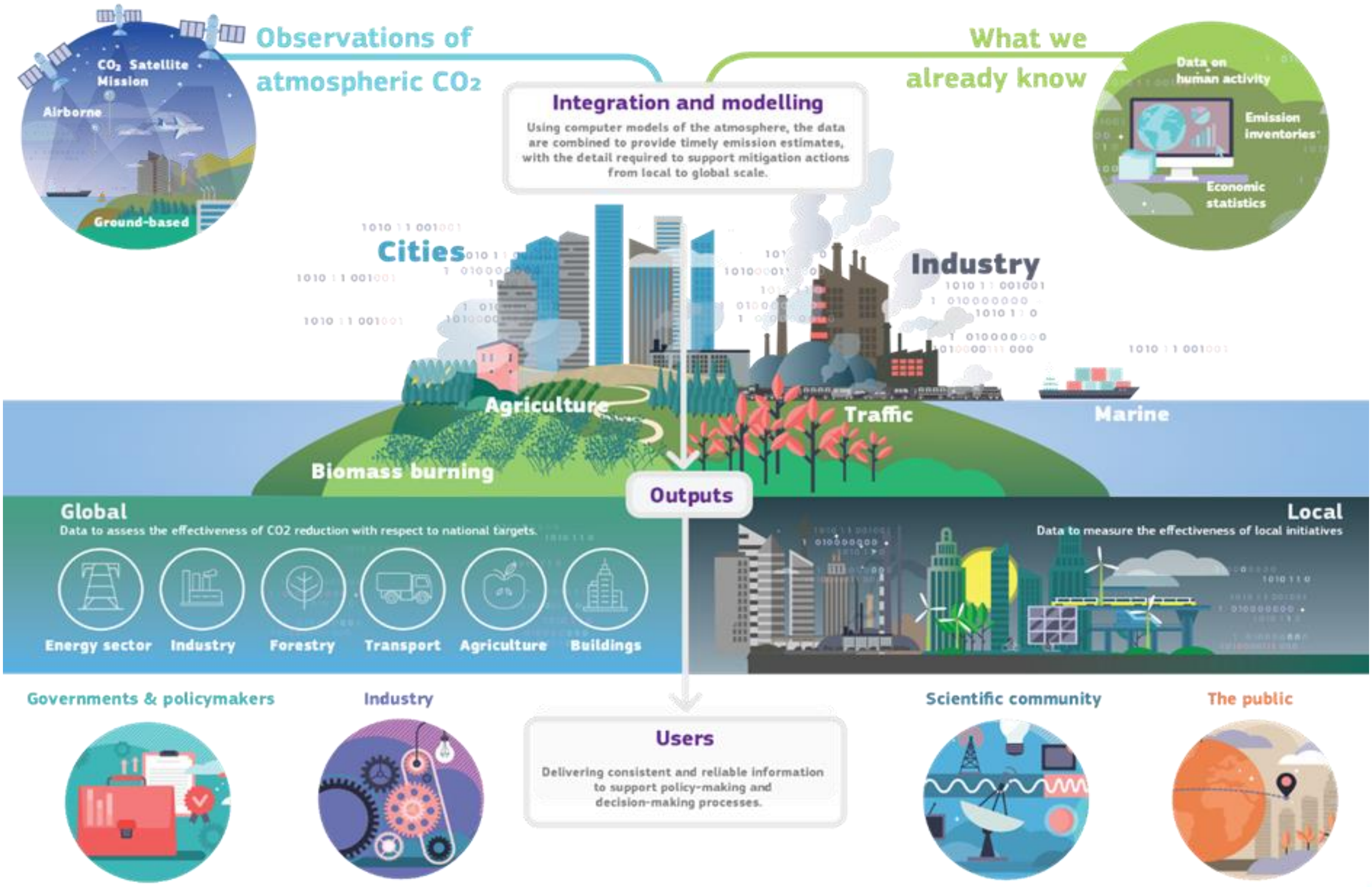
ETC/CME Eionet Report | 4/2021

Inverse modelling as a tool to support national greenhouse gas monitoring in Europe

December 2021



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European Topic Centre on Climate change mitigation and energy

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The diagram on the cover of the report is provided by Copernicus/EC/ECMWF, and schematically reflects the Copernicus anthropogenic CO_2 emissions monitoring and verification support capacity (CO2MVS)

More information on the European Union is available on the Internet (http://europa.eu).

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Acknowledgements

This report was prepared on request by the European Environment Agency (EEA) by its European Topic Centre on Climate change Mitigation and Energy (ETC/CME). The ETC/CME is a consortium of European institutes assisting the EEA to support European Union (EU) policy in the field of air pollution and climate change mitigation.

Paul Ruyssenaars (ETC/CME) and John van Aardenne (EEA) ensured the coordination of this report. The authors were, in alphabetical order: Richard German (Aether), Bradley Matthews (UBA-Vienna), and Paul Ruyssenaars (RIVM). John van Aardenne and Peter Iversen (EEA) reviewed the report.

The task team is grateful to all inventory compilers taking part in the online questionnaires and follow-up interviews. The team furthermore thanks the invited speakers and participants from the respective inventory and inverse modelling communities that attended the dedicated webinar that was held in November 2021.

Executive summary

Key messages:

- Inverse modelling (IM) integrates *prior* information on emissions and fluxes within a framework containing inter alia atmospheric transport and chemistry models and observations of atmospheric greenhouse gas and air pollutant concentrations. Through an optimization procedure (that is sensitive to the uncertainties within the IM framework), the prior emissions and flux estimates are constrained so that an acceptable agreement between the simulated and observed atmospheric concentrations is achieved.
- IM represents a potentially useful tool to support national emissions monitoring by providing pseudo-independent estimates of emissions and fluxes that can be compared with inventory estimates to validate and/or improve national emissions inventories.
- Currently, only Switzerland and the UK (former EEA member country) implement IM and report in the inventory IM comparisons in their National Inventory Reports. However, scientific research and development (e.g. the H2020 projects CHE and VERIFY and the Horizon project CoCO2) is allowing IM to mature and could lead to operational applications within other national emissions monitoring systems.
- IM data products will emerge from the Copernicus Atmospheric Monitoring Service (CAMS) and these products will supported by a dedicated User Uptake component. Contact with inventory compilers of the EEA member countries furthermore revealed that European national inventory teams are following developments on IM. Some representatives furthermore indicated initial plans to utilize emerging IM data products while a couple of countries indicated that respective national IM systems could be developed in the future.
- A webinar was organised to allow inventory compilers of EEA member countries to exchange perspectives and initial plans on IM and share these thoughts with scientists and experts working on IM. Inventory compilers communicated general issues and concerns on IM uncertainties at the national scale as well as fundamental differences between the surface-atmosphere fluxes estimated by IM and the emissions and removals estimated by inventories. For instance, the Land Use, land-Use Change and Forestry sector (LULUCF) was highlighted as an area of national inventories where uncertainties are large. However, concerns were raised over the utility of comparisons against IM estimates of land-based biogenic CO_2 fluxes due to fundamental differences between LULUCF carbon stock changes and the land-surface exchange of CO_2.
- Further and intensified communication between the respective inventory and IM communities is thus recommended. Given its network of contacts and connections to both experts working on national emissions inventories and experts working on IM, EEA is well positioned to facilitate enhanced communication between the two communities.

