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Inconsistencies in national greenhouse gas emissions reports and their potential effect on the Global Stocktake

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This discussion paper presents pre-publication stage research in order to stimulate discussion and critical comment in preparation for formal publication. Feedback is welcome and should be sent to eda.kosma@tufts.edu.

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Introduction

Accurate and consistent reporting of emissions is crucial for the successful design and implementation of domestic policies and to track country progress towards the United Nations Framework Convention on Climate Change (UNFCCC) objective of stabilizing atmospheric greenhouse gas concentrations "at a level that would prevent dangerous anthropogenic interference with the climate system." External calculations of some country emissions have been shown to exceed the quantities stated by those countries in their reports to the UNFCCC. Despite comprehensive, internationally recognized guidelines on greenhouse gas (GHG) emissions inventory calculation, evidence has emerged of the inconsistent application of these guidelines in national reports submitted by parties to the Paris Agreement, particularly in the estimation of carbon sinks and other high uncertainty emissions factors. For example, one study found that in its Third Biennial Update Report, Malaysia overestimated the net impact of its forest carbon sink by as much as four times (Mooney et al 2021).

The aim of this research is two-fold, to understand the size of the gaps between country emissions that are reported within the bounds of the Paris Agreement and those reported outside the UNFCCC system, and to assess how these inconsistencies will affect the level of international climate ambition recommended by the first Global Stocktake, set to release findings in 2023.

This research is focused on the world's top-twenty emitting countries, comparing Party submissions of inventory reports to the UNFCCC and external national publications in search of discrepancies in total GHGs reported. Four distinct discrepancies emerged in the analysis: 1) reported discrepancies, where different emissions totals are noted; 2) reporting lags, where different emissions totals are noted but subsequently explained as recalculation in external reporting not yet published to the UNFCCC; 3) reported alignment, where emissions totals are found to be in agreement; and 4) low data availability, where GHG data of the same year and type is unable to be identified and compared. Given constraints in dataset availability and research capacity, it was most practical to bound the scope of the research to comparisons between UNFCCC and external ministry reports by each country.

There is an emphasis in the literature on the uncertainty of carbon sink estimation pointing to lack of robust data at the country level, particularly in land use change and forest soil organic carbon. These gaps are critical to understand as country reports directly inform the Global Stocktake. Any inconsistencies between reported emissions and total emissions could lead to divergence in the Parties' collective understanding of the level of needed emissions reductions to meet the UNFCCC's objective.

Literature Review

Emissions Inventories

Inventories of greenhouse gases have long been understood as the key source of information needed to develop effective international environmental agreements and improve climate mitigation actions (Pacyna and Graedel 1995). In their simplest form, inventories represent a full accounting of greenhouse gas (GHG) emissions from an organization's relevant boundaries (Russel and Sotos 2010).

In practice, however, the development of these emissions inventories is necessarily approached in very different ways by the scientific community, national and sub-national governments, practitioners of emissions trading systems, and the private sector (Ascui and Lovell 2011). These constituencies use emissions inventories to fulfill diverse needs, and GHG accounting guidelines tailored to each of their specific applications ensure that the data collected from these groups is relevant and comparable from year to year across entities.

Generally, the predominant differences in emissions inventories include the boundary of the inventory, the reporting period, its use of a top-down or bottom-up approach, and the categorization of the emission or removals (IPCC TFI 2021). The GHGs included in the inventory can vary significantly, though the IPCC suggests CO_2, CH_4, and N_2O should be included at a minimum (ibid). Inventories can be produced at many different activity levels or geographic scales, from individual product or project life cycles, sub-national entities like administrative regions or corporations and their supply chains, to the national and global level.

For the purposes of this paper, we focus on emissions inventories at the national scale in high-emitting countries. National-level GHG inventories provide an estimate of emissions from all sectors within a country, to include electricity generation, buildings, transport, industry, as well as agriculture, forestry and other land-use changes (AFOLU). Given their scale, official country-prepared national inventories are estimated in a “bottom-up” fashion using economic data (Russell and Sotos 2010). While these methods can estimate fossil fuel emissions with good accuracy, estimates of emissions and removals from AFOLU are less reliable (Crisp and Dowell 2021), and national inventories do not extend to international bunkers – international aviation and maritime activity (IPCC TFI 2021).

By contrast, unofficial country-level and global emissions inventories, often generated by the scientific community, draw from many sources that include both top-down and bottom-up measurements (Deng et al 2021; Climate Watch 2022; Jones et al 2022), in addition to including the unattributed emissions above or other processes such as permafrost thaw. Climate Watch, for example, estimates India’s total GHG emissions in 2016 as 19.5% higher than what India itself reported that year.

