Observatory. GeoCarb is a satellite mission by NASA which, building on OCO-2, has the objective to monitor plant health and vegetation stress throughout the Americas, and to probe the natural sources, sinks and exchange processes that control CO_2, CO and CH_4 in the atmosphere.
NCAS	National Centre for Atmospheric Science (UK)
NCEO	National Centre for Earth Observation (UK)
NDC	Nationally Determined Contribution
NERC	Natural Environment Research Council (UK)
NERC FAAM	NERC Facility for Airborne Atmospheric Measurements
NERC FSF	NERC Field Spectroscopy Facility
NRF	Nomenclature for Reporting
NIWA	National Institute of Water and Atmospheric Research (NZ)
NO_2	Nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration (USA)
NOAA/ESRL	NOAA Earth System Research Laboratory
NO_X	Nitrous oxides
NPL	National Physical Laboratory (UK)

NRT	Near-Real-Time
O_2	Oxygen
OCO-2	Orbiting Carbon Observatory-2 (satellite). OCO-2 was launched in 2014 with the purpose to measure atmospheric CO_2.
OCO-3	Orbiting Carbon Observatory-3 (satellite). OCO-3 was launched in 2019 with the purpose to measure daily variations in CO_2.
PDD	Pulse Discharge Detector
PRISMA	Swedish-led technology mission to demonstrate formation flying and rendezvous technologies (in-orbit servicing). PRISMA is funded by the Swedish National Space Board (SNSB) and receives contributions from the DLR, the Technical University of Denmark (DTU), and CNES.
RHUL	Royal Holloway University of London
Ruisdael Observatory	National atmospheric network for the Netherlands
SAM	Snapshot Area Map
SCIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY. SCIAMACHY was an imaging spectrometer on board the Envisat mission. Its primary objective was to perform global measurements of trace gases in the troposphere and in the stratosphere.
Sentinel 5	Atmospheric monitoring mission within the European Copernicus program (formerly GMES)
Sentinel-2	Earth observation mission from the European Copernicus Programme
Sentinel-4	Earth observation mission from the European Copernicus Programme
SF_6	Sulphur hexafluoride
SIC	Standard Industrial Classification
SIF	Solar Induced Fluorescence
SNAP	Selected Nomenclature for sources of Air Pollution
SO_2	Sulphur dioxide
STFC/RAL	Science and Technology Facilities Council/Rutherford Appleton Laboratory
Tansat-2	Constellation of satellites aimed at monitoring anthropogenic CO_2 and CH_4 emissions (China)
TCCON	Total Carbon Column Observing Network
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, Netherlands Organisation for Applied Scientific Research
Top-down emission estimate/inventory	An approach using an atmospheric understanding to quantify emission estimates. Data would likely be measured at high spatial and temporal resolution via networks of ground-based stations and aircraft
TROPOMI	TROPOspheric Monitoring Instrument (satellite)
UAV	Uncrewed Aerial Vehicle
UK CEH	UK Centre for Ecology & Hydrology
UKSA	UK Space Agency
UNFCCC	United Nations Framework Convention on Climate Change
UNFCCC-SBSTA	UNFCCC's Subsidiary Body for Scientific and Technological Advice
VERIFY	Research and Innovation project funded by the European Commission under the H2020 programme
VUV	Vacuum Ultraviolet Spectroscopy
WGIC	World Geospatial Industry Council
WMO	World Meteorological Organisation
WMO/GAW	World Meteorological Organization Global Atmosphere Watch
Worldview-3	Imaging and environment-monitoring satellite (USA)
XCO_2	Column integrated CO_2