,
Horizon 2020 Societal challenge 5: Climate action, environment, resource efficiency and raw materials

VERIFY
Observation-based system for monitoring and verification of greenhouse gases
GA number 776810, RIA

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Contributor(s):	CMCC
Internal reviewer:	CEA (P. Peylin)

1. Changes with respect to the DoA

The content of the deliverable do not change with respect to the DoA. However the delivery date was shifted by 6 months (in agreement with the project officer) due to unexpected sick leaves of the primary responsible of this deliverable at UNIVBRIS (Joanna I. House).

2. Dissemination and uptake

The material presented in this deliverable is of primary interest to all partners of the VERIFY consortium and it should also be distributed outside the project, especially to stakeholders.

3. Short Summary of results (<250 words)

Transparency, accuracy, completeness, comparability, and consistency of national Greenhouse gas inventories in ensured through Quality Assurance and Quality Control (internal checks and reviews) and Verification (review using independent data and methods). The inventory reports and the progress of mitigation actions under NDC and the support provided by developed countries are subject to a **technical expert review** to check with the modalities, procedures and guidelines of the enhanced transparency framework. Under the Global Stocktake (every five years starting from 2023) the countries' collective progress is assessed towards the long term goals of the PA based on the best available science.

Data for independent review includes that compiled by other data providers e.g. FAO, EDGAR, USEPA. In the land sector, satellite and other airborne senor data (e.g. radar, Lidar) can provide estimates of land cover change and biomass which can be sued for developing or verifying inventories. Atmospheric concentration of greenhouse gasses from satellites and tall towers can also be sued with inverse modelling techniques to derive greenhouse gas flux, however this works best for fossil fuels and other industrial sources, especially when isotopes and other tracer gasses are used. These techniques are already in use with the UK and Swiss inventory. . For the land sector it is not possible to separate emissions and removals due to natural and anthropogenic causes, although site specific measurements and other trace gasses can be used to indicate some sources as has been done to support the methane inventory BUR in India.

4. Evidence of accomplishment

The content of this report represents the accomplishment of the work.

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Version	Date	Description	Author (Organisation)
V0	18/11/18	Creation/Writing	Joanna I. House, Viola Heinreich (UoB), Daniel Hoare (UoB), Lucia Perugini (CMCC)
V1		Writing/Formatting/Delivery	Joanna I. House, Viola Heinreich (UoB), Daniel Hoare (UoB), Lucia Perugini (CMCC)
V2		Formatting/Delivery on the Participant Portal	Frederic Chevallier (CEA) Philippe Peylin (CEA)

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1. Country Reporting of GHG sources and sinks under UNFCCC

1.1. General Overview of reporting

National governments that are Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are required to submit National Greenhouse Gas Inventories (GHGIs), reporting on all anthropogenic emissions and removals commencing in the year 1990 to the latest available complete calendar year.

There are five general reporting principles of the UNFCCC: **transparency, accuracy, completeness, comparability, and consistency** (TACCC) (UNFCCC/COP5, 1999).

The Framework considers the different greenhouse gases (GHG) measuring and reporting capacities of countries and has broadly divided countries into the following groups, depending on their commitments:

- **Annex I** Parties include developed countries as well as those with economies in transition (EIT) (UNFCCC, 2019a). Parties within this group are required to submit annual reports of their GHGI on the main GHGs (UNFCCC/COP9, 2013). Every four years Parties submit the GHGI as part of their *'National Communication*' report (NC). Furthermore, Parties are requested to submit Biennial Reports (BRs) every two years.
- **Annex II** Parties are the Annex I Parties who are members of the Organisation for Economic Co-operation and Development (OECD) and provide financial resources to developing countries for emissions reduction activities and to help with adaptation strategies to climate change. The Parties also "take all the practicable steps" for promoting the development and transfer of environmentally friendly technologies to EIT Parties and developing countries (UNFCCC, 2019a).
- **Non-Annex I** Parties are mostly developing countries, some of which are recognised as being vulnerable to the adverse impacts of climate change, for example low-lying coastal countries. Other Parties in this group may be those that rely on fossil fuel production income and therefore feel more susceptible to prospective economic impacts following climate change response measures (UNFCCC, 2019a). Parties within this group are required to submit their GHGI within NC report every four years, and submit Biennial Update Reports (BURs) every two years containing updates of GHGI.
- **Least developed countries (LDCs)** Parties are given special consideration given their limited capacity to respond to climate and associated adverse effects (UNFCCC, 2019a). Parties within this group submit their GHGI at their own discretion.

1.2. Use of the IPCC Guidelines

The UNFCCC reporting guidelines state that the 2006 Guidelines for National GHGI, provided by the International Panel on Climate Change (IPCC) must be used by Annex I Parties (IPCC, 2006). Non-Annex I Parties can decide on whether to use the 2006, 2003 or 1996 guidelines (IPCC, 2003; IPCC 1996), though they are encouraged to use the most up to date version wherever

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possible. Under the Paris Agreement, Katowice Rulebook, form 2020, is obligatory for all Parties, including developing parties, to use IPCC 2006 (see section 2.1.1).

Under the IPCC guidelines, inventories rely on a few concepts for which there is a common understanding to ensure that they are comparable between countries and to avoid double counting or omission of emissions or removals (IPCC, 2006, Vol1Ch1). Among these, is grouping related processes, sources and sinks into sectors within which GHG emissions and removals are estimated:

- Energy
- Industrial Processes and Product Use (IPPU)
- Agriculture Forestry and Other land use (AFOLU)
- Waste
- Other (e.g. indirect emissions from nitrogen, deposition from non-agriculture sources).

Within each of these sectors, the emissions from sources and removals from sinks are estimated, which are then aggregated to provide a national net emissions estimate for a given year or period.

The IPCC 2006 Guidelines provides more information on the methodologies to estimate emissions and removals within each sector, using a *Tier*-based approach. There are three tiers of methodological approaches, Tier 1, 2, and 3, each with increasing methodological complexity, data requirements, and generally increasing accuracy too. This tier-based approach is designed such that estimating emissions and removals is possible for all member-Parties.

At its simplest, the methodological approach to estimate emissions or removals due to anthropogenic activity is to combine information on human activity (*activity data*) and multiply this by so-called default *emission factors*, which gives a numerical value to the associated emissions per unit activity (IPCC, 2006; vol1, ch1). The default data (Tier 1 methods) includes readily available national and international statistics that can be combined with default emissions factors, making it feasible for all countries to calculate emissions estimates, regardless of their state of development.

Higher tier methods and data include country specific and spatially explicit data and modelling methods.

1.3. Quality Assurance (QA) and Quality Control (QC) and verification system

One key aspect to compiling a GHGI is having a Quality Assurance (QA) and Quality Control (QC) and verification system in place, which should be applied at each step when compiling the report (IPCC, 2006, vol1, ch1). This system supports the development of GHGI that can be easily assessed in terms of their quality, and therefore, improves inventories. Within the IPCC guidance QA, QC and verification are defined as follows:

{From 2019, vol1, ch6, p6.6}

- *Quality Control* (QC) system, is one of routine technical activities to assess and maintain the quality of the inventory, throughout the compiling process, ensuring data integrity, correctness, completeness as well as identifying any errors and omissions and documenting the material. Table 6.1 in IPCC, 2006 vol1, Ch6 provides an overview of the general QC procedures.

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- *Quality Assurance (QA)* system, is a review procedure managed by personnel not directly involved in the inventory development process. These are usually carried out by independent reviewers, who verify that the inventories have been compiled using the best possible estimates of emissions and removals considering the current state of scientific knowledge and data availability.
- *Verification* is the collection of activities and procedures that help to establish its reliability for use as an inventory. It refers to the methods that are completely external to the inventory process, using independent data, and different methods, as well as comparing GHGI estimates made by other bodies.
-

1.3.1. QC procedures

QC checks on emission factors should be carried out, on both the IPCC default emission factors and the country-specific ones. In case of the former, it is good practice for the inventory compiler to determine the applicability of the factors to the national circumstances. In the latter, it is important to carry out QC checks on the data used to develop the emission factors, and any models used to obtain the emissions factor values.
Similarly, QC checks on the activity data used are important as the data are not normally just prepared by the inventory compiler for the GHGI. The activity data are usually from national secondary data sources or based on site-specific data. The compiler should therefore check the reference source and if it adheres to the general inventory QC procedures of the IPCC. The compiler should, where possible, compare the national activity data to other, independent activity data sources. For example, the United Nations Food and Agriculture Organisation (FAO) contain many of the activity data in the AFOLU sector as these are independently provided by government statistics. Further independently derived activity stemming from scientific literature for example should also be used where possible.

1.3.2. QA procedures

It is good practice for QA procedures to include an expert peer review within each sector, including a review of the calculations, assumptions made and methods used. The reviewers should be from an independent organisation or institution. Furthermore, the use of audits can help to evaluate the effectiveness of the inventory compiler, and their ability to keep to the QC specifications. The auditor should be independent from the compiler, and rather than focusing on the results of the inventory, as the peer- review would, they should focus on the procedures taken to compile the inventory.

1.3.3. QC/QA and Uncertainty estimates

While the QC/QA scheme and uncertainty estimates are independent from one another, the two provide valuable information for the other. By comparing these two it is possible to understand both the uncertainty level and inventory quality, which are two pieces of information that can be used to help improve the overall inventory. This may include improving the methods and data sources available. Furthermore, it is good practice to apply QC procedures to uncertainty estimates, as this will ensure calculations are correct and the methods and data are well documented and conform to the UNFCCC principles (TACCC).

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1.3.4. Verification

A main purpose of verification activities is to provide information on how a country's GHGI may be improved. By comparing inventory estimates to independent data, it may highlight significant differences which could be associated to either or both methods used. National estimates from different independent sources using different methods can be compared to GHGI within the individual sectors. This type of comparison helps to identify major calculation errors or may highlight a key subcategory in any sector that may have been omitted or falsely allocated in calculations.

Overall, having a suitable QA/QC and verification system in place is fundamental as the inventories are subject to external expert review prior to being made publically available ad used within further analysis.

VERIFY Deliverable D5.2 has introduced a few of the approaches and methods that can be used for independent comparisons, which will be referenced to where appropriate.

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2. Reporting and Review under the Paris Agreement

The Paris Agreement phase of MRV starts in 2020. Verification procedures (in its broader and not prescriptive sense) of the GHG estimations and achievement of targets are carried out under the Paris Agreement at three different levels:

1) Parties internal verification procedures of their GHG inventory, following the IPCC 2006 guidelines (QA/QC process), where results of the estimations are compared with independent data (See section 1.3.4);
2) Independent verification of the inventories through Technical Expert Review (every two years), that checks the consistency of the information submitted by parties with the modalities, procedures and guidelines of the enhanced transparency framework;
3) Global Stocktake (every five years starting from 2023) where the countries' collective progress is assessed towards the long term goals of the PA based on the best available science.

A general overview of the enhanced transparency framework and global stocktake processes are here provided in the light of the recent advancements achieved at COP 24 in Poland with the Katowice Rulebook (Dec. 2018).

2.1. Enhanced Transparency Framework (ETF)

Article 13 of the Paris Agreement established the Enhanced Transparency Framework (ETF) of action and support, the backbone of the Agreement aimed at providing a clear understanding of climate change action tracking the progress towards the Accord's objectives. The ETF is aimed at building trust and confidence among signatory Parties on the effectiveness of the undertaken actions. The framework is also key to inform the global stocktake (Paris Agreement Article 14) in terms of reduction achieved and future trajectories of foreseen actions under the Nationally Determined Contribution (NDC). The Modalities, Procedures and Guidelines (MPGs) for the ETF are defined in the Katowice Rulebook (decision 18/CMA.1) where the details of the implementation of the ETF are provided.

The MPGs requires to ALL Parties to provide, on a biennial basis, the following information in their **Biennial Transparency Report**:

- **National inventory report of anthropogenic emissions and removals**, consisting of a national inventory document and common reporting formats;
- **Information to track progress of targets** as defined in the National Determined Contributions;
- **Developed countries need to provide information on support provided** in terms of financial support, capacity building and technology transfer, while developing countries may provide information on support needed and received;
- If a Party wishes, adaptation action can be reported too.

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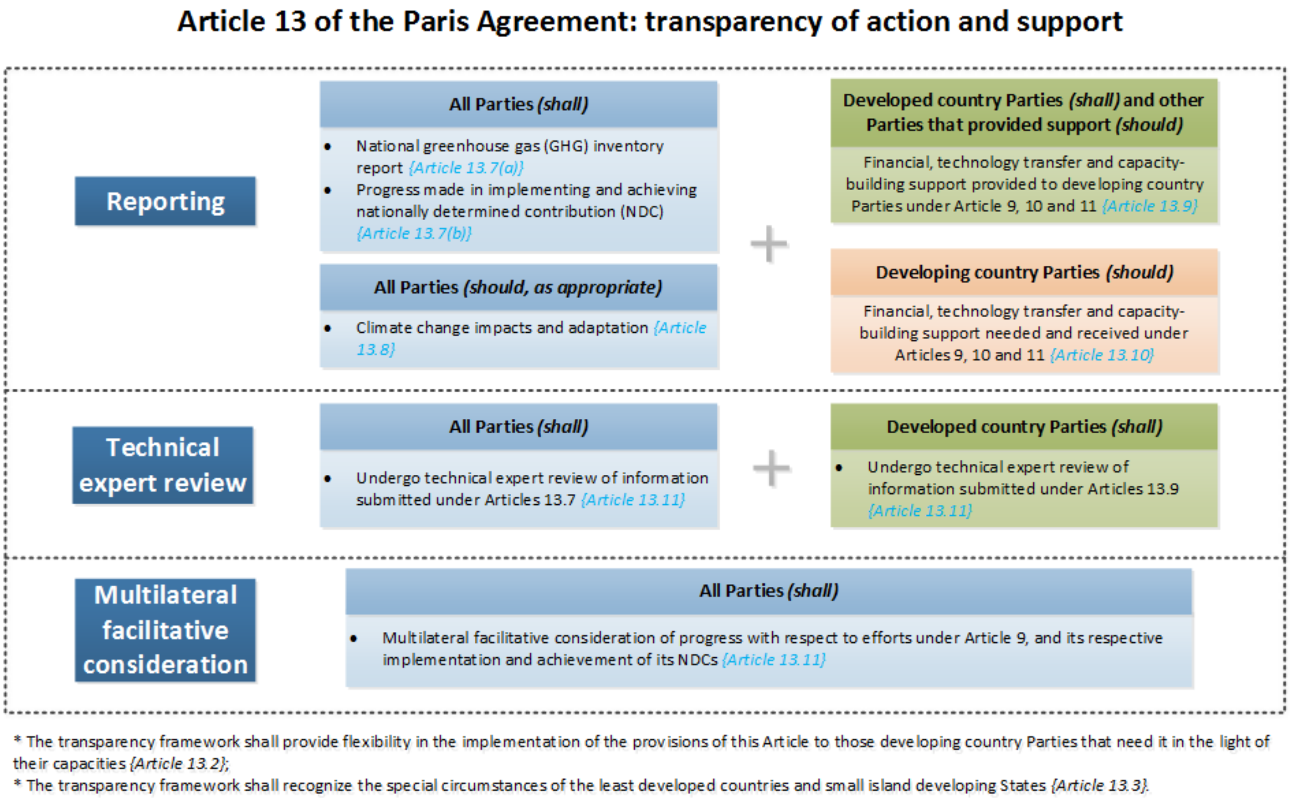

Figure 1 - Summary of the transparency process under Article 13 of the Paris Agreement (source: UNFCCC https://unfccc.int/process-and-meetings/transparency-and-reporting/the-big-picture/what-is-transparency-and-reporting). Note "*shall*" means the party must take the action, "*should*" means it is recommended the party takes the action.

In order to guarantee a full participation by all Parties, flexibility to developing countries is guaranteed in light of their capacities, which are self-determined, although they should define why they need such flexibilities and provide time frames to improve reporting. Such flexibilities are related to the scope of reporting, frequency, level of details and scope of the review.

2.1.1. National GHG inventory report requirements

The reporting requirements strongly build on the convention arrangements and will supersede them. Very little will change in terms of reporting obligations for developed countries under the convention, while big changes will occur for developing countries, since such requirements will be extended to all Parties, although with some flexibility related to the scope of reporting, frequency, level of details and scope of the review.

A great advancement of the new modalities and procedures under the PA is the harmonization of the use of guidelines for all Parties. In fact, the Katowice Rulebook establishes that the use of the IPCC Guidelines 2006 is obligatory for all, while previously different guidelines were applicable to developing and developed countries under the Convention. The application of the

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IPCC 2006 implies that all Parties will need to apply the verification procedures as defined in the Quality Assurance/Quality Control and Verification chapter (Volume 1, Chapter 6), as previously described (Section 1).

Regarding the metrics to be used for expressing the GHG values in an aggregated form, it was decided to use the global warming potential (GWP) from the fifth assessment report, or any 100-year-time-horizon GWP values from the subsequent agreed IPCC assessment reports. This metric will be used to express the aggregated emissions and removals in CO_2 equivalent. Under the Convention, the metrics used where those reported by the AR4 (see decision 24/CP.16), thus it is foreseen that for developed countries time series previously submitted under the Convention will be subject to a recalculation under the Paris Agreements.

Emissions and removals estimations for all categories of gases and carbon pools should be reported by Parties from 1990, following the IPCC 2006 Guidelines. Developing countries are warranted of some flexibility on the starting date of reporting, although it is compulsory to include any base year/period that is used in the country NDC and the estimations from 2020 onward.

Seven Greenhouse gases are to be reported by all Parties: carbon dioxide, (CO_2); methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3). Developing countries have the flexibility to limit their reporting to the most important gases (CO_2, CH_4 and N_2O) as well as any of the additional gas that is included in their NDCs.

Each Party should also provide information on the following precursor gases: carbon monoxide (CO), nitrogen oxides and non-methane volatile organic compounds (NMVOCs), as well as sulfur oxides, and on a voluntary basis also the indirect CO_2 from the atmospheric oxidation of CH_4, CO and NMVOCs, presented as aggregated and separated category with the national totals.

The details of some formats such as Common reporting tables, formats for the national inventory documents and of the biennial transparency reports, as well as the expert review formats, are still to be defined by Parties by 2020.

2.1.2. Tracking of NDC progress: accounting methods

The Katowice Rulebook provides guidance for **tracking progress on the achievement of Parties' National Determined Contributions (NDCs) (Dec 18/CMA.1)**. Such guidance can be applied on voluntary basis on the first NDC, and obligatory on the second submitted NDC. Given the wide variety of types of targets contained in the NDCs, the guidance is general enough to accommodate all possible options, mainly focusing on providing transparency information on the targets and its achievement. At first, when submitting their NDC, Parties *shall* provide the

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description of their NDC, such as the target type (base year or period, reference points, levels, baselines etc), scope and coverage (sectors gases, categories. etc), intention to use cooperative approaches (Art. 6 of the PA) and updates against the previously reported information. The parties *should* also identify the indicator(s) selected to track progresses on the basis of the type of NDC submitted. Indicators are self-determined by countries and can be qualitative or quantitative. For example, they could include net GHG emissions and removal, percentage of reduction of GHG intensity, or hectares of reforestation etc. In other words, while the reporting framework is clearly based on GHG inventories following a single set of guidelines (IPCC, 2006), the tracking of progress is more flexible, and it could be expressed in terms that could differ from GHG reductions including with non-quantifiable indicators, as some NDCs do not contain a quantified target.

The methods to track the progress (i.e. accounting approaches and methods) are defined by the Parties, however it is required to describe such accounting approaches including metrics used, indicators, IPCC guidelines used, sector specific targets and methodologies, potentially building on the existing approaches under the convention and the Kyoto Protocol. Parties should also explain how double counting is avoided. All information should be duly described and summarized in a structured summary, which format is still under discussion.

2.1.3. Expert review

The inventory reports, the progress of mitigation actions under NDC and the support provided by developed countries are subject to a **technical expert review**. As defined in the Paris Agreement, the review process will be implemented in a "*facilitative, non intrusive, non-punitive manner, respectful of national sovereignty and avoid placing undue burden on Parties*". The review process builds on what has been carried out for developed countries under the Convention so far, with the difference that under the Paris Agreement the review will apply to all parties. However, in reviewing developing countries, the team will have to consider the flexibilities warranted to them and will also identify capacity building needs in the course of their review. The process is coordinated by the Secretariat that will compose the team selecting among those nominated by Parties in the UNFCCC Roster of Expert, taking into consideration the needed competencies in respect to the report to be reviewed and the balance of experts between developing and developed countries, also ensuring gender and geographical balance. As performed under the Convention, the review may be centralized, in country, desk or simplified, according to specific circumstances.

The modalities and procedures guidelines of the ETF are contained in the Katowice Rulebook.

2.2. Global Stocktake

The *Global Stocktake* (GST) is established under the Paris Agreement (PA) as the periodical assessment of the collective progress towards achieving the purpose of the PA and its long-term goals (art.14 of the PA and Decision 19/CMA.1).

The GST must include information about mitigation and adaptation processes, and the means of implementation and support, based on the best available science and the equity concept. The process should inform Parties whether the cumulated efforts of the Parties is in track with the 2°C temperature goal, thus providing indication on how to enhance and update their actions at national level and through cooperation. The outputs of the GST should thus provide indication of opportunities and challenges for enhancing action and support. The process needs to be transparent, in the light of equity and best available science and it is strictly political (Party driven), although external experts are invited to participate to support the process.

The Global Stocktake shall assess whether the "collective progress" resulting by the sum of the GHG inventories from Parties is in line with the "well-below 2°C trajectory" as defined in the IPCC Assessment Report (AR), thus produced from atmospheric observation by the climate scientific community. The trajectory should be defined by the cumulative effects of the NDCs. Any identified gaps should result in an increased mitigation ambition by countries in successive rounds of NDCs. As consequence, climate science is playing a crucial role in the UNFCCC framework, providing data and methods for GHG estimations on the global level and, in the view of the PA implementation, also as "benchmark" for assessing the achievement of the 2°C temperature goal (Grassi et al., 2018).

The details of the GST are defined in the Katowice Rulebook (decision 19/CMA.1) including the three components of the process, described hereafter:

1. ***Information collection and preparation component***: This consists in gathering, compiling and synthesizing information for the following phases, undertaken by the subsidiary bodies under the PA with the assistance of the UNFCCC Secretariat. The Secretariat will gather and summarize the information with the support of the constituted bodies under the convention (e.g. Standing Committee on Finance, Adaptation Committee, Technology Executive Committee). A call for inputs will be launched by the Chairs of the subsidiary bodies that may be opened to non-Parties Stakeholders, with inputs to be provided at least three months before the technical assessment phase will start. However, it is decided that collection of information will need to end no later than six months before the consideration of output phase.
2. ***Technical assessment:*** This consists on taking stock of both the implementation of the PA long-term goals and the opportunities for enhanced action and support to achieve the goals. The assessment will take the form of a technical dialogue focusing on the three thematic areas of the GST (mitigation, adaptation and means of implementation), where the exchange of views, information and idea will take place in in-session workshop, round tables and other activities. Constituted bodies and experts are also invited to participate. The dialogue will involve also the IPCC. The output will be a summary report and overarching factual synthesis.
3. ***Consideration of output***: which consists on the discussion of the implications of the assessing findings at the political level. The output will be identification of opportunities

and challenges in enhancing action and support for the collective progress, with a summary of key political messages.

The GST phases are conducted by a joint contact group of the two subsidiary bodies under the Convention (SBI and SBSTA). Discussions are guided by a set of questions to be proposed by the chairs of SBI and SBSTA, to be submitted one session before the GST process starts. The time table of the first GST as defined in Katowice is reported below (Figure 2).

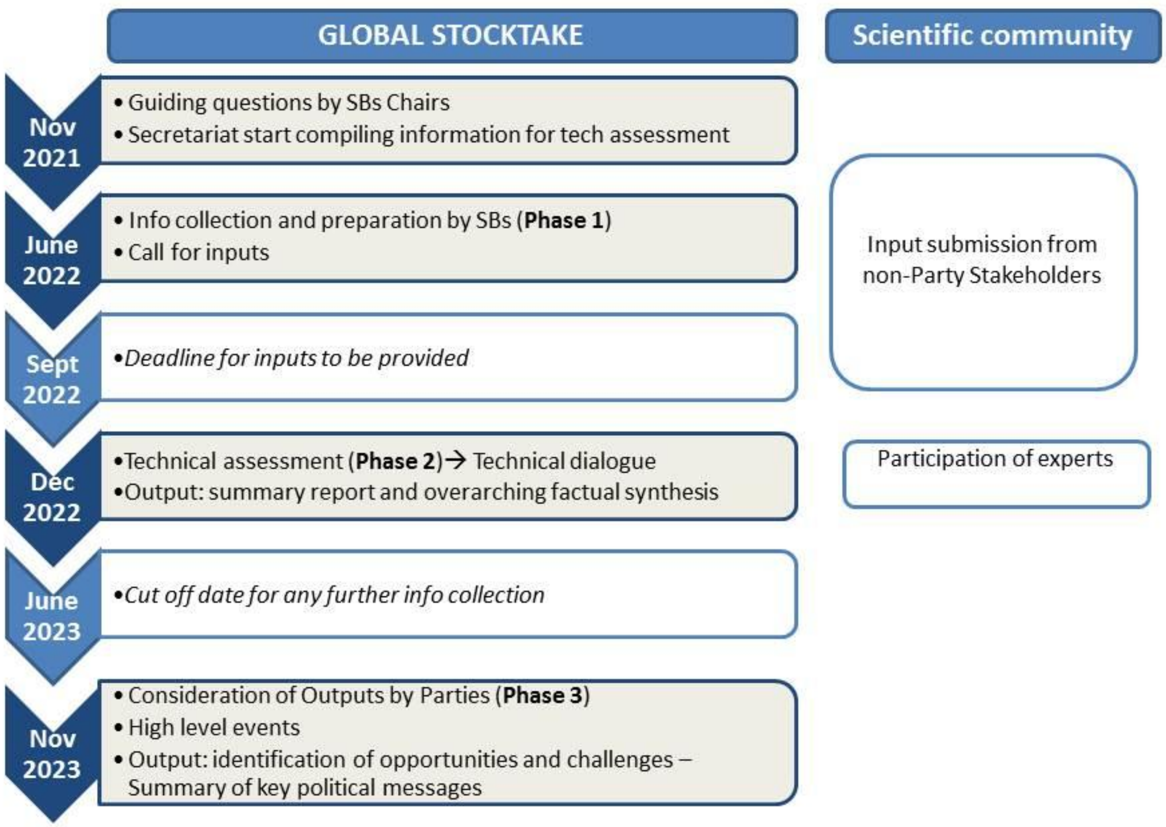

Figure 2 - Timeline of the first Global Stocktake

Source of inputs of the Global Stocktake may come from different sources, and they will include:

1. reports and communications from Parties (including Biennial Transparency Reports and GHG Inventories);
2. latest reports of the IPCC[1];
3. reports of the subsidiary bodies;

[1] As the IPCC assessment report follows a seven years cycle, the IPCC is currently considering options for aligning the work of the IPCC during its Seventh Assessment Report (AR7) cycle with the needs of the global stocktake under the Paris Agreement.

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4. reports from relevant constituted bodies and forums and other institutional arrangements under the Paris Agreement and the Convention;
5. synthesis reports by the secretariat produced during the first steps of the GST process;
6. relevant reports from United Nation agencies and other organizations supportive of the UNFCCC process (thus including the UNEP gap report);
7. voluntary submissions from Parties;
8. relevant reports from regional groups and institutions;
9. submissions from non-Party stakeholders and UNFCCC observer organizations,

With the last point, the process opens the door to any input coming from any non-governmental institution, including academy or scientific institutions. In fact, non-Party stakeholders are represented by Observer organizations admitted by the UNFCCC, that are further categorized into three types: the United Nations System and its Specialized Agencies, intergovernmental organizations (IGOs), and non-governmental organizations (NGOs). IGOs and NGOs can register delegates once they have received observer status and they include a wide variety of universities and research institutions.

The timing of the overall process is summarized in Figure 3.

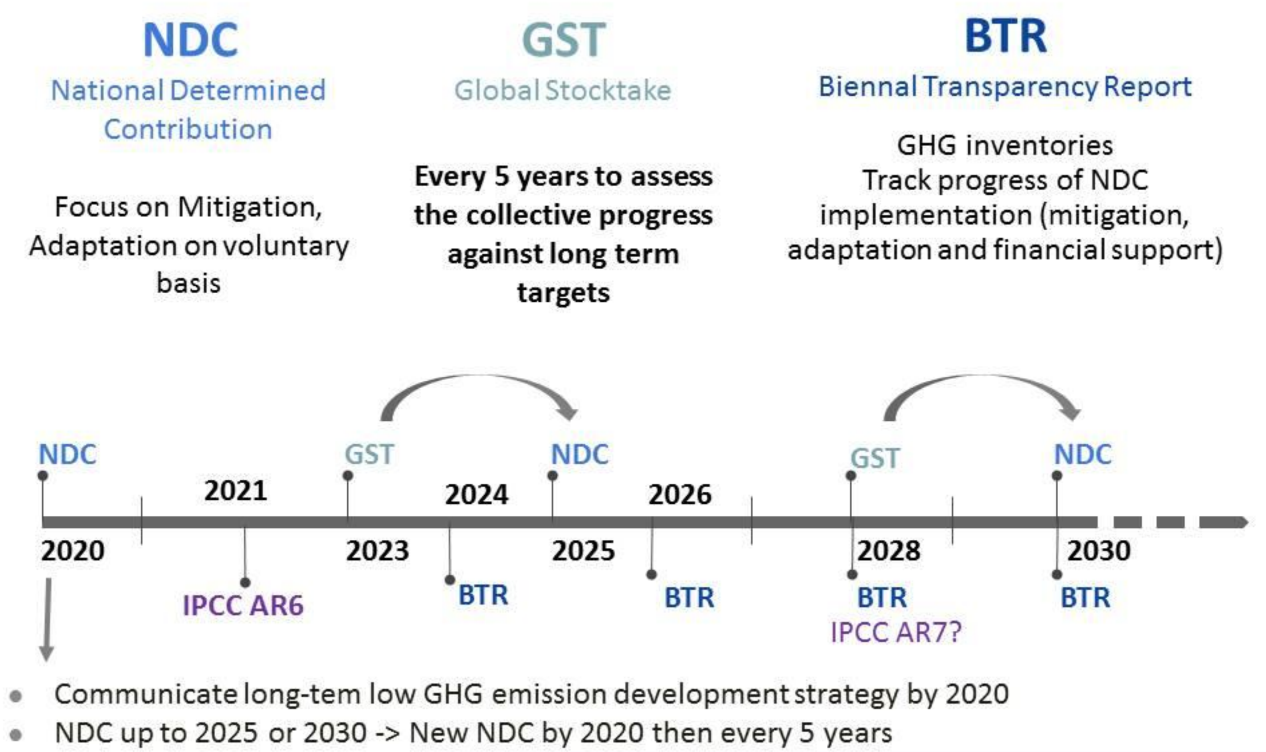

Figure 3 - Timeline of the transparency and global stocktake processes under the Paris Agreement

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3. Requirements and methods for reporting and verification in the different Sectors under UNFCCC

3.1. Energy, Industrial Processes and Waste sectors

The energy sector contains straight forward methods for compiling national inventories, where activity data is multiplied by emission factors. Activity data includes information such as national fuel sales, as well as number of vehicle miles driven. Higher tiers report using more locally applicable emission factors, and activity data broken up by vehicle type for instance.

The Industrial Processes and Product Use sector is a much more complicated set of methods. Generally, the method is specific to the industry or process. Lower tier methods include using chemical production volumes combined with emission factors, and higher tier methods may involve direct measurements of industrial production. For these higher tiers, parameters that are highly specific to individual production plants may be needed. In such cases, data must be collected from a selection of plants to ensure that the measurements are representative of the country.

This sector may also have issues regarding confidentiality of data, where industries dominated by a few producers may need their data aggregated to retain anonymity. Such cases may lead to increased uncertainty of spatial distributions which feeds into verification methods such as inversion modelling (see below).

In the Waste sector, emissions are modelled using First Order Decay models, with default emission factors provided for Tier 1 methods. Tier 2 methods use the same models, but with emission factors measured for local waste facilities, as this will vary based upon disposal methods and waste composition.

3.1.1. Data sources available for QA/QC/Verification

QA/QC for higher tier estimates involve comparison to lower tier estimates. For instance, if data from individual sites is available and compiled to produce emissions from chemical manufacture, this should be compared to calculations using total national production values. Likewise, vehicular emissions calculated from total miles driven should be compared to emissions calculated by total fuel sales.

One verification method available to all inventory teams, is comparison with freely available 3rd party products. The Emission Database for Global Atmospheric Research (EDGAR) provides global estimates of anthropogenic GHG emissions. Global products may contain lower tier data than a national inventory but provide the opportunity for an easy initial comparison that could highlight large scale errors. The (2006/2019) IPCC guidelines provide examples of institutions that provide public data that may be useful.

Trends in data should also be analysed for consistency. If sudden changes are detected in inventories, or components such as activity data, error checking should be performed. If no errors are found, an explanation for the change should be found and documented.

From the 2019 IPCC Guidelines Refinement: “An ideal condition for verification is the use of fully independent data as a basis for comparison. Measurements of atmospheric concentrations provide such datasets, and recent scientific advances allow using such data as a basis for emission modelling.” Verification using atmospheric inversion techniques is discussed separately in Section 4.

3.2. AFOLU sector

Volume 4 of the IPCC Guidelines for National Greenhouse Gas Inventories (GHGI) (IPCC, 2006, 2019 refinement – in prep.) describes the methods used to estimate GHG emissions and removals from the Agriculture, Forestry and Other Land Use (AFOLU) sector. Typically, the agricultural activities of the AFOLU sector are reported on separately. This includes emissions from enteric fermentation, manure management, agricultural soils and urea application. The remaining ‘FOLU’ is then often referred to as Land use, Land Use Change and Forestry (LULUCF) and is split up into six broad land-use categories. Countries are required to report on associated emissions and removals of CO_2 and other non-CO_2 GHGs estimates within each of the categories as well as the agricultural activities mentioned above:

- **Forest Land** – all land with woody vegetation consistent with the definition of Forest Land within the national GHGI. Where woody vegetation is present on other lands, but does not meet the national GHGI definition for forest land, the area of vegetation will fall into the other land-use category.
- **Cropland** – all cropped land and agro-forestry where any woody vegetation structure present does not meet the national GHGI definition for Forest land.
- **Grassland** – includes both rangelands and pastures that are not considered cropland, and other wooded lands that do not fit the Party’s forest land definition.
- **Wetland** – areas of peat extraction and land, covered or saturated by water for all or part of the year.
- **Settlements** – all land with infrastructure such as roads as well as settlements.
- **Other Land** – includes all bare soil land, rock surfaces, and land does not fall into one of the other five categories.

(IPCC, 2006, v4, c3)

The categories are then further sub-divided into land remaining in the same category (e.g. forest land remaining forest land) and land converted to another (e.g. Forest converted to cropland) and associated GHG emissions and removals estimates are calculated within these sub-categories.

The main GHGs within the AFOLU sector are CO_2, N_2O and CH_4. Agricultural activities mainly emit non-CO_2 gases, while LULUCF activities predominantly emit and remove CO_2 (IPCC, 2006; v4,ch2). The activities to which the gas emissions pertain are summarised in D5.2 (Section 2: Data Sources).

The AFOLU sector is unique in that the factors governing emission and removals can be both natural and anthropogenic (direct and indirect, *see Figure 4*) and that the factorial causes can be difficult to distinguish from one another. To account for this issue, a key assumption made in the AFOLU sector is the so-called "managed land proxy". This assumption means that countries are required to report on *all* emissions and removals of GHGs that occur on managed lands, regardless of their drivers. In other words, all effects (emissions by sources and removals by sinks) that take place on land are considered to be anthropogenic. This includes direct-, indirect-anthropogenic and natural effects that may take place on these lands (*see Figure 4*). The term *'managed land'* refers to any lands where human interventions and practices have taken place for production, ecological or social purposes, and each country defines what constitutes "managed lands" within certain parameters. According to the Guidelines, it is *good practice* to monitor and quantify the area of unmanaged land for completeness and consistency (IPCC 2006; v4, ch1). Once land has been classified as "managed" it must remain in this category – i.e. it must always be included in reporting.

3.2.1. General methods for GHG emission and removals estimates in AFOLU

GHG fluxes can be estimated within the six land use categories respectively, and ultimately aggregated for the entire sector, in two ways (IPCC 2006; v4, ch1):

1) Estimating net changes in **carbon stock** over time, which is used to estimate CO_2 emissions and removals (IPCC 2006; v4, ch2). Wherever possible, countries are required to report on movement of carbon between five carbon pools: **Biomass** (Above- and Below-ground biomass), **Dead organic matter** (Dead wood and Litter), **Soils** (IPCC 2006; v4, ch1). Within each of the pools, the changes in carbon stock in the land-use category are estimated for land remaining in the same land-use category and land converted to a new category. The convention is to report any emissions and removals from land-use change in the *new* land-use category.

2) Using **gas flux rates** to and from the atmosphere which is primarily used for non-CO_2 GHGs, especially in the agriculture sub-sector of AFOLU. Livestock and manure management is key for CH_4 and N_2O emissions, as well combustion from biomass, deadwood and litter and N_2O emissions from soils within different categories (IPCC, 2006; v4, c1). The gas flux rates are calculated using the general method for calculating emissions/removals estimates by multiplying activity data by an emission factor.

3.2.2. Data sources and methods for AFOLU

Identifying the land-use category requires the use of land-use datasets, which can be sourced from databases prepared for other purposes (national or international databases), collected by sampling or compiling a complete land inventory. When using pre-existing land-use data, it is important to consider the varying definitions of the categories between databases and the national inventory and to harmonize these to reduce gaps or overlaps (IPCC, 2006, v4, c3).

From the 2019 IPCC GL refinement, v4, c3: "Methods for estimating land-use and land-use change estimation are increasingly relying on remote sensing products due to their numerous potentials. At their simplest, they can be applied to identify the land cover and land cover change. Remote sensing data is also used to attribute the cause of the land-use change, to a disturbance e.g. cropland burning, wildfires, harvesting, clearing etc. Finally, by identifying land use categories, it can give an indication of the state of the land-use category e.g. its growth stage, or condition."

Once the land-use categories have been identified, they will be applied to one of the two methods (section 2.2.1). From the 2019 IPCC GL refinement, v4, ch2*: "A Tier 1 approach will rely on default emission factors and activity data as described above occurring within each of the categories. A Tier 2 approach may apply country-specific and more detailed emissions factors. Many Tier-3 inventories are increasingly using various models such as empirical, process-based, hybrid and/or other types of models, each with different suit abilities for estimating emissions and removals from the carbon pools and non-*CO_2 *gases across the land use categories. The models can be run separately for the different land use categories and carbon pools or combined into a single framework. Nevertheless, the models will still require data sources to calibrate and validate the models".* Thus, carbon changes within the biomass pool can be estimated using standard biomass growth curves (Tier 1) or using national-derived data from other inventories e.g. national forest inventories and/or using models (Tiers 2 and 3). "*This includes the use of allometric models to estimate carbon stocks at a Tier 2 level. Airborne or terrestrial platforms of remote sensing can be used for deriving variables used for constructing and validating allometric models*" (IPCC 2019 GL refinement)

The remote sensing developments have also allowed for the construction of biomass density maps which can be used for biomass estimation at Tier 2 and 3 levels (e.g. Avitabile et al., 2012; Baccini et al., 2012; Saatchi et al., 2011; Avitabile et al., 2016). The biomass density maps can be combined with activity data to estimate emissions factors. Another approach may be to estimate the temporal biomass change using multi-temporal biomass density maps. A recent study (Baccini et al., 2017) has used remote sensing data to monitor changes in biomass density over time. In creating temporal biomass change maps, this approach would enable activities such as degradation, regrowth and management to be included. In order for such an approach to be used in the inventory process it would require well-calibrated maps based on ground and remote sensing data, which has not been achieved yet for national GHGIs. Biomass maps can also be used with a time series of land use change data, obtained from remote sensing data, and/or integrated with Tier-3 process models, to identify the sources of emission estimates.

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All these approaches for using biomass maps require consistent definitions of the land use categories, field data verification measurements and at an appropriate spatial resolution if it is to be used as a method within the inventory. Furthermore, the key consideration with remote sensing data is only above-ground biomass is directly measured. Corresponding below-ground biomass will need to be inferred from the resulting data."

3.2.3. Verification in the AFOLU Sector

Within the AFOLU sector, verification can be done at two stages within the inventory process, the first is validating the input data used to compile the GHG flux estimates, the second is to compare the GHG Flux estimates to independent estimates. The latter can either be done using vegetation model estimates or by using atmospheric concentrations of the gas in question used within inverse modelling approaches (so-called top-down models), although these approaches are more typically used in the energy sector (see section 4). This is particularly important for non-CO_2 gases. From 2019 IPCC GL refinement v1,ch6: *"For example* N_2O *emissions by agricultural soils can be estimated using inverse modelling, so far application of this is largely limited to the US and Europe (Manning et al., 2011; Miller et al., 2012; Bergamaschi et al., 2018)".* Within the 2006 and 2019 IPCC guidance, there is very little information on verification of non-CO_2 gases specifically in the AFOLU sector using this inverse modelling methods. Alternatively, country-specific information within international databases such as FAOSTAT and EDGAR are recommended if no local data is available for verification (see section 3.3.2), although note that for LULUCF, EDGAR are currently changing their methods to be more conceptually similar to what is considered LULUCF by UNFCCC, and new data should be available in 2019 or 2020. Given that it is harder to verify CO_2 emissions using the inverse modelling approach in the AFOLU sector, a bottom-up approach is typically used for verifying emissions using remote sensing data and carbon models.

3.2.4. Remote sensing data

From the draft 2019 IPCC GL refinement, v4, ch3: "*Remote sensing products can be used for constructing land cover datasets and producing biomass maps, both of which can be used as part of the inventory process or as means of verification. Examples of global land cover products include the ESA Climate Change Initiative Global Land Cover Products, the Global Forest Watch and MODIC land cover type products. As these products may have a different spatial resolution, land classification scheme and accuracy compared to the national inventory definitions, the inventory compiler should consider the purpose of the products carefully. If the products are not used within the inventory, they can be used as independent verification tools of the land-use categories*."

The example using biomass density maps within inventories was already detailed above (section 3.2.2). This kind of approach can also be used for verification in countries where the biomass maps cover large areas and so the spatial resolution may not be representative for the country or where the definitions of the land-use categories and/or carbon biomass pools are not consistent with national definitions of the category or pool. Therefore, instead of using it within the inventory, it can be used for independent comparisons and verifications.

The remote sensing technologies for producing biomass density maps include Optical, Synthetic Aperture Radar (SAR) and Light Detection and Ranging (Lidar) sensors. The suitability of optical sensor data relies heavily on the spatial resolution, ranging from coarse (250m e.g. MODIS sensor), to medium (10-80m e.g. Landsat products and Sentinel 1 and 2) to fine resolution (<10m e.g. Rapideye or SPOT). The active sensors, SAR and Lidar use microwave and pulses and laser pulses respectively to derive metrics to estimate height, volume or biomass of the land-use category.
Remote sensing technology can also provide the data needed to verify allometric models. Terrestrial laser scanning, a ground-based active form of remote sensing, uses laser pulses to measure key allometric variables such as tree height, stem diameter etc.

There is no reference within the IPCC guidelines (2006, 2019) to using remote sensing data to *verify* non-CO_2 GHG emissions from biomass fires within the AFOLU sector. However, Lin et al. (2012) used MODIS measurements of active fire counts from agricultural burning and compared these results to GHGI estimates of emissions from agricultural burning. They showed that remote sensing can be used as an effective means for comparing, and potentially improving future inventory reporting of agricultural biomass burning in the future if combined with census data, field experiments and expert opinion.

While the applications of remote sensing within the AFOLU sector has increased significantly since the IPCC 2006 guidelines were written, they will continue to improve following the 2019 IPCC GL refinement, with more research on its potential being conducted and more remote sensing missions at higher resolution and varying data bandwidths starting soon. One such example is ESA's Earth Explorer Biomass product, which is due to launch in 2021. One of its mission objectives is to improve understanding and quantification of the carbon flux from land use change (ESA, 2019). These sorts of products will most certainly be used in either the inventory process or as means of verification.

3.2.5. Independent dataset source of GHG estimates

FROM IPCC 2006, v4, ch2: "*National GHGI estimates from Tier 3 models can be difficult to verify because alternative measurements often do not exist at the national level [for the whole AFOLU sector] … there may however be opportunities to verify component estimates against independent data*."

D5.2 introduced some of the main independent methods that could be used to compare different GHG estimates with those produced by inventories within AFOLU sector (see D5.2, Table 1 for examples of independent data sources). For example, CH_4 emission estimates from GHGIs can be compared to the JRC's EDGAR dataset as well as FAOSTAT, which is particularly relevant within the agricultural sector and activities occurring within this sector (see D5.2 Figure 22).

Another option is to compare GHGI estimates to bottom-up models used within the carbon science community (see D5.2, Figure 16). A recent study (Grassi et al., 2018) carried out a comparison of the GHG flux estimates in the LULUCF sector as calculated by independent science bodies and by national GHGIs. Focusing on CO_2 emissions, they explore the differences between the estimates and ways to reconcile them. Over the period 2005-2014, they identify a difference of 4 $GtCO_2year^{-1}$ in the global CO_2 net emissions from LULUCF between the independent science-based estimates and countries' GHGI. A large proportion (80%) of the difference can be explained by conceptual differences between the definition of the term 'anthropogenic land use CO_2 flux' used by the methods (Figure 4). As previously stated, the IPCC guidelines for national GHGI apply the "managed land proxy", which includes effects other than direct human impact, due to the difficulty in developing a scientifically robust method to isolate direct human-induced effects (Figure 4 Top panel - b and c). In contrast, the science-based approaches are largely able to separate these effects and treat the indirect-human induced effects and naturally occurring effects, collectively as the "residual sink" or "land sink". While both approaches are valid in their respective context, they are not directly comparable. However, given that it is likely that both national GHGI and independent scientific estimates will be used in the upcoming 5-yearly global stocktakes to determine the collective progress towards achieving the goals of the Paris Agreement, the difference between the two approaches needs to be reconciled.

In this study, Grassi et al. (2018) combine the science-based approaches to aim to reconcile the difference. They aggregate the direct, indirect and natural effects occurring on "managed land" as calculated by the science-based models and compare the sum (Figure 4 bottom panel - grey bars) to the fluxes from the GHGIs (Figure 4 bottom panel – green bars). This approach largely reconciles the differences between the two approaches and provides a method that could be applied within the global stocktake in the future. A similar approach, using managed forest area data, may therefore be possible at the national scale and provide a means of comparing CO_2 emissions estimates with national GHGI in the AFOLU sector.

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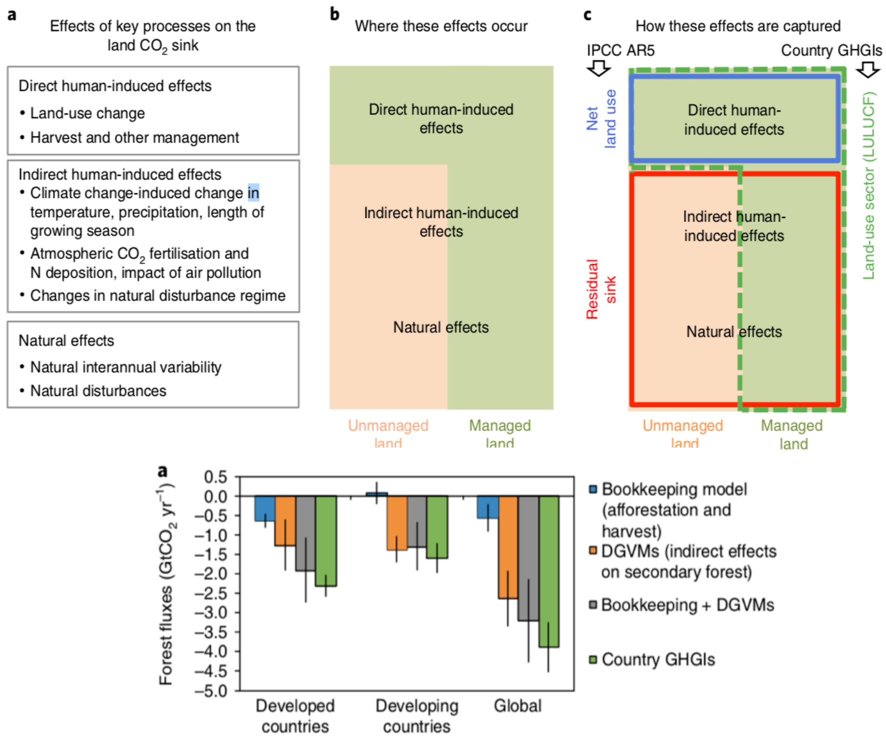

Figure 4 Summary of the main conceptual differences of the 'anthropogenic land CO_2 flux' within LULUCF sector (top panel) and a way to reconcile these differences (bottom panel). Top panel - the effects of key processes (a) and where they occur (b), as well as how these effects are captured in the science-based approaches (collectively - IPCC AR5) compared to in the National GHGIs. Bottom panel – comparison (blue, orange and green bars) and reconciliation of net global forest CO_2 fluxes. (Figures from Grassi et al., 2018).

Another study carried out a comparison of CO_2 equivalent emissions within AFOLU using the

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EDGAR and FAOSTAT dataset as well as Houghton et al. (2012)'s bookkeeping model (Tubiello et al., 2015). While the results from all the datasets and methods were within the same order of magnitude, the EDGAR dataset exhibited higher emissions values compared to the other two approaches which were largely similar. They attribute these differences to EDGAR counting energy emissions from agriculture in the AFOLU sector rather than the energy sector. Furthermore, the EDGAR dataset does not follow either the IPCC Guidelines or standard carbon cycle approaches within LULUCF in contrast to FAOSTAT and Houghton data. Their results therefore stress the need for a multi-source data approach when comparing to independent dataset sources, rather than relying on simply one source for independent comparison. As stated, EDGAR is currently updating their methods and estimates for LULUCF.

4. Atmospheric inversion methods for verification

4.1. Inversion methodology

Atmospheric inversions treat the atmosphere as a large-scale integrator of fluxes, with measurements of GHG concentration made at one point being affected by all emission sources upwind of the measurement. Over long enough time scales and with enough sampling sites, the measurements will allow building a picture of emissions in the surrounding areas. A single site can be sensitive to an entire country and its background (Manning, O'Doherty et al. 2011), but adding more sites increases the resolution of the system.

By combining a network of measurement sites with an atmospheric transport model and a statistical (often Bayesian) framework, inversion modelling allows for a spatially and temporally resolved estimation of GHG emissions constrained by observations. The skill of the inversion model is dependent upon having a network with sufficient coverage of the geographic area of interest, and an accurate transport model.

Inversion models generally require a "prior" emissions estimate (i.e. a first expert estimate of emissions), which can provide initial information about the spatial distribution on emissions and constrain emissions within a given uncertainty range. This prior may include a national inventory, a global product, or a combination of the two. A useful inversion will provide a posterior emission estimate with much lower uncertainty than the input prior. This is where the Bayesian component of the model is used – the information contained in the prior inventory is combined with information from atmospheric measurements to give the best estimate.
Inverse modelling relies on measurement networks that require expert maintenance and calibration to ensure accurate measurements, and inverse models require expert judgement in their operation and selection of parameters.

Currently, three countries refer to inversion modelling as part of the verification process in their annual UNFCCC reports. These countries will be analysed further in order to demonstrate practical application and good practices of inversion modelling. The "EU inventory system &

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quality assurance programme" report (UE Commission 2013) also suggests that inverse modelling, based upon current research taking place in the EU, could be used as a verification activity.

4.2. Inversion method applicability to different Gases

4.2.1. CO_2

Carbon dioxide is a difficult gas to verify with inversion models. The primary reason for this is the large contribution of natural sources/sinks to the total CO_2 flux. As the atmospheric concentration of a gas is a combination of fluxes from all sources, additional information is required to separate anthropogenic and natural fluxes. This can be done for fossil fuel CO_2 emissions with measurements of radiocarbon and co-emitted tracer gases such as CO and NOx [D5.2 report].

One consideration in use of inversions to verify fossil fuel CO_2 emissions is that national inventories already have relatively low uncertainty, and inversion uncertainties arising from transport modelling, and sectoral disaggregation could in principle be larger than the national inventory GHG emissions estimates.

For CO_2 flux in the LULUCF category, inversions can be used to identify the total net biosphere CO_2 flux (net of all emissions and removals due to both anthropogenic and natural drivers) by deriving it from other CO_2 flux term: If fossil fuel CO_2 emissions from the inventories are treated as "truth", (i.e. prescribed in the inversion systems), the biosphere flux is derived as the residual of the total flux minus fossil fuel flux and assumed ocean uptake (White, Rigby et al. 2019). However, atmospheric measurements can only provide the total net flux from the land and cannot separately attribute it to anthropogenic (LULUCF) and non-anthropogenic emissions and removals.

There is currently much effort placed in research towards city-scale CO_2 inversions using purpose built, dense networks. By having much denser networks, a greater spatial resolution is achieved, and some separation of anthropogenic and natural sources may be possible based on source location (Shusterman, Kim et al. 2018). At these local scales, inventories also suffer from higher uncertainty, making inversions more attractive. [BEIS verification report]

4.2.2. CH_4

From the draft 2019 IPCC GL refinement: *"Methane (CH_4) is considered a favorable candidate to which inverse modelling techniques can be applied because of the strong atmospheric signal to noise ratio of measurements and the generally high uncertainty in emission estimates that arise from uncertainty of activity data and emission factors*."

Like for CO_2, the contribution of natural CH_4 fluxes should also be included in the inversion systems. Prior information on the natural CH_4 fluxes are usually taken from various modeling

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approaches and the quality of the emission retrievals will also highly depend on the uncertainty associated to the natural fluxes.

4.2.3. Nitrous Oxide

From the draft 2019 IPCC GL refinement: "*Nitrous oxide emissions by agricultural soils are known to have large uncertainty because of patchy heterogeneous emission patterns and significant temporal variability, leading to uncertainty in activity data, emission factors and emission rates, which makes it useful to test the estimated emissions with inverse modelling*."
Like for CO_2 and CH_4 the natural nitrous oxide fluxes should also be included and their uncertainty will play a key role in the estimated N_2O emission fluxes and uncertainties.

4.2.4. F-Gasses

F-gasses include HFCs, PFCs and SF_6. These are gases that are nearly exclusively of anthropogenic origin and have some of the highest Global Warming Potential of known atmospheric constituents. The F-gasses are prime targets for inversion modelling as there is no issue with separating anthropogenic and natural sources and inventories carry high uncertainties.

4.3. Inversion method application case studies

4.4. Case Study – UK

The UK includes verification with inverse modelling in its NIR to the UNFCCC, with detail given with a public national document, "Annual Report 2018: Verification of UK greenhouse gas emissions using atmospheric observations". The UK is a world-leader on reporting verification with inverse modelling, applying it to the largest number of GHGs.
The UK uses a purposely-built network of monitoring sites to provide the observations for its inversions. The UK Deriving Emissions related to Climate Change (DECC) network is composed of a background monitoring site at Mace Head and three tall towers at Ridge Hill, Tacolneston and Bilsdale. A fifth affiliated site at Heathfield that is not directly a part of DECC is also available for use in inversion modelling. For use with methane only, data from an additional site in The Netherlands is provided courtesy of ECN [annex 6 UK NIR].

The UK uses the bespoke "inversion Technique for Emission Modelling" (inTEM) model to perform inversions, which splits atmospheric concentrations into a time-varying baseline and regional perturbation. The model also spatially aggregates emissions based on proximity to observations, respecting administrative boundaries where important.

inTEM uses the NAME atmospheric transport model, driven by meteorology from the MetOffice, to link emissions and atmospheric observations and uses a Bayesian approach to find the emissions map which gives the best agreement to observations.

In order to stay independent of the UK inventory being validated, inTEM is run using EDGAR emission information, with UK emissions spread uniformly in space with high uncertainty. By taking this approach, the model is guaranteed to be driven primarily by the observations rather than the prior. However, when run in this mode emission estimates require averaging over longer periods than if gridded national inventory data was used.

Verification of inventory estimates of HFC-134a highlighted discrepancies between the inventory and observations. This prompted a re-analysis of the inventory methods used for the gas. From this, revisions of the refrigeration and air conditioning model used for the gas, which led to the inventories agreeing better with observation.

4.5. Case Study – Switzerland

Switzerland has the second highest level of inverse modelling within the verification section of its UNFCCC NIR. It is applied to some F-gasses and to methane, with preparations for modelling N_2O already started.

For the F-gasses, atmospheric measurements are taken from an alpine research centre, Jungfraujoch. Meteorological parameters are used to select only observations that are heavily influenced by air coming from Switzerland itself, which gives around 7-15 days of observations per year. The modelling is done with a tracer-method, with CO used as an auxiliary tracer to interpret HFC and SF_6 measurements.

The results of the inversions are used to highlight possible discrepancies between atmospheric observations and the inventory, and where such discrepancies exist the inventory methods are reanalysed to improve the estimate. There is an important caveat with the F-gasses, in that some inventory reports are based upon country of production rather than country of release, which may be incompatible with atmospheric observations.

Methane modelling uses a GHG network consisting of 4 sites, of which 3 are still active as of the 2018 report. These sites measure both CO_2 and CH_4, and atmospheric modelling was used to ensure that the selected sites cover the Swiss Plateau where most emissions are expected.

Similar to the UK, the Swiss inversion model separates observations between a baseline and a regional perturbation, and aggregates spatially such that the model has higher resolution closer to observations. In contrast to the UK modelling, Switzerland uses a gridded form of its own national inventory as a prior to the model, with the TNO/MACC-2 inventory for external emissions. It compared this with EDGAR as a prior and concluded that the national inventory agrees better with the observations.

In order to apply QA/QC to the verification, sensitivity studies are performed on the inversion, varying different parameters to observe the effect on the posterior emissions estimate. When

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the inversion highlighted an area of the country with much higher emissions than given in the gridded inventory, a short-term monitoring campaign was set up to observe this hot spot. From this campaign, it was concluded that the hot spot was an artefact, but without any noticeable impact on the national total estimate. This example highlights the increased uncertainty when analysing smaller regions from inversion results, and that additional measurements may be needed to verify that local emission patterns are not artefacts allowed by a sparse network.

4.6. Case Study – Australia

Australia only makes minor mentions of inversion modelling as verification in its UNFCCC NIR, although the Australian government has performed previous work on a range of F-gases [“Australian HFC, PFC, Sulfur Hexafluoride and Sulfuryl Fluoride emissions”]. A measurement site on Cape Grim is used to observe SF_6, and an inversion model is used to derive national emission estimates of this F-gas.

From this inversion, the emission factor relating to leakage of SF_6 was adjusted so that the inventory better agrees with observations. Indeed, this parameter has large prior uncertainty and is expected to change over time as industry adopts new technology.

4.7. Potential gaps for further use of inversions

From 2019 IPCC GL refinement “*It should be recognized that the technical complexity as well as the limited application potential of atmospheric models to inventory verification, particularly at a national level, can restrict their utility to many inventory compilers*.”

Specialised equipment and expert labour are required to use inverse modelling as a verification technique. If countries are to routinely use inversion modelling as a verification tool, then countries must foster long-term plans to ensure that expertise is funded and maintained in local academic or government institutions. Alternatively, international organisations of inversion modellers may be formed to provide expertise to member countries. In a previous attempt to expand an inversion modelling network, availability of operational experts was found to be a limiting factor [personal correspondence]. Geographical considerations may also apply. For instance, south-westerly winds often bring clean, ocean air to the UK, allowing for easy measurements of a western baseline in order to isolate regional contributions. Australia also has ample opportunity to measure clean ocean air.

Air flow does not respect national borders - this may make it difficult to separate national contributions in areas with high emission densities from multiple countries. An example of this is western Europe around Belgium, the Netherlands and the western edge of Germany, where dense populations and industries are spread across several borders. Overcoming such an obstacle may be possible with a dense network of atmospheric observations, which is able to

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separate out a ‘dirty’ variable background airflow coming from a neighbouring country. Alternatively, atmospheric data from multiple countries could be aggregated and verified at the EU level rather than the country level.

Finally, the inventories need to provide the emissions in specific categories that may not be easily singled out in atmospheric data. For example, considering IPPU and Energy sector, it may be very difficult to estimate emission derived from energy and non-energy use of fuels/feedstock (e.g. in the chemical or iron and steel industry). In order to allow for independent verification, at least in this specific case, the emissions from the various categories have to be taken into account and summed up. Another example is the systematic distinction of a specific plant (e.g. steel plant or a refinery) in different source categories in the inventory within a sector. Regarding the land sector, it could be difficult to separate the anthropogenic and natural emissions/removals.

4.8. Measurement Needs

Atmospheric modelling should be used to ensure that any GHG network is sensitive to the entire region in which emission verification is desired. Increasing the number of observation sites and the number of useful observations at each site will decrease uncertainty and provide an estimate that is more independent of the prior inventory used. Studies have shown that network design has the potential for high impact on both urban (Turner, Shusterman et al. 2016) and national (Ziehn, Law et al. 2016) levels.

Any measurements made must also be precise enough to accurately measure the contribution of regional emissions to the atmospheric concentration. The forward model component of an inversion model may be used to estimate the precision requirements based upon the existing national inventory, and location of measurements.

The current generation of satellite observations of atmospheric chemistry are too sparse to be useful in small or cloudy locations such as the UK. There is also reduced coverage during winter time in the northern hemisphere when using the reflection of solar radiation to observe GHGs. However, the next generation of satellites such as TROPOMI are expected to be much more useful due to an increase in spatial resolution and measurement density.

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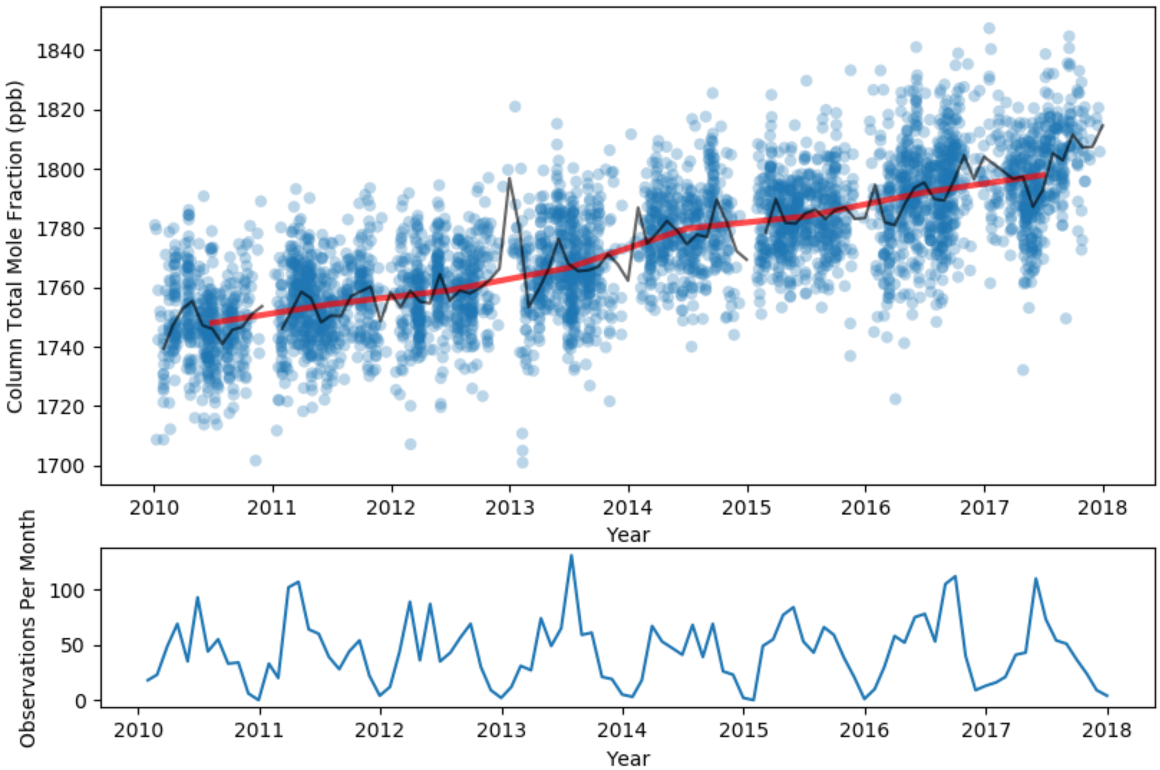

Figure 5 - Example of GOSAT methane observations over the UK, showing a lack of successful retrievals during the winter months.

In some locations without surface networks, such as India, a combination of satellite and airborne atmospheric observations have been useful to verify emissions (Ganesan et al. 2017). Such techniques may be useful in extending inversion modelling verification to the inventories of other countries which do not have the resources to maintain their own inversion network.

Measurements of radiocarbon and co-released tracers such as CO or NOx in the case of CO_2, may allow for inversion models to be able to separate anthropogenic and natural emissions, however, such a work is still under active development within the inversion research community.

4.8.1. Modelling Needs

Comparisons between different inversion models show a large spread in results, greater than the theoretical uncertainty of some individual models (Bergamaschi, Karstens et al. 2018). Such a spread suggests that the best techniques for inversion are not fully (or widely) understood and more work must be done to ensure that models are consistent with each other. If models do not agree, then the choice of model used may have a significant effect on the quality of verification or result in different standards for different countries.

Further work to decrease the uncertainty within inversion models would also increase their usefulness for verification. One of the largest sources of uncertainty comes from the atmospheric transport model. Work being done in the UK using radon detectors will seek to better constrain inverse models through transport, as radon sources are well known.

Another method available for countries unable to operate a national network would be to use published results from academic research. Various groups perform inversions at global or regional scales, from which country totals could be extracted. These emission estimates may not be as accurate as results from a national network but would allow independent verification for a number of countries at low cost.

One example of this global inversion data comes from the Copernicus Atmosphere Monitoring Service (CAMS), implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF). CAMS provide global inversion results for CH_4, CO_2 and N_2O using surface network observations.

Developing standards for comparison to global inversions for a variety of gasses using surface and satellite observations may allow a low-cost path for many countries to verify their emission inventories against independent data. Care must be taken as extracting information from small regions of a global inversion may be subject to large uncertainty, and could be inappropriate for countries with small land area.

For many country-level inversion models, a Lagrangian model is used such as NAME [BEIS report, CSIRO report “Australian atmospheric measurements and emissions estimates…”], FLEXPART [Swiss NIR] or STILT (Bergamaschi, Karstens et al. 2018). These models are efficient for modelling transport related to a low number of sites. With the increase in column data availability from next-generation satellites such as TROPOMI, Lagrangian models may become prohibitively expensive. Either data-reduction techniques or switching to Eulerian models may be necessary for regional or country inversions.

4.8.2. Collaboration with inventory teams

In order to obtain the greatest utility from atmospheric inversions, inversion modellers and inventory teams must work together closely, with each of their results feeding into the methods of the other. If Bayesian statistics are used, then the quality of the gridded inventory will affect the inversion results. A high accuracy inversion result can be fed back to adjust inventory techniques.

The case studies of the UK and Australia both show examples of the verification process leading to an evolution of the inventory method. This allows for a greater understanding of the processes contributing to the emissions as well as more accurate reports.

Inventory teams can also help inversion modellers by providing gridded inventories to be used as priors for the models. If modellers are in contact with inventory teams from the start, they

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can communicate the features of the inventories that would be useful for modelling. Inventory teams will also be able to highlight inventories that are most in need of verification.

4.9. Further Analysis of Scientific Literature

It has been suggested that national reporting switches from being bottom-up-based (model/emission factor and activity data) to top-down-based (atmospheric inversion) for non-CO_2 greenhouse gases, although this has been estimated to cost $500m over 20 years for a global monitoring network of 500 stations able to resolve most countries (Leip, Skiba et al. 2018), irrespective of the availability of experts to run such a network. In this new paradigm it is imagined that high tier inventory methods would be applied to hot spots, combined inversion results and with local verifications using some direct flux measurements, in order to plan for mitigation actions. These methods could still be used in the current paradigm where inversion modelling is a verification tool.

The inversion models currently in use for UNFCCC reporting collect data from stationary, ground based, in-situ continuous measurements. These provide consistent coverage at high precision but are less flexible than other methods. Flask measurements, where air is stored and later processed in a lab, allows for more advanced measurements such as radiocarbon analysis to infer ffCO2 (Cui, Newman et al. 2019).

Another type of stationary ground measurement uses Fourier Transform Spectroscopy, which measures column abundance similar to satellites. The Total Column Carbon Observing Network (TCCON) has several stations throughout Europe and has been used to infer European emission (Wunch, Jones et al. 2019). One primary use of the TCCON network is to verify satellite measurements and is expected to be used to verify upcoming TROPOMI data (Hu, Landgraf et al. 2018). These sites then are helpful for evaluating the products used to evaluate the inventories.

There are also several different types of mobile measurements that have been used to monitor GHG atmospheric concentration. Aircraft mounted measurements have been used to infer regional emissions (O'Shea, Allen et al. 2014, Pitt, Allen et al. 2018) and shipborne measurements have been used at the national scale (Helfter, Mullinger et al. 2019).

Plume mapping is also possible with vehicle-based measurements. Car mounted measurements have been used to measure plumes from waste disposal facilities to better characterise their emissions (Zazzeri, Lowry et al. 2015), and a train mounted sensor has been used to monitor urban concentrations and map methane plumes to specific industries (Mitchell, Crosman et al. 2018).

Although Australia currently only reports verification using inversion for SF_6, work has been produced that identified cost effective potential sites to expand a GHG network for CO_2, CH_4 and N_20 (Ziehn et al. 2016). An expanded GHG network may allow for further verification work provided there are people to operate the models.

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EU-wide inversions have been performed for CH_4 (Bergamaschi, Karstens et al. 2018) and for HFCs (Graziosi, Arduini et al. 2017) by academic groups. Results from studies such as these could be used to verify EU totals or be segregated down to individual countries.

A study has shown that methane inversions for France are improved by using EU network sites from outside of France (Pison, Berchet et al. 2018). This study also looked at the temporal and regional scales that the network was able to constrain, with 1 week and 50 000 km^2 being the finest resolutions possible with the 4 internal and 5 external sites available.

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