Innovations in Greenhouse Gas Monitoring

It is impractical to directly measure almost all types of emissions sources, and bottom-up estimations that use fuel inputs and representative sampling of equipment, land use, other proxy measures to approximate emissions continue to be prevalent in GHG inventories. A notable exception to bottom-up methods are the energy and industry sectors, where continuing innovations in direct measurements of gas concentrations are reducing inventory uncertainties with respect to electricity generation and other stationary activities (Ackerman and Sundquist 2008). Direct measurement has proven feasible using Continuous Emissions Monitoring Systems (CEMS), which samples select gas concentrations by percent of emission volume. Where CEMS were once limited to single gas measurements (EPA 2016), current products can measure multiple gases with high precision and have extended to portable spectrometer applications (Ohyama et al 2021).

Remote sensing of GHG emissions from satellite and infrared spectroscopy is becoming increasingly available. Successful aircraft-mounted light detection and ranging (LiDAR) mapping for methane detection and quantification have also proliferated (Johnson et al 2021), but applications are not continuous and are therefore more relevant for operators, supply chain stakeholders, or regulators, rather than for national-level emissions inventories. The cost of these applications is also unaffordable for many least developed countries.

Notably, top-down estimates of GHGs generated by the scientific community have increasingly shown that direct measurements of atmospheric CO_2 and other GHGs tend to be higher than the emissions reported by countries in their official inventories submitted to the UNFCCC (Zhang et al 2014; Deng et al 2021; Minx et al 2021; Mooney et al 2021; Lu et al 2022). Top-down measurements, conducted via satellite GHG monitoring (Kuhlman et al 2019; Dasgupta et al 2021), can provide consistent spatial and temporal coverage of global emissions. Individual satellites are often limited to one or two GHGs and face challenges in addressing data noise (e.g. cloud cover, commingled biospheric gases) and the inability to identify plume sources (Crisp and Dowell 2021). New advancements are fast overcoming these barriers at the facility level by merging data from vast networks of satellites and sensors, in addition to reducing noise through artificial intelligence, to create a real-time picture of total global emissions (Gore 2022). However, while they may serve as a helpful means of quality assurance (Eggleston 2007), these innovations will have limited applicability for country-generated emissions reports until they can produce reliable, territorially-bounded inventories (Chevallier et al 2022).

Despite their differences, both national GHG inventory compilers and the scientific community share the goal of producing an accurate picture of country GHG emissions, ideally reaching identical results for net emissions after accounting for spatial and temporal variations (Pacyna and Graedel, 1995).

UNFCCC Inventory Requirements and IPCC Guidelines

Under the UNFCCC, all Parties are obliged to regularly communicate how they are upholding their commitments to the Convention (UNFCCC 1992, article 12), to include the compilation of GHG inventories. Requirements for all Parties to ’regularly provide’ national GHG inventories using estimation methodology prepared by the Intergovernmental Panel on Climate Change (IPCC) were codified in the Paris Agreement (Article 13 paragraph 7(a)).

In light of national circumstances and in line with the principles of common but differentiated responsibilities and respective capabilities (CBDR-RC), developed and developing country Parties have historically had different reporting requirements under the UNFCCC. These differences are most evident in 1) the frequency of reporting, and 2) the methodology that Parties are required to use in their GHG inventories.

Initially developed in 1991 at the request of the UNFCCC, the guidelines were produced by standard IPCC procedure through a group of nominated international experts. They were later updated to the 1996 and 2006 IPCC Guidelines for National Greenhouse Gas Inventories, with the most recent refinement to the guidelines issued and adopted by the IPCC in 2019 (IPCC TFI 2019). The methodology is intended to standardize national GHG inventory estimation in line with the principles of transparency, consistency, comparability, completeness, and accuracy (Todorova et al 2003; Pulles 2017).

Annex I (developed country) Parties have been obligated to submit GHG inventories annually, beginning in 2014, in addition to a Biennial Report (BR) and a quadrennial National Communication (NC) summarizing the country's climate mitigation and adaptation measures (UNFCCC 1999). In 2013, Parties revised reporting requirements and mandated that Annex I countries use the 2006 IPCC Guidelines for National Greenhouse Gas Inventories in their reporting (UNFCCC 2014).

Non-Annex I (developing country) Parties, with the exception of least developed countries (LDCs) and small island developing states (SIDS), should have begun in 2016 to regularly submit similar Biennial Update Reports (BUR) and quadrennial NCs, to include a GHG inventory. The IPCC suggests that non-Annex I Parties use the less complicated 1996 IPCC guidelines – in addition to several supplements – to conduct national inventories. While some developing countries have already started to use the 2006 IPCC guidelines, most continue to face significant challenges in the development of timely and accurate emissions inventories. As of 2021, all 44 Annex I Parties (except for Ukraine) had submitted all three required biennial reports, where only 55 of 156 non-Annex I Parties had submitted at least one of three required biennial reports (Weikmans and Gupta 2021).