In the context of the workplan for 2021, ETC/CME was asked by EEA to provide support in stocktaking in the area of science as well as developments at the EU MS/ EEA country level (and UK) related to use of atmospheric GHG measurements and inverse modelling frameworks to support independent assessment of greenhouse gas emission inventories.

Deliverables in the course of 2021 were:

1) A **technical note**. ETC/CME has assessed science developments related to the use of atmospheric GHG measurements and inverse modelling frameworks over the past decade, starting with the recommendations in the ETC/ACM report 2011/13: *GMES Services and Emission Inventories.* This technical note summarises the findings of this stocktaking exercise, with the aim to inform inventory experts in the EU Member States on science developments in this area. Scientific literature/project reports have been synthesised. Some relevant case studies have also been included.

2) A **questionnaire**, sent out to MMR Working Group 1, to find out to what extend they are familiar with alternative methodologies for verification. The other aim of the questionnaire was to find out the current position and plans of MS with respect to Inverse Modelling, in the context of verification support of their inventories.

3) An **assessment of EU Member States' 2021 National Inventory Reports (NIR).** What do MS report with respect to verification activities in their NIR?

4) A **webinar** to present and discuss the findings of this work. EIONET National Reference Centres (NRCs) for greenhouse inventories and air pollutant inventories were invited. The aims of the meeting were:
   - to raise awareness of the opportunities and challenges associated with the use of alternative methods for verification of GHG inventories by MS/EEA countries and EU;
   - to discuss/brainstorm on the way forward for this work in the context of the Paris Agreement.

5) This **report**, synthesising the findings of the activities mentioned above. The main outcomes are summarized below.

Inverse modelling (IM) is emerging as a tool to support national greenhouse gas (GHG) emissions monitoring. Utilising atmospheric transport and chemistry models, IM frameworks constrain prior emission/flux estimates so that simulated GHG concentrations agree with respective in situ and/or remote observations of the atmosphere. Significant scientific progress on IM has been made over the last decades and these advances have led to reduced uncertainties as well as increased spatial resolutions at which IM estimates can be made. Further anticipated advancements, particularly the increased temporal and spatial resolution in atmospheric GHG observations from space (e.g. the CO2M mission starting in 2026), looks set to facilitate increased operational implementation of IM to support national emissions monitoring in Europe.

Switzerland and the UK have already developed national IM systems based on in situ GHG observations and report on these systems and the comparison with their inventory estimates in their National Inventory Reports (NIRs). While no EU-27 country currently documents the use of IM in their NIRs, work is currently ongoing within the European Copernicus programme to develop operational IM systems utilising ground- and space-based atmospheric observations. With the launches of the Sentinel-4, Sentinel-5 and Sentinel-7 (CO2M) missions over the next few years, the Copernicus Atmospheric Monitoring Service (CAMS) plans to produce country-scale, observation-based GHG and air pollutant emissions estimates within the period of the current CAMs 2.0 phase. Use of these data products by key stakeholders (such as national inventory compilers) will be supported by a dedicated outreach component.

This ETC/CME task investigated current perspectives and plans of European inventory compilers with regard to IM. This was done by sending out an online questionnaire to members of the Working Group I and following up with willing participants through short online interviews. Furthermore, inventory compilers of the Working Group I (as well as other experts and stakeholders) were invited to a dedicated webinar to inform participants on current activities on IM and to discuss perspectives on the potential operational implementation of IM to support national emissions monitoring. Generally, inventory compilers are closely following developments in IM and there was a large number of national inventory compilers attending the webinar. Despite the current lack of information in the respective NIR reports, some national inventory teams of the EU-27 are exploring options to incorporate IM into their emissions monitoring systems. Nonetheless, perspectives vary within the inventory community and the questionnaires, interviews and the discussions at the webinar indicated that there are hurdles to overcome before widespread operational implementation of IM/uptake of IM data products can be realised. In addition to concerns about current IM uncertainties at the national scale, inventory compilers indicated the need for consultation with the scientists responsible for IM to discuss and resolved agreement or discrepancy between IM and inventory estimates. A view that IM estimates would need to separate the biogenic and anthropogenic contributions to the net flux to allow for a meaningful comparison seemed to be shared by many of the participating inventory compilers. Finally, concerns were expressed about the utility of IM with respect to the LULUCF sector. While LULUCF often represents the most uncertain sector of national GHG emissions inventories, a comparison with an IM estimate of the biogenic CO_2 flux is complicated by the way LULUCF carbon stock changes have to be calculated as per UNFCCC and EU GHG reporting requirements.

Despite the above concerns, examples of operational implementation of IM exist and these cases underline the importance of collaboration and cooperation between those working on national inventories and those working on IM. Given the Bayesian nature of IM frameworks, in-depth discussion and analysis of the comparison between inventory emissions estimates and IM estimates can help identify potential issues/biases with the inventories (prior estimates) as well as potential issues/biases in the IM models and observations. Addressing these issues can then lead to subsequent iterations of the IM system with improved component parts that lead to reduced uncertainty in the inverse emissions estimates and enhanced utility to support emissions monitoring.

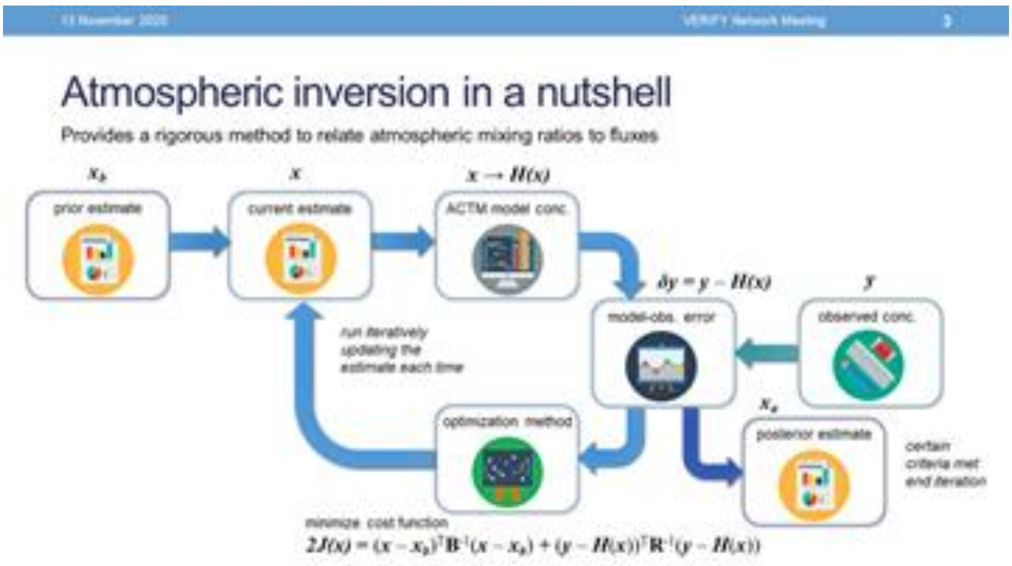
Continued and enhanced exchange between national inventory compilers and scientists working on IM is therefore recommended. As demonstrated by this ETC/CME task, EEA is well positioned to facilitate such enhanced communication between these two communities due its network of contacts and connections to both experts working on national emissions inventories and experts working on IM. Furthermore, in addition to mediating more frequent stakeholder meetings on IM, as a European institution, the EEA can contribute to sustained exchange.

1 Introduction

1.1 Brief overview of the inverse modelling technique

Inverse modelling (IM) frameworks utilise observed temporal and spatial patterns in atmospheric GHG and air pollutant concentrations to constrain initial (*prior*) estimates of emissions of respective species[1]. These prior estimates can be based on reported national annual inventory estimates that are mapped out in time and space, or regional/global emissions datasets that have been independently compiled. By adjusting the *prior* emissions estimates and simulating the subsequent atmospheric transport (and potential chemical transformation), the modelling framework produces *posterior* emissions estimates with which the measured atmospheric concentrations can be reproduced by the model simulations (Figure 1.1). As the figure below illustrates, initial prior emissions estimates (x_b) - for example national GHG inventories - are used as drivers of an atmospheric model. The model simulates (inter alia) GHG concentrations in time and space (H), which can be compared against measured GHG concentrations (y). Through an optimisation process, the modelling framework iteratively adjusts the prior estimates until an *acceptable* agreement between the simulated and observed concentrations is reached with the final posterior emissions estimates, i.e. the final emissions estimates from the inverse modelling framework (x_d).The difference between the prior and posterior can be used to identify potential quality issues within the national GHG inventories, and thus form a relatively independent quality check of the GHG inventory.

Figure 1.1 Conceptual model of the functioning of an inverse modelling framework (Re-used with permission of the copyright holder, Rona Thompson)



(1) Bergamaschi et al (2018). Atmospheric monitoring and inverse modelling for verification of greenhouse gas inventories. https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/atmospheric-monitoring-and-inverse-modelling-verification-greenhouse-gas-inventories

1.2 Emergence of inverse modelling as a tool to support operational emissions monitoring

Inverse modelling has of course been used for decades to infer - inter alia - the global net CO_2 flux to the atmosphere. However, it is only within the last ten years or so that scientific advances in atmospheric modelling and observation have reached the stage whereby IM can, in the near-term, be operationally implemented to provide robust independent emissions estimates at the scale of nation states. A point may therefore soon be reached, whereby IM could feasibly be implemented by countries to support national emissions monitoring and improve national inventories and/or be used centrally to verify emissions reported by countries under international climate legislation. That this aforementioned capability of IM appears on the immediate horizon is underlined by recent developments in international scientific and policy fora on climate change.

Furthermore, in supporting countries in implementing/utilising inverse emissions estimates, the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, includes an updated and expanded subchapter on *Comparison of greenhouse gas emission estimates with atmospheric measurements* within national systems for QA/QC and verification purposes.

Focusing on Europe, it can be argued that inverse modelling has been risen up the climate policy agenda over the last three decades. Since in the 1990s, the European Commission's Joint Research Centre has organized several science-stakeholder meetings on this emerging topic[2]. Furthermore, in 2011 the European Environment Agency also held a workshop that brought together European scientists and experts from the emissions inventory-, atmospheric modelling-, and in situ and remote observation communities to highlight *near future* options whereby GMES (the predecessor of the Copernicus programme) could improve GHG and air pollutant emissions inventories. Subsequently in 2015, the European Commission's CO_2 Task Force published a report outlining a vision for a European inverse modelling system, that based on satellite (and in situ) GHG observations will allow independent monitoring of national (and even subnational) GHG emissions across the whole globe. This was followed by two subsequent reports in 2017 and 2019 outlining the system architecture and system requirements of the envisaged *CO_2 Monitoring and Verification Support (MVS) Capacity*. Indeed, the Commission is investing heavily in this vision, with the Horizon 2020 projects CHE and VERIFY devoted to the required research and development of component parts. The follow-up H2020 project CoCO2 began in 2021 and is tasked with developing a protype MVS system and it should also be noted that a dedicated satellite observation mission, CO2M is set to be launched in 2025/2026. Indeed the upcoming CO2M as well as the sentinel 4 and 5 missions will provide improved and higher resolution satellite observations of atmospheric greenhouse gas and air pollutant concentrations. Harnessing these upcoming data streams, the Copernicus Atmospheric Monitoring Service will generate further IM data products within the next phase of the programme (CAMS 2.0) including emissions estimates for European countries. Use of these products by key stakeholders (such as national inventory compilers) will be supported by a dedicated outreach component.

Datasets of GHG emissions for European countries estimated by inverse modelling are already available from H2020 projects devoted to the development of the CO_2 MVS capacity. The VERIFY project for instance recently published its ensemble datasets of multi-year emissions estimates for the EU27 (plus UK) (Figure 1.2) and the individual MS[3,4]. These data can be downloaded from the project website[5]. As

(2) See for instance Bergamaschi, 2007: Atmospheric Monitoring and Inverse Modelling for Verification of National and EU Bottom-up GHG Inventories - Report of the Workshop "Atmospheric Monitoring and Inverse Modelling for Verification of National and EU Bottom-up GHG Inventories". https://publications.jrc.ec.europa.eu/repository/handle/JRC38074

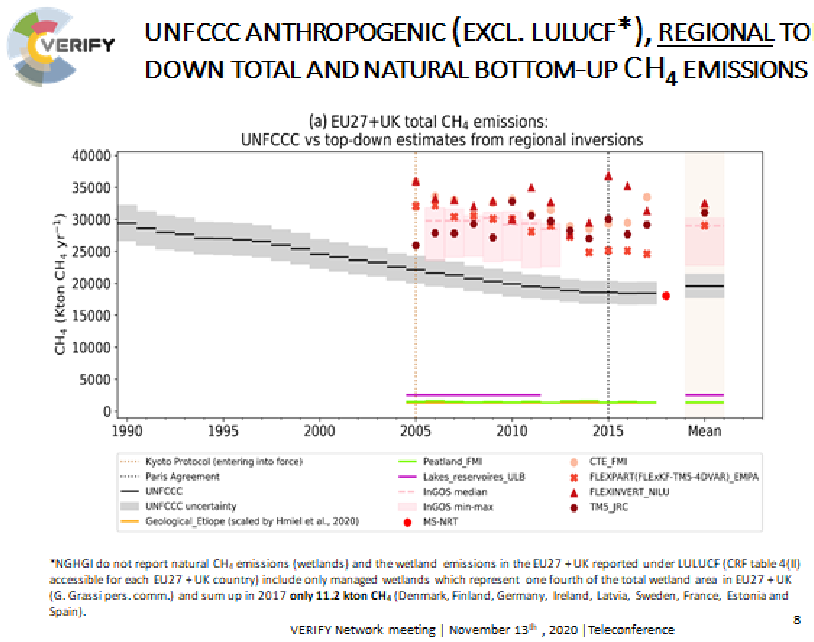
(3) Petrescu et al 2020. The consolidated European synthesis of CO_2 emissions and removals for EU27 and UK: 1990–2018. https://essd.copernicus.org/preprints/essd-2020-376/

(4) Petrescu et al 2020. The consolidated European synthesis of CH_4 and N_2O emissions for EU27 and UK: 1990–2018. https://essd.copernicus.org/preprints/essd-2020-367/

(5) http://webportals.ipsl.jussieu.fr/VERIFY/FactSheets/

the graph below illustrates, these estimates allow for comparisons between inventories and inverse estimates in terms of both emission levels and recent emission trends. The graph below compares ensemble inverse estimates of methane emissions for the EU27 and the UK against respective estimates reported to the UNFCCC. Despite the considerable range in different regional inverse estimates, comparison against the official inventory estimates indicates that reported methane emissions may be underestimated. It should be noted that the inversion results also include emissions from natural sources (peatland, lakes) that are excluded from the official inventory reporting to UNFCCC. While these natural fluxes can be estimated and subtracted from the IM estimate, the IM-inventory discrepancy could of course be due to biases in the inventory, biases in the bottom-up estimates or biases in both.

Figure 1.2 Regional (EU27 & UK) top-down and bottom-up comparisons for CH_4 from H2020 VERIFY



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1.3 Inverse modelling in National Inventory Reports

Some countries have begun implementing national inverse modelling systems and documenting these systems in their national GHG emissions reporting under the UNFCCC. The National Inventory Reports (NIR) of e.g. Australia (Australian Government, 2020), Switzerland (FOEN, 2020) and UK (Ricardo-AEA Ltd., 2020) document the current use of top-down inversions using in situ measurement data to validate national emissions estimates certain GHGs.

For example, the Swiss NIR documents the use of inverse modelling for verification of CH_4, N_2O and F-gas (HFCs and SF6) emissions. For F-gases, national emissions are estimated using the “tracer ratio” method: concurrent changes in concentrations of F-gases and CO are measured at a high-altitude site, during periods where meteorological models predict the sampled air to include emissions from pollution events in Switzerland. The relationship between the changes in F-gas and CO concentration is then used to infer F-gas emissions based on the more robust bottom-up inventory of CO emissions. For CH_4 and N_2O, modelling employs continuous measurement data from tall towers and high-altitude sites (both in Switzerland and outside), alongside *a priori* gridded emissions estimates from the Swiss inventory and a

European-level inventory for neighbouring countries. For each gas, differences are found between the inventory and inverse modelling results in the level and/or trend of emissions (and in the case of CH_4 and N_2O, the spatial distribution of emissions). This has provided some interesting insights:

- Despite use of HFC-152a in industry almost ceasing in 2009, emissions have only slowly declined, likely due to the gas leaking from existing products during use;
- Estimates of N_2O emissions in inverse modelling are higher than the inventory for agricultural soils, but lower for non-agricultural sources, suggesting that emissions from urban areas may be over-estimated in the inventory.

Similarly, the UK NIR reports a verification methodology for CH_4, N_2O and F-gas emissions, based on a network of tall tower and remote observation stations, both in the UK and elsewhere in Europe. Dispersion and meteorological modelling techniques support the inverse modelling in determining the emission distribution that most accurately reproduces the network's observations. Notable findings include:

- For HFC-134a, inventory estimates have been consistently higher than modelled estimates, which has led to investigations and subsequent revisions to the refrigeration and air conditioning model, resulting in better agreement in the current inventory;
- For CH_4, inventory estimates in the early part of the timeseries are considerably higher than modelled estimates, which has prompted a review of the model used to estimate emissions from landfill sites.

Given the above developments, it is therefore timely to investigate the extent to which EU MS are applying or planning to apply inverse modelling within their national GHG monitoring systems. As part of this ETC/CME study, the most recent 2021 National Inventory Reports of the EU 27 were reviewed to identify which MS currently document using inverse modelling within their national GHG monitoring systems.

It was found that, at present, no EU MS documents the use of inverse modelling for the verification of emissions inventories in their NIRs. Only the NIR of the Netherlands explicitly refers to the planned integration of inverse modelling into their national inventory system, as they consider the results of previous research and progress in the VERIFY and CoCO2 projects.

2 Plans and perspectives on the use of inverse modelling by EEA member countries

It is of course clear that only limited conclusions on the current and prospective implementation of inverse modelling can be drawn from the review of the EU MS NIRs described in section 1.3. It could not be ruled out that some EU MS may currently be using or developing national inverse modelling systems and/or are planning to utilise inverse modelling outputs from the Copernicus Atmospheric Monitoring Service (CAMS) and the foreseen CO_2 MVS capacity, but have not yet documented this in their NIRs. Therefore, as part of this ETC/CME study, a online survey was sent out to the national inventory experts of the Working Group I, which includes representatives of the EU MS as well as some of the non-EU EEA member countries.

The questionnaire included questions relating to:

- Current knowledge and awareness of the respondent about IM and its use in verification
- Confirmation of use (or not) of IM for inventory verification or improvement
- Reasons why IM has not so far been used
- Plans for developing future national IM systems or use of independent IM estimates
- Barriers to developing such plans
- Suggestions for how to increase knowledge of IM

The full set of questions is provided in Annex 1.

The questionnaire was accompanied by a technical note, which essentially included the same information as in section 1 of this report. The subchapters below briefly summarise the results of the questionnaire, as well outcomes from the follow-up interviews with those inventory compilers who agreed to elaborate on their questionnaire answers.

2.1 Online survey and summary of results

Participants

In June 2021, the questionnaire was sent to the members of Working Group 1 under the EU Monitoring Mechanism, where all EEA countries are represented, including the 27 EU Member States. By the end of July, responses had been received from 16 EU Member States and additionally, from 2 non-EU EEA countries.

Summary of findings

The large majority of respondents indicated that they were aware of IM - only 3 of the 16 respondents indicated that they were not aware of inverse modelling (IM) as a technique to support verification of greenhouse gas inventories. Nonetheless, none of the respondents stated that IM was currently utilized at the moment. Various reasons were indicated:

- 9 respondents indicated that there is no national system for IM in place;
- 8 respondents indicated they are unaware of available IM estimates for their country;
- respondents are aware of IM estimates for the country, but do not use them.

As main reasons for not using available IM estimates, these respondents indicated:

- The perceived uncertainty of the IM results;
- The lack of expertise to handle and interpret inverse modelling results (most frequent answer);
- The lack of access to data for comparison of IM results and inventories;
- Insufficient collaboration between inventory experts and modellers; and

- The fact that independent verification is not mandatory.

Despite the lack of current use of IM, some countries indicate they are starting to explore the possibilities of IM; e.g. via the work of the Copernicus Atmospheric Modelling Service (CAMS); however, lack of policy support (and related funding, as well as the lack of technical capacity, are mentioned as potential hurdles that could restrict uptake of IM.

Six respondents were positive about the possibilities to apply IM in the upcoming years. One other MS indicates it will consider the use of IM after the VERIFY project. Three of these countries aim at developing a national inverse modelling system based on satellite data and in situ measurements. The other four of the seven MS considering applying IM indicated that they would make use of independent inverse estimates, based on Copernicus products.

Despite no current plans to use IM for verification, 2 countries indicated they are aware of ongoing or planned research and development activities to develop a national inverse modelling system. Six countries are not aware of ongoing or planned research and development activities.

Interestingly, two countries are aware of current or upcoming systems to produce inverse modelling estimates for their country, but do not plan use these. Following reasons are mentioned:

- Uncertainty in IM;
- Lack of expertise in this area;
- Insufficient collaboration between inventory experts and experts in the area of measurements and modelling;
- The fact that IM is not mandatory.

Some countries answered the question how to overcome barriers, by providing following suggestions:

- Work on lowering uncertainties in IM results;
- Improve accessibility to data from IM for comparison with inventory data
- Training of experts

Finally, the following suggestions for increasing uptake of IM were provided:

- Webinars and presentations at Working Group 1 meetings
- Presentations to be given by countries that apply IM
- Consider a demonstration project in EU
- Consider a coordinated step-wise approach towards EU use.

2.2 Follow-up interviews and summary of outcomes

In addition to the questions on plans and perspectives on IM, the survey also asked respondents if they would be willing to take part in short follow-up interviews with members of the ETC task team. Follow-up interviews were conducted with representatives of 6 EU MS and 1 non-EU EEA country. The main findings of these interviews are summarized below.

(1) Generally no “national systems” in place, no concrete plans on the short term

Except for one of the countries, there are no concrete plans to develop a national system for independent verification of greenhouse gases yet. The one country considering a national system does not expect this will be operational before 2030.

(2) Most countries show interest in ongoing projects in Europe

Though the interviewees generally do not consider development of their own national system, they show interest in projects conducted at European scale (Verify, CoCO2, Copernicus Atmospheric Modelling Service (CAMS)) and have given thought to the use of tools/products that result from these European activities.

Some indicate that uptake of IM is a process that will require patience and careful consideration. The ongoing developments within e.g. Horizon and Copernicus may certainly help countries think about what they can do with IM and other tools to improve verification. Some are conducting smaller national studies, that may help connecting measurement and modelling experts and inventory experts. Taking small steps at the time may help this work forward anyway; though not at high speed. There is lack of budget at national scale because verification is not mandatory under the UNFCCC or within EU; so it's not a high priority either.

(3) Views on the need for a national IM system

Some countries questioned whether there is an actual need for "national systems" for verification, like those in place in the UK and Switzerland. Some suggest not to focus on the development of national systems, but on development of tools/tool-boxes that may help countries to do verification studies for specific sectors and/or specific gases, such as CH_4 and N_2O. Most countries indicated that would be interested in applying verification tools for air pollutants, too.

(4) Views on the use results of IM studies for review purposes

Some countries would not favour using results of IM studies for review purposes; or only under the condition that discrepancies between IM studies and inventories can be clarified and explained. Even then, the usual question and answer format during reviews and issuing of recommendations may not be appropriate for this purpose, and a different format may be required. Some are concerned that the complexity of the inventory cannot be covered by results of IM studies. Up to now, IM studies cannot distinguish between sectors. Distinguishing between emissions from anthropogenic- and natural sources is also very uncertain.

(5) Improve communication

Inventory experts and modelling/measurement experts tend to operate in their own communities. There is a clear need to develop some "common language" and better mutual understanding. In that context, the VERIFY project started with engaging inventory experts in this merely modelling and measurement oriented project. Several workshops were organised to help exchange between inventory experts and modelling & measurement experts.

There are also signals that both communities are not always aware of what is ongoing outside their communities. Modelling and measurement studies - particularly those related to satellite observations - are sometimes technology driven and financed by ministries covering science and technology development; whereas greenhouse gas inventories are the responsibility of ministries of environment.

3 Webinar

3.1 Organisation and agenda

As per the 2.2.02.1 task description, a webinar was organised by EEA and ETC/CME, with the aim to take stock on where we are in Europe with respect to inverse modeling and its operational implementation to support national greenhouse gas emissions monitoring. The webinar was announced through various fora with invitations sent out through the EEA's networks, in particular Working Group I and the EIONET National Focal Points (NFPs) and the National Reference Centres for Mitigation of air pollution and climate change. Invites were furthermore sent out to other experts and stakeholders within the EEA, the European Commission and the Joint Research Centre and Copernicus. In addition to the invited speakers, invites were furthermore forwarded to researchers and experts working on inverse modelling through the VERIFY and CoCO2 projects.

The webinar took place in the afternoon of the 23rd November 2021 and over 60 experts participated in the meeting. A copy of the agenda is provided below. Outcomes from the presentations and discussions are summarised in the following subchapters.

EEA/ETC-CME on-line webinar
Inverse modelling as a tool to support national greenhouse gas emissions monitoring
- final agenda -
23 November 2021 13:00 – 15:45 CET (via Microsoft Teams)

13:00 Opening and introduction by the co-chairs
Peter Iversen, EEA and Bradley Matthews, ETC/CME: UBA-Vienna

13:10 Introduction on inverse modelling and activities within the coming Copernicus programme
Richard Engelen, ECMWF

13:30 Results of the VERIFY project. What has been the added value of the verify project for the inventory compilers?
Phillipe Peylin, LSCE

13:45 Inventory compiler perspective on a developed national inverse modelling system. Has the use of an IM system brought new insights for the improvement of the national inventory?
Peter Brown, Ricardo PLC, UK

14:00 Inventory compiler perspective on planned future use of IM. Some pitches
Representatives FI, NO, AT, DE & NL

14:30 Short break

14:40 Dedicated discussion round inviting perspectives from the Audience.

15:30 Concluding remarks
Co-chairs

15:45 Closure

3.2 Summary of presentations

Please note that the 3 presentations have been added to this report in Annex 2.

Richard Engelen: Introduction on inverse modelling and activities within the coming Copernicus programme

Richard Engelen is Deputy Director of the Copernicus Atmosphere Monitoring Service (CAMS) at ECMWF and responsible for the ramp-up within CAMS of the new anthropogenic CO_2 emissions monitoring & verification support capacity (CO2MVS). He also is coordinator of the CoCO2 project, which prepares the prototype systems for the CO2MVS.

His presentation showed the ramping-up of a new operational anthropogenic CO_2 emissions monitoring & verification support capacity as part of the European Union's Copernicus Earth Observation programme. The talk furthermore elaborated on the national scale, observation-based emissions data products that will be generated as part of the CAMS 2.0 phase that commenced this year. The presentation also made the link to some of the potential user communities (European Commission and member states) and how CAMS hopes to work with these user communities to exploit this new observation-based information data stream.

His presentation led to some discussion on how to distinguish between anthropogenic- and natural fluxes based on Earth observation data. Several techniques are available, but the result is always a combination of several data sources. Science on how to distinguish between these fluxes is still developing.

Philippe Peylin: Results of the VERIFY project

Philippe Peylin, Laboratoire des Sciences du Climat et de l'Environnement (LSCE), is the coordinator of the European VERIFY project, which is dedicated to the preparation of a pre-operational system to support national GHG flux inventories with observation based estimates.

His presentation summarized the methodology developed in the VERIFY project to provide observation-based CO_2 / CH_4 / N_2O flux estimates at country level for Europe and provides key results obtained so far. The project has produced net total CH_4 and N_2O fluxes and net land-based CO_2 fluxes for the EU27+ UK as a whole as well as respective national scale estimates. He illustrated in his presentation the main finding for the EU27 + UK for the three different GHG’s, focusing on the benefit of the so-called atmospheric inversion approaches. These findings are accessible at the project webpage[6]. His talk underpinned that better collaboration between inventory agencies and modelling and measurement experts is necessary to achieve better priors for inverse modelling that lead to better posterior estimates.

In response to a question from the audience on how VERIFY distinguishes natural fluxes from antropogenic fluxes, Philippe indicated that natural fluxes are modelled; a.o. based on satellite observations.

Peter Brown: Inventory compiler perspective on a developed national inverse modelling system

Peter Brown, Ricardo Energy & Environment, is the Greenhouse gas lead for the UK National Atmospheric Emissions Inventory (NAEI), which Ricardo delivers and reports on behalf of the UK government.

(6) http://webportals.ipsl.jussieu.fr/VERIFY/FactSheets/

His presentation discussed how the UK Inventory Agency interprets and utilises the findings from inverse modelling. He showed some specific examples where confidence in the inventory can be higher due to agreement with the IM estimate, or raise questions for consideration in the inventory and inverse modelling improvement programmes. In the case of F-gases, the IM time series seem to verify both the reported emission levels and trends from the inventory. This of course raises confidence is using the inventory data and methods for monitoring and forecasting (scenarios) purposes. In terms of CH_4 emissions, the comparison of the IM and inventory estimates appears to verify recent CH_4 emissions, but large discrepancies between estimates for the 1990s and early 2000s were cause for concern. Interestingly the discrepancy is not seen immediately as an inventory error but rather an issue that can only be resolved by looking at potential errors in the IM framework as well as potential inventory biases. Work to resolve this issue is currently ongoing.

In response to a question, Peter raised that the UK uses a rather simple prior in the model for the UK, that is based on population distribution. Advantage of that prior, is that it is independent from the greenhouse gas inventory.

3.3 Inventory compiler perspectives on planned future use of IM

Short presentations (*Pitches*) from Finland and Norway show that specific circumstances may give difficulties in applying IM. Norway is a small, long country with a long shore line and many lakes. Use of IM that resolves fluxes for quite large raster tiles that would cover both land and water was highlighted as a concern/limitation regarding the use of IM. Additionally, both countries have a very large LULUCF sector and highlighted the issue of separating anthropogenic and natural emissions from the inverse estimate of the net flux. Both countries expressed concern that comparability from IM results and the inventory for LULUCF will be difficult also because of the specific UNFCCC/IPCC inventory calculation rules for LULUCF. Certain carbon stock changes included in LULUCF (e.g. biomass carbon stock losses) differ fundamentally from the land-atmosphere exchange of CO_2 in both time and space, thus limiting the use of such comparisons. Nonetheless, both countries follow what is ongoing in the scientific arena. A comparison for CH_4 based on an IM study performed by the Finnish Meteorological Institute (FMI) showed good comparability between top down and bottom up estimates.

The Austrian inventory team indicated that it is taking its first steps with the topic of the IM. European developments on IM and Earth Observation (EO) in general (H2020 projects, emerging Copernicus data products and satellite missions) have stimulated considerations on using EO-based tools to support national GHG emissions monitoring. This has led to a recent national research call to develop prototype systems that enable the integration of Copernicus atmospheric observations into the national greenhouse gas monitoring system. The Austrian inventory team has been heavily involved in the development of the research call and will also steer the project’s implementation. The project is due to begin in 2022.

In Germany, the national government made a substantive budget available (15 million euro) for work on an integrated national system to become operational in the longer term (2030). The German Environment Agency has performed a study for NO_2 detection, that can be seen as a first stepping stone in the world of verification. Also TNO is commissioned to build a verification tool box that may help improve QA/QC activities. The German initiative will provide a collaborative platform for inventory experts and modelling/measurement experts.

The Netherlands is also just getting started with activities on verification. No concrete actions yet; but the ambition level is to add in future (e.g. 5 years from now) an Annex to the NIR, comparable to UK and Switzerland, including results of checks against independent inverse emissions estimates for the country. Several workshops engaging the inventory community, measurement and modelling experts and policy have been organized to discuss the status of science developments and inventory needs. No concrete action as yet, a.o. as a result of budget constraints.

3.4 Outcomes of the discussion session

After the initial talks and short presentations from the inventory compilers of Finland, Norway, Austria, Germany and the Netherlands of the first session, the second session was dedicated to an open round of discussions on IM. Parallel to the discussions, the participants were furthermore invited to complete a Mentimeter questionnaire. The results of the Mentimeter questionnaire are provided in Annex 3 and below we summarise the main issues that were addressed during the open discussions.

(1) IM would become more attractive for use in the inventory community, if understanding of the methods and results could be increased through intensified communication between those working on IM and those working on national inventories. This is acknowledged and attempts are being made to increase dialogue and transparency. For example, in the VERIFY project, several meetings between inventory agencies and measurement& modelling experts have been organized to exchange on scientific developments and needs of the inventory community. This webinar thus served as good platform to raise further awareness of the next and final networking meeting of the VERIFY project.

(2) IM may not be useful for all countries, given their specific circumstances (e.g. special geographical circumstances and large natural fluxes) or due to their limited spatial extent. It seems that robust inversions can currently be made at the regional scale, but at the level of European countries, uncertainties can be very large. This of course limits the use of these data for validation purposes. In future, the planned high-resolution satellites may bring more detail and allow for higher resolution modelling and reduce uncertainties at the European country scale.

(3) Inventory experts would like being able to distinguish inversion results at the sectoral level (in line with UNFCCC and IPCC reporting guidelines). This ambition level may not be able to achieve. However, comparisons of totals and trends can make a valuable contribution to inventory QA/QC procedures (in line with the presentation by Peter Brown) and investigation of discrepancies (spatial patterns) could nonetheless indicate issues coarse sectoral resolution. The diesel-gate scandal was for example cited as a reason why IM estimates of NOx emissions were often found to be higher than respective inventory estimates.

(4) The issue of time lag in inventories was discussed. The 2-year lag in inventories (submission year is 2 calendar years after the end of the time series) is often cited as a drawback and indeed the inverse modelling approach would allow for online and *nowcasting* of emissions once data streams and modelling calculations become automatized. This is acknowledged as a potential benefit of the top down approach, though the reporting of proxy inventories by EU MS should not be forgotten (time lag < 12 months), though estimates are much more uncertain. Furthermore, the first full emissions inventories are reported to the EU in January constituting only a 13-month lag compared to the end of the emissions time series.

(5) Collaboration between modelling/measurement experts and inventory experts is crucial and should be stimulated further. As both the talks of Philippe Peylin and Richard Engelen stressed, the inverse modelling system is a Bayesian system that is sensitive to the uncertainties of the component parts i.e. uncertainties in the priors, the models, and the observations. Intensified collaboration between modelling/measurement experts and inventory experts can thus prompt mutual learning and allow for improvements in the data inputs e.g. national experts could potentially help to identify more appropriate methods to the disaggregated the prior emissions in time and space. Furthermore, as stressed in Peter Brown’s talk, the analysis of discrepancies should be conducted together, to confirm and rule out the various potential sources of error that lead to diverging estimates.

In this context, it should be noted that the webinar appeared to be much appreciated by the audience and hopefully will lead to active and enhanced participation of inventory compilers at the joint network meeting in May 2022 that will be organized by VERIFY in a combined effort with CoCO2.

4 Conclusions

This ETC/CME task reviewed the status of IM as a tool to support national GHG emissions monitoring in Europe and investigated current perspectives and plans of European inventory compilers with regard to IM.

Significant scientific progress on IM has been made over the last decades and these advances have led to reduced uncertainties as well as increased spatial resolutions at which IM estimates can be made. Further anticipated advancements, particularly the increased temporal and spatial resolution in atmospheric GHG observations from space (e.g. the CO2M mission starting in 2026), looks set to facilitate increased operational implementation of IM to support national emissions monitoring in Europe. Switzerland and the UK have already developed national IM systems based on in situ GHG observations and report on these systems and the comparison with their inventory estimates in their National Inventory Reports (NIRs). While no EU-27 country currently documents the use of IM in their NIRs, work is currently ongoing within the European Copernicus programme to develop operational IM systems utilising ground- and space-based atmospheric observations. Furthermore, exchanges with national inventory compilers of the EU-27 and other non-EU EEA countries, showed that European inventory teams are closely following developments in IM.

Despite the current lack of information in the respective NIR reports, some national inventory teams of the EU-27 are exploring options to incorporate IM into their emissions monitoring systems. Nonetheless, perspectives vary within the inventory community and the questionnaires, interviews and the discussions at the webinar indicated that there are hurdles to overcome before widespread operational implementation of IM/uptake of IM data products can be realised. In addition to concerns about current IM uncertainties at the national scale, inventory compilers indicated the need for consultation with the scientists responsible for IM to discuss and resolved agreement or discrepancy between IM and inventory estimates. A view that IM estimates would need to separate the biogenic and anthropogenic contributions to the net flux to allow for a meaningful comparison seemed to be shared by many of the participating inventory compilers. Finally, concerns were expressed about the utility of IM with respect to the LULUCF sector. While LULUCF often represents the most uncertain sector of national GHG emissions inventories, a comparison with an IM estimate of the biogenic CO_2 flux is complicated by the way LULUCF carbon stock changes have to be calculated as per UNFCCC and EU GHG reporting requirements.

Despite the above concerns, examples of operational implementation of IM exist and these cases underline the importance of collaboration and cooperation between those working on national inventories and those working on IM. Given the Bayesian nature of IM frameworks, in-depth discussion and analysis of the comparison between inventory emissions estimates and IM estimates can help identify potential issues/biases with the inventories (prior estimates) as well as potential issues/biases in the IM models and observations. Addressing these issues can then lead to subsequent iterations of the IM system with improved component parts that lead to reduced uncertainty in the inverse emissions estimates and enhanced utility to support emissions monitoring.

Continued and enhanced exchange between national inventory compilers and scientists working on IM is thus recommended. Such exchange at the European level has so far taken place largely within the scope of research and development projects (e.g. H2020 and Horizon Europe) and will likely continue within such settings. Nonetheless, additional fora may be required to significantly increase the frequency of exchange between national inventory- and IM communities. In this regard, EEA is well positioned to facilitate such enhanced communication. Given its connections to both experts working on national emissions inventories (EIONET network) and experts working on IM (connection to and role within the

Copernicus programme) EEA could operate as moderator between the two communities. Furthermore, as a European institution, the EEA can contribute not only to enhanced- but also sustained exchange.

Abbreviations, units and symbols

CAMS	Copernicus Atmospheric Monitoring Service
CH_4	Methane
CO_2	Carbon dioxide
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EEA	European Environment Agency
ETC CME	European Topic Centre on Climate Change Mitigation and Energy
EU	European Union
EU MMR	EU Monitoring Mechanism Regulation
GHG	Greenhouse gas
IM	Inverse modelling
LULUCF	Land use, land-use change and forestry

Annex 1: Questionnaire

ETC/CME sent out a questionnaire to the experts in Working Group 1 under the EU Monitoring Mechanism Regulation. Following questions were raised. Results are summarized in chapter 3.

- Representing the country of:

- Is inverse modelling currently used for independent verification of your country's GHG emissions inventory? (We have reviewed the 2021 NIR submission and note that use of inverse modelling is not currently documented there).
  <Note that depending on your answer you will be taken to the page with appropriate follow-up questions>

- For which gases is it used?
  <Could you please provide a link/reference to where this information can be found, and briefly describe your current inverse modelling activities for these purposes>

- Have the verification activities contributed to any previous or planned changes in the GHG inventory methods?
  <Could you please provide a link/reference to where this information can be found, and briefly describe your current inverse modelling activities for these purposes>

- Which of the following best describes the reason why IM is not yet used for inventory verification? Please select all that apply:
  - No national inverse modelling system currently in place
  - Unaware of any available inverse modelling estimates for your country
  - Aware of available inverse modelling estimates, but do not use them because of (specify reasons below):
    - Perceived high uncertainty in the inverse emissions estimates
    - Lack of expertise to handle and interpret inverse modelling results
    - Lack of access to data
    - Insufficient collaboration with inverse modellers
    - It is not mandatory to use these data for verification purposes
    - Other reason.
      <Please add any other explanation you wish to provide on why IM is currently not used in the text box below>

- Do you plan to use (or expand use of) inverse modelling for independent verification in upcoming GHG emissions monitoring activities (i.e. in the next few years)?
  <Note that depending on your answer you will be taken to the page with the appropriate follow-up questions>

- What will the future use of IM be based on? Please select all that apply:
  - A national inverse modelling system based on (please specify below):
    - In situ GHG measurements
    - Satellite GHG observations
  - Independent inverse estimates from (please specify below):
    - Copernicus Atmospheric Monitoring Service (CAMS)
    - Other
      <Please provide a link/reference to where further information on these future plans can be found, or briefly describe any additional details of these plans in the text box below (details of the inverse modelling planned, gases covered, its integration into the GHG monitoring system and the timing of its introduction are of interest to this study)>

- As far as you are aware, have there been any discussions (within your inventory team and with your respective ministry) about the possibility of introducing inverse modelling techniques for GHG monitoring and verification?

- Despite no current plans to use IM for verification, are you nonetheless aware of ongoing or planned research and development activities to develop a national inverse modelling system?
<If Yes, please provide a link to further information or briefly describe below>

- Which of the following best describes the reason why there are no near-term plans for IM to be used for inventory verification? Please select all that apply:
    - No plans to develop a national inverse modelling system
    - Unaware of any available or upcoming systems to produced inverse modelling estimates for your
    - country
    - Aware of current or upcoming systems to produce inverse modelling estimates for your country, but
    - do not plan use these because of (specify reasons below):
        - Perceived high uncertainty in the inverse emissions estimates and sceptical on the extent this uncertainty will be reduced in the near term
        - Lack of expertise to handle and interpret inverse modelling results
        - Lack of access to data
        - Insufficient collaboration with inverse modellers
        - It is not mandatory to use these data for verification purposes
        - Other reason (please specify)

- What would help you to overcome barriers preventing you from using inverse modelling for GHG monitoring and verification?

- Would you be prepared to take part in an interview to discuss your current activities and plans for inverse modelling, or barriers to developing such activities or plans?

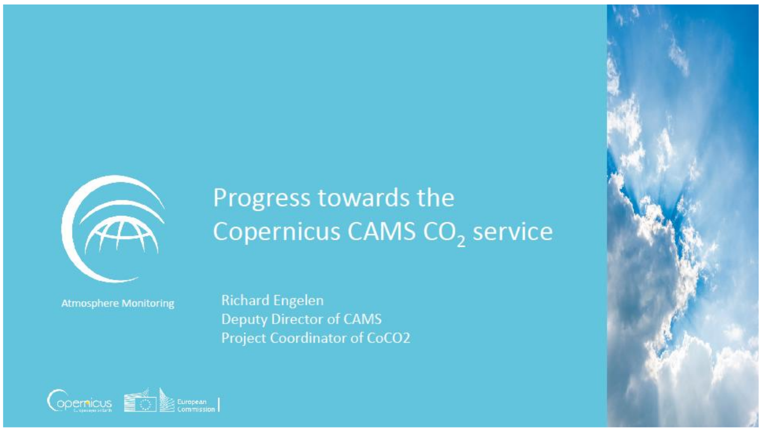
- Was the summary note accompanying the questionnaire helpful?

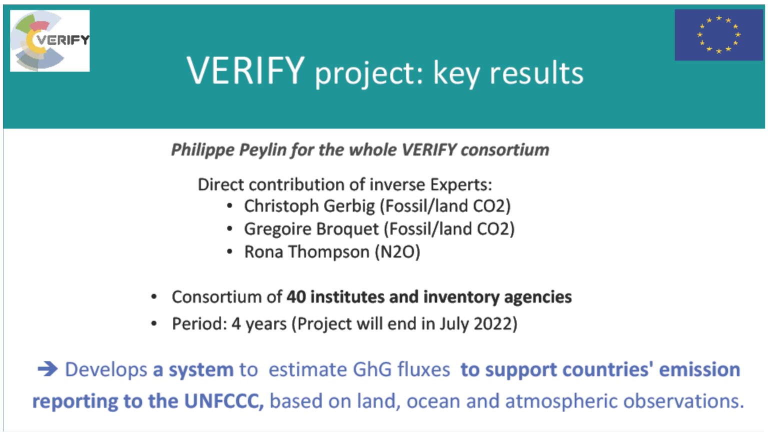
- Do you have any suggestions for how knowledge of the application of inverse modelling to constrain and verify emission inventories could be increased in the inventory compilation community?

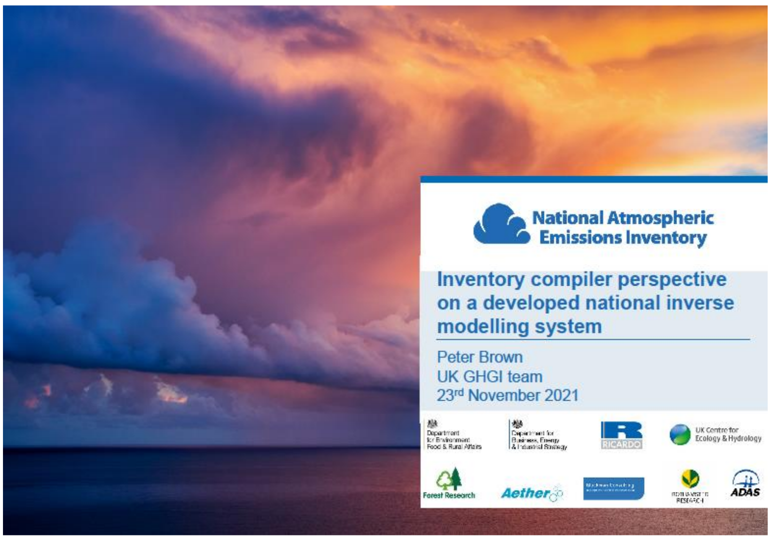
- Do you have any further comments on inverse modelling for GHG emission monitoring which have not been captured by the questions above?

Annex 2: Presentations during the webinar 23 November 2021

The presentations are available on the ETC/CME we, https://www.eionet.europa.eu/etcs/etc-cme/products/etc-cme-webinars/2021-webinar-inverse-modelling-as-a-tool-to-support-national-greenhouse-gas-emissions-monitoring

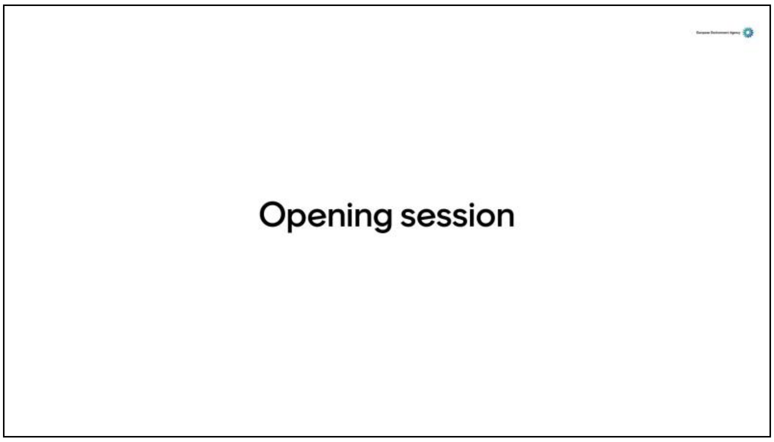






Annex 3: Results of the webinar Mentimeter survey

The results of the Mentimeter are available on the ETC/CME website:
https://www.eionet.europa.eu/etcs/etc-cme/products/etc-cme-webinars/2021-webinar-inverse-modelling-as-a-tool-to-support-national-greenhouse-gas-emissions-monitoring



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