The 2006 IPCC Guidelines provide standardized methodology for “estimating emissions (and removals as appropriate) for each gas in mass units” and group emissions into four main categories: energy, industry, land use, and waste (IPCC TFI 2019). As a bottom-up methodology, the IPCC calculates emissions as the product of an activity or input and its related emission factor. Countries are free to identify their own emission factors or use estimates supplied by the IPCC in the Emission Factor Database (IPCC TFI 2021). Similarly, the guidelines do not recommend specific global warming potential (GWP) values to convert non- CO_2 gases into CO_2 equivalents and leaves this methodology to the discretion of the inventory compilers (IPCC TFI 2019).

Recommended methodologies are provided in three tiers with increasing complexity. Tier 3 is considered to be the most demanding in terms of data requirements and site-specific modelling. Higher tiers are generally viewed as more accurate, and Parties are encouraged to use the most precise tier possible provided that adequate data is available. Due to national circumstances, however, many non-Annex I countries are limited to using more basic Tier 1 approaches for large portions of their inventories, though they are generally associated with higher uncertainty levels (Perugini et al 2021). To date, every country who has submitted a national inventory to the UNFCCC uses Tier 1 guidelines for at least one component (Yona et al 2022).

The 2006 Guidelines also provide instructions on conducting an uncertainty assessment and find uncertainty estimates important to identify areas for inventory improvement, as well as compare inventory results with atmospheric measurements and inversions calculations (IPCC TFI 2019). Comprehensive data on the percentage of national GHG inventories that include uncertainty assessments was not available and would be helpful to gauge estimation similarity between country compilers of official national GHG inventories and scientific emissions inversions.

In line with the IPCC’s principle of continuous improvement, countries are encouraged to update and revise data and methodology for emissions estimation with each iteration of report.

Any temporal lag between reports submitted to the UNFCCC and those published externally could result in discrepancies due to use of newly updated data.

IPCC Inventory Uncertainties

High accuracy, low uncertainty inventories are critical for monitoring the implementation of climate treaties (Bun et al 2009). Many studies have assessed uncertainty across entire national GHG inventories (e.g., Bun et al 2010; Jarnicka and Zebrowski 2019), though none have found a commonly accepted understanding of uncertainty.

The problem of uncertainty is most clearly demonstrated in estimates of CO_2 sequestration and sinks for the purposes of land use, land use change, and forestry (LULUCF), AFOLU, and forest soil organic carbon. Net emissions from land-use change are particularly challenging to separate from actual emissions, and there are persistent, large uncertainties in the estimate of LULUCF (Friedlingstein et al 2021; Grassi et al 2021), often showing significant variations in the same country between successive inventory submissions (Pulles 2017). Some studies even recommend omitting LULUCF data when analyzing emissions trends as uncertainties are considered large enough to skew findings (Jarnicka and Zebrowski 2019).

Estimates of CO_2 uptake by land sources have proven particularly controversial in national inventories (Mooney et al 2021) given low data availability and limited oversight. Of note, McGlynn et al (2022) found that uncertainty from LULUCF in national GHG inventories ranged from 12% in Colombia to 102% in Cambodia, and that four of the five major emitting countries (China, United States, Russia, India) show 'sufficiently large' uncertainty in their LULUCF emissions that planned reductions presented in their first Nationally Determined Contributions (NDCs) are at risk of failing statistical confidence tests. Yona et al (2022) attributes this in part to the IPCC failing to update LULUCF-relevant portions of its GHG estimation guidelines in line with the latest scientific research in its 2019 refinement.

Despite these many concerns, top-down models interestingly show that a larger global land sink for CO_2 than estimated by countries in their national inventories might be available (Deng et al 2021), though this is possibly explained by incomplete UNFCCC reporting by many countries. The first round of NDCs indicated that 25% of planned GHG reductions by 2030 will come from

LULUCF and other land sink sources (Grassi et al 2021), making LULUCF uncertainty estimation a key priority for further research and guideline assessment.

In sectors other than LULUCF, estimates seem to remain consistent in annual reporting and within uncertainty ranges (Pulles 2017). These issues open the possibility that either IPCC guidance on carbon sink sources do not result in high confidence estimates or that guidelines are open to a variety of interpretations by different countries and experts.

IPCC estimation guidelines have proven difficult to update given the desire to maintain data comparability among historical country inventories. There are also political considerations to bear in mind. The UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA) must typically invite the IPCC to begin work on a particular area and later adopt the final guidelines for use by UNFCCC parties. The consensus needed to adopt the final changes can be difficult to obtain, as estimation guideline changes translates into progress towards or away from any given country's NDCs (Yona et al 2022).

Considerations for the Global Stocktake

Article 14 of the Paris Agreement establishes a regular stock taking of the collective progress made by Parties towards achieving the goals of mitigation, adaptation, and adequate financing and capacity-building to support these aims (UNFCCC 2022). Known as the Global Stocktake (GST), the exercise is a key accountability mechanism and meant to drive Parties to increase the level of ambition in their NDCs. The Global Stocktake represents an opportunity for Parties to own the accountability process and acknowledge that increasingly ambitious NDCs and subsequent action are necessary to meet the goal of limiting anthropogenic warming to 1.5 degrees Celsius.

The first GST findings will be released at the Conference of the Parties in 2023 and will consider various inputs, though it is expected to rely heavily on country progress assessment such as the Biennial Reports and National Communications. Accurate and high-quality national emissions inventories are critical in maintaining international confidence that progress is being made towards the goals of the Paris Agreement. However, given the current variability in quality and precision of national GHG inventories, there are significant challenges in tracking this progress (McGlynn et al 2022).

Methodology

The first portion of my research is based on analysis of primary GHG inventory reports produced by Parties and subsequently reported to the UNFCCC. In collecting these reports, we relied on documentation available on the UNFCCC website, specifically the National Communications (NCs), National Inventory Reports (NIRs), Biennial Reports (BRs), and Biennial Update Reports (BURs). These national reports were accessed from the relevant UNFCCC websites, indicated in Table 1 below.

For the second phase of my research, we sourced primary data from reports on national GHG emissions published by countries on their own, outside the UNFCCC system. we searched ministry websites for reports on national GHG inventories that included numerical data on total or net CO_2 emissions or sector emissions. Searches were concentrated around ministries denoted as involved in the creation of the UNFCCC emissions inventory. For the purposes of this study, we used online translation tools to perform searches for GHG inventories in non-English languages. Using third-party rankings for total country net CO_2 emissions in 2019 (Climate Watch 2022), we prioritized my research on the twenty highest-emitting countries, shown in the appendix.

Table 1 – List of UNFCCC GHG Inventory Data Sources *(Retrieved June 15, 2022)*

Submitted NCs from Annex I countries: https://unfccc.int/NC7
Submitted NCs from Non-Annex I countries: https://unfccc.int/non-annex-I-NCs
Submitted BRs from Annex I countries: BR1: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/national-communications-and-biennial-reports-annex-i-parties/biennial-report-submissions/first-biennial-reports-annex-i BR2: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/national-communications-and-biennial-reports-annex-i-parties/biennial-report-submissions/second-biennial-reports-annex-i BR3: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/national-communications-and-biennial-reports-annex-i-parties/biennial-report-submissions/third-biennial-reports-annex-i BR4: https://unfccc.int/BR4
Submitted NIRs from Annex I countries: https://unfccc.int/ghg-inventories-annex-i-parties/2022
Submitted BURs and NIRs from Non-Annex I countries: https://unfccc.int/BURs

After collecting information on available UNFCCC and country reporting, We identified years of overlapping GHG inventory coverage and compiled a dataset for corresponding reported years of data available. In the case of Annex I countries with multiple recent reports, the most recent NIR on the UNFCCC portal was chosen for comparison. In countries with overlapping datasets, we compared the GHG emissions in $MtCO_2e$ – either total or net including LULUCF or other sinks and removals, depending on availability – and verified which IPCC reporting methodology was employed in each report. If comparable data could not be found in the most recent report on the UNFCCC portal, the next most recent report was used for assessment.

In assessing the compiled data, we identified patterns and similarities among country reports and propose four classifications, discussed in the findings below. We opted for a qualitative attribution assessment due its alignment with the core of my research question. Indeed, the purpose of this study is to understand where inaccuracies in a country's inventory estimation might lead to discrepancies in its official GHG totals and how these inconsistencies might affect the Global Stocktake, rather than their exact quantification. Additionally, there is a level of acceptable uncertainty in all bottom-up GHG estimation assessments, and exact, finite quantification is not feasible. Uncertainty depends heavily on the IPCC Tier used to calculate each sector and sub-sector's emissions, as well as the global warming potential used to calculate CO_2 equivalents.

The aforementioned methods were also limited by a number of considerations. First, the evaluation approach used here assessed only discrepancies between the total or net CO_2 emissions reported. We did not consider inventory uncertainty assessments, follow-up commentary from UNFCCC technical reviewers, or subsequent revisions published after the initial stage of data collection including current data up until June 2022. Research methods were also limited by technological and linguistic constraints, as not all pdf-file reports are text-readable for the purposes of online translation tools.

Lastly, despite the mandate of regular reporting, timeliness and punctuality of country inventory submission are highly variable. Each of the top-twenty emitters included in this study have submitted at least one national GHG emissions report to the UNFCCC, though some GHG data was quite old; for example, both the Democratic Republic of the Congo and the Islamic Republic of Iran use GHG data from 2010 in their most recent reports provided to the UNFCCC. In the reports assessed for this study, the average lag between report year and data year was 2.5 years for Annex I countries and 4.23 years for non-Annex I countries. Country GHG inventory reports published outside the UNFCCC system are even more lacking. Though the most recent national reports were analyzed where possible, the timing of their publication varies greatly. While in some cases both internal and external data could be found, data year or data types may not have overlapped in a way that allowed for comparison.

Findings

This analysis of discrepancies in national GHG inventories is intended to explore systemic causes of these gaps, rather than function as an exhaustive empirical assessment of the quality of individual country GHG reporting. In assessing national GHG inventories reported to the UNFCCC and outside the system, we identified patterns of discrepancies in total net emissions and sectoral emissions. Similar to McGlynn (2022), LULUCF or AFOLU totals, when reported in inventory uncertainty assessments, often ranked highly as a cause of discrepancy. This is illustrated in the case of Viet Nam, which estimates the uncertainty of its AFOLU removals at 100.2% of the reported sector total in its Third BUR (Socialist Republic of Viet Nam 2020). The findings are summarized in Table 2 below, with comprehensive results available in the appendix. As each country is being assessed against its own reporting and independently of others, it is not necessary to account for the UNFCCC Annex classification.

We identify four main trends when comparing UNFCCC and external national GHG inventories sourced from the top-twenty highest emitting countries and categorize them as follows: 1) reported discrepancies, where GHG data of the same year and type (total or net CO_2e emissions) are compared between reports available on the UNFCCC portal and national GHG reports available on external ministry websites and different emissions totals are given; 2) reporting lags, where different emissions totals are given for GHG data of the same year and type but can be explained by recalculations provided on ministry reporting not yet published to the UNFCCC; 3) reported alignment, where emissions totals for GHG data of the same year and type are found to be in agreement between reports on the UNFCCC portal and external ministry websites; and 4) low data availability, where GHG data of the same year and type was unable to be found on external ministry websites.

Table 2: Categorization of top-twenty emitters in discrepancy analysis

	Count	Countries
Group 1: Reported Discrepancy	5	Indonesia, Brazil, Japan, Mexico, Türkiye
Group 2: Reporting Lag	2	Australia, South Africa
Group 3: Reported Alignment	9	China, United States, India, Canada, Germany, South Korea, Pakistan, Viet Nam, Thailand
Group 4: Low Data Availability	4	Russia, Iran, Saudi Arabia, D.R. Congo

Within Group 1 (Reported Discrepancy), five of the reviewed countries reported discrepancies between the total emissions stated to the UNFCCC and externally on country ministry websites, including Indonesia, Brazil, Japan, Mexico, and Türkiye. Brazil had the largest discrepancy of the group, reporting figures for its 2016 total net CO_2e emissions on its website that were 11.63% larger than figures given to the UNFCCC. This discrepancy was calculated based on figures that appear in reports that were both released in 2020; to the UNFCCC in its Fourth BUR and on the Brazilian Ministry of Environment's website as *Brazil's Fourth National Inventory Report* (Government of Brazil 2020). Both reports note using the same IPCC methodology guidelines. In the case of Indonesia, the Ministry of Environment and Forestry reports figures for its 2019 total net CO_2e emissions that are 1.16% larger than figures cited to the UNFCCC. Both reports purport to use the same IPCC methodology, though Indonesia's *Annual GHG Inventory Report* (Government of Indonesia 2021) indicates that it is conducted separately from the UNFCCC inventory reporting process, providing an explanation for the difference. By contrast, Mexico in its non-UNFCCC inventory (Government of Mexico 2018) reports its 2015 total net CO_2e emissions as 2.95% smaller than its official 2015 emissions reported to the UNFCCC. A possible explanation for this reported discrepancy lays in the difference in IPCC methodologies relied upon to create the reports. Reported discrepancies for Japan and Türkiye are small, under 1%, falling within the likely range of acceptable uncertainty.

In two instances, reported discrepancies at the country level were able to be explained by a lag in data officially reported to the UNFCCC, forming Group 2 (Reporting Lags). In the case of Australia, while its reports show a high degree of transparency, key data elements were incomparable between figures officially reported the UNFCCC and presented on government websites. In its 2022 NIR, Australia reports only its net emissions for 2020, whereas on its government website, the sole GHG inventory dataset shows 2020 values only in total emissions. Due to this incomparability, figures from the next most recent UNFCCC report, the Fourth BR published in 2019, were used and discrepancies from the 2017 data year identified. In its 2022 NIR, however, Australia demonstrates recalculations that account for the 2017 discrepancy. The complexity of Australia's discrepancy is attributed to the outdated nature of the Fourth BR. As of June 2022, Australia's Fifth BR had not been published but should be assessed to determine similarity. In a similar fashion, discrepancies were identified for South Africa. The country's 2021 NIR reports its 2017 total net emissions as 2.56% smaller than the same figure reported in South Africa's *National GHG Inventory Report* (Government of South Africa 2022) published on the Ministry of Environment's website. The 2022 report states that it is intended to be submitted to the UNFCCC to serve as the country's NIR, however it has yet to be posted on the UNFCCC portal.

Group 3 (Reported Alignment) was the most commonly identified category and accounts for 45% of the countries assessed. The group includes the largest three largest GHG emitters – China, the United States of America, and India – as well as Canada, Germany, the Republic of Korea, Pakistan, Viet Nam, and Thailand. All of the Group 3 countries published both their UNFCCC and ministry reports in either 2021 or 2022, with the exception of China which published its most recent report in 2019. Within the assessed countries, the majority of emissions figures presented on ministry websites are displayed in press releases announcing the release of new information to the UNFCCC, or in reports that reiterate the emissions inventory conducted for the purposes of its Paris Agreement obligations. On the U.S. Environmental Protection Agency website, for example, the *Inventory of U.S. Greenhouse Gas*

Emissions and Sinks report (United States EPA 2022) is the same document that is accessible through the UNFCCC portal. In this way, these country emissions figures are likely not the result of independent GHG inventories, rather duplications of existing reports sent to the UNFCCC.

Group 4 (Low Data Availability) consists of four of the top-twenty most emitting countries, including the Russian Federation, the Islamic Republic of Iran, the Kingdom of Saudi Arabia, and the Democratic Republic of the Congo. Each country has submitted at least one GHG emissions inventory report to the UNFCCC. However, in the case of Saudi Arabia, the emission reported in its Fourth NC are listed separately by CO_2, CH_4, N_2O, without conversion to CO_2 equivalents using global warming potentials, thus limiting its comparability for data on its total GHG emissions. Additionally, while most ministry websites mention existing country plans to reduce emissions, no data on country historic totals of CO_2e emissions was found despite extensive searching. For example, only one mention of total national CO_2e was found for the Russian Federation (Russian Federation 2020). However, the figures listed as historic emissions do not have accompanying units, restricting their use in this comparative study.

Discussion

There are a myriad of possible reasons for both discrepancies and alignment when comparing total emissions in the reports assessed. GHG inventory preparers, particularly from non-Annex I countries, have critiqued IPCC guidelines as unclear, overly technical, and exceedingly complex (Climate Analytics 2021; Yona et al 2022). There are also challenges in comparing reports released at different times; even if the data used is purportedly from the same year, datasets are often updated to reflect the latest available numbers (Climate Analytics 2022).

Given the highly technical nature of GHG inventory production, countries with very large data discrepancies are likely constrained by minimal emissions data availability, low familiarity with elements of the IPCC GHG estimation guidelines, or limited administrative capacity. At the same time, countries that have high technical capacity and high data availability are also likely to report discrepancies in their total emissions, though the inconsistencies are likely to be much smaller and within an acceptable range of uncertainty.

Countries must be fastidious in ensuring that their administrative reports are updated in a timely manner to ensure consistency across all levels of reporting. Yona et al found that some countries centralize the inventory compilation process at the highest level – as opposed to conducting separate sub-national assessments using the same primary data and then combining them – due to a high risk that the concurrent assessments would produce different estimates (Yona et al 2022).

Of note, funding for capacity building in support of national GHG inventory assessments has been made available through the Global Environmental Facility (GEF 2012). These funds have been used by virtually all non-Annex I countries, however improvements are yet to be seen in the formation of formal national GHG inventory teams or reporting timeliness (Kawanishi and Fujikura 2018). Country capacity in national GHG inventory production may well have increased over time, but these improvements are thus far masked by long gaps in reporting. While Kawanishi and Fujikura identify additional training as helpful, they point to the establishment of permanent staff at the country level charged with regular emissions monitoring as overlooked in growing institutional capacity.

As countries improve their GHG emissions methodology and become capable of using the higher tiers of IPCC estimation methodology, the accuracy of their GHG inventories is likely to improve. Jarnicka and Zebrowski raise the point that this improved accuracy could reveal that national mitigation policies undertaken to date could be less effective than previously estimated (Jarnicka and Zebrowski 2019), which may have repercussions in national willingness to engage in transparent reporting. Conversely, more accurate inventories may also reveal that certain policies are more effective than expected, making historical inventory recalculation a key area of analysis of national mitigation strategies.

Greater frequency and quality of country GHG reporting will also hopefully manifest under the Enhanced Transparency Framework (ETF) as differentiated transparency requirements are synced beginning in 2024 (Gupta and van Asselt 2019). However, expectations that the ETF will be able to close the gap between reported and total emissions are overly optimistic as the underlying gaps are a result of the IPCC estimation methodology which will remain the same until SBSTA calls for an update of its guidance.

My finding that many of the top-emitting countries have alignment in their GHG reporting suggests that discrepancies between UNFCCC and country emission inventories are unlikely to have an outsized impact on the level of ambition recommended in the forthcoming GST output. Through the course of this research, we recognize that Parties are ultimately obliged only to be informed by the GST output, which means that even the presence of discrepancies may not affect Party motivation to increase mitigation goals and targets.

While the research was constrained by methodological limitations, it does provide value in its confirmation of two issues. First, reporting lags between GHG data collection and inventory creation persist and, in some cases, are leading to discrepancy and mismatch around the level of a country's total emissions. Second, emissions recalculations can shift a sector's emissions totals precipitously, particularly in areas like LULUCF or AFOLU that have been previously flagged in uncertainty assessments. In this way, further research could benefit from thorough monitoring of the size of emission recalculations. It would be very interesting to track the average change in sectoral emissions as recalculations are periodically assessed.

There are several other gaps in my findings that leave ample room for future research. A logical next step to build on this study would research discrepancies in reporting between country-reported total emissions to the UNFCCC and independent third-party assessments of country-level total emissions. It would be interesting to see the difference between research that aggregates multiple bottom-up datasets, for instance Climate Watch (Climate Watch 2022), and country top-down inversion studies like those conducted by Deng et al (2021) and Minx et al (2021). Additionally, in-depth exploration of methods by which LULUCF and AFOLU emissions calculations can be improved, particularly for non-Annex I countries with low data availability or capacity. Future research might look at, for example, national emissions inventories like Cambodia and Viet Nam that have identified an uncertainty of land source removals over 100%.

Further study around the implementation of the Enhanced Transparency Framework would also prove helpful in understanding the changing landscape of data comparability and reporting lag with regards to inventories. It would be helpful to understand what sectors within IPCC-calculated country inventories typically show the highest level of uncertainty and what types of data improvements might be made to address them. Additional research on the effects of country capacity advancements on inventory recalculations is increasingly necessary to understand whether changes in historic emissions trends will emerge as data quality improves.

Conclusion

Global emissions cannot be effectively reduced without a clear understanding of the sources, sectors, and actors behind their production. National GHG inventories are not only a means to measure individual progress towards a country's respective NDC, but they also represent a large portion of how the Global Stocktake will measure the international community's collective progress towards the mitigation goals of the Paris Agreement.

There are concerns that the gap between country reported and total atmospheric emissions could artificially inflate the GST's perceived progress towards the Paris goals. While the inconsistencies detailed in this research do not rise to the level of significance that would skew the results of the entire Stocktake in this way, the identified potential discrepancies are, in some cases, as large as 5% to 11%. Even in cases where discrepancies are attributed to recalculations, international confidence in national GHG reports relies on the ability of countries to consistently prove accurate inventories using the IPCC's estimation methodology.

The discrepancies in reported total emissions uncovered through this research reveal that countries have much room for improvement in increasing the accuracy and timeliness of their GHG reporting. Increased capacity building assistance to developing countries is necessary to facilitate much of this process improvement. The gaps and areas of high uncertainty in carbon sinks also point to a need to revisit discussion on whether IPCC estimation for LULUCF is due for further adjustment. With the Global Stocktake set to produce an output that highlights effective paths towards emissions reductions, its findings must include provisions to encourage Parties to improve their collection of emissions sources and factors, open the door to IPCC methodology updates, and quantify the gap between total and reported emissions.

Appendix: Comprehensive Findings

Country	Climate Watch Ranking*	UNFCCC designation	UNFCCC Report (Report Year)	UNFCCC GHG Data Year	UNFCCC IPCC Methodology Used?**	UNFCCC GHG Emissions Reported	Non-UNFCCC Source (Report Year)	Non-UNFCCC GHG Data Year	Non-UNFCCC Report IPCC Methodology Used?**	Non-UNFCCC GHG Emissions Reported	Assessment Results	GHG Emissions Percent Difference
China	1	Non-Annex I	BUR2 / NC3 (2019)	2014	Revised 1996, 2006	11,186 $MtCO_2e$ (total)	China Mobile Source Environmental Management Annual Report (2019)	2014	Not specified	11,186 $MtCO_2e$ (total)	Reported Alignment (3)	—
United States	2	Annex I	NIR (2022)	2020	2006	5,222.4 $MtCO_2e$ (net)	Inventory of U.S. Greenhouse Gas Emissions and Sinks report (2022)	2020	2006, 2019 Refinement	5,222.4 $MtCO_2e$ (net)	Reported Alignment (3)	—
India	3	Non-Annex I	BUR3 (2021)	2016	Revised 1996, 2006	2,531 $MtCO_2e$ (net)	Indian Ministry of Environment website (2022)	2016	Not specified	2,531 $MtCO_2e$ (net)	Reported Alignment (3)	—
Indonesia	4	Non-Annex I	BUR3 (2021)	2019	2006, 2019 Refinement	1,845 $MtCO_2e$ (net)	Indonesia's Annual GHG Inventory Report (2019)	2020	2006, 2019 Refinement	1,866.6 $MtCO_2e$ (net)	Reported Discrepancy (1)	Non-UNFCCC report is 1.16% larger than UNFCCC report
Russian Federation	5	Annex I	NIR (2020)	2018	2006	1,629.5 $MtCO_2e$ (net)	—	—	—	—	Low Data Availability (4)	—
Brazil	6	Non-Annex I	BUR4 (2020)	2016	Revised 1996, 2006	1,306 $MtCO_2e$ (net)	Brazil's Fourth National Inventory Report (2020)	2016	Revised 1996, 2006	1,467.3 $MtCO_2e$ (net)	Reported Discrepancy (1)	Non-UNFCCC report is 11.63% larger than UNFCCC report
Japan	7	Annex I	NIR (2022)	2020	2006	1,096 $MtCO_2e$ (net)	Japanese Ministry of Environment press release (2022)	2020	2006	1,106 $MtCO_2e$ (net)	Reported Discrepancy (1)	Non-UNFCCC report is 0.91% larger than UNFCCC report
Iran	8	Non-Annex I	NC3 (2018)	2010	2006	832 $MtCO_2e$ (net)	—	—	—	—	Low Data Availability (4)	—

Country	Climate Watch Ranking*	UNFCCC designation	UNFCCC Report (Report Year)	UNFCCC GHG Data Year	UNFCCC IPCC Methodology Used?**	UNFCCC GHG Emissions Reported	Non-UNFCCC Source (Report Year)	Non-UNFCCC GHG Data Year	Non-UNFCCC Report IPCC Methodology Used?**	Non-UNFCCC GHG Emissions Reported	Assessment Results	GHG Emissions Percent Difference
Canada	9	Annex I	NIR (2022)	2020	2006, 2019 Refinement	672 $MtCO_2e$ (net)	Canadian Ministry of Environment and Climate website (2022)	2020	2006	672 $MtCO_2e$ (net)	Reported Alignment (3)	—
Saudi Arabia	10	Non-Annex I	NC4 (2022)	2016	2006	Individual gases only - total CO_2e emissions not reported	—	—	—	—	Low Data Availability (4)	—
Germany	11	Annex I	NIR (2022)	2020	2006	728.7 $MtCO_2e$ (total)	German Federal Environment Agency Press Release (2022)	2020	2006	729 $MtCO_2e$ (total)	Reported Alignment (3)	—
Democratic Republic of the Congo	12	Non-Annex I	NC3 (2015)	2010	Not specified	Sector emissions only - total CO_2e emissions not reported	—	—	—	—	Low Data Availability (4)	—
Mexico	13	Non-Annex I	NC6 (2019)	2015	2006	551 $MtCO_2e$ (net)	Mexico's National GHG Inventory Report (2018)	2015	Revised 1996, 2006	535 $MtCO_2e$ (net)	Reported Discrepancy (1)	Non-UNFCCC report is 2.95% smaller than UNFCCC report
Republic of Korea	14	Non-Annex I	BUR4 (2022)	2018	2006	727.6 $MtCO_2e$ (total)	Republic of Korea Ministry of Environment website (2020)	2018	2006	727.6 $MtCO_2e$ (total)	Reported Alignment (3)	—
Australia	15	Annex I	BR4 (2019)	2017	2006	554.1 $MtCO_2e$ (total)	Australian Department of Climate Change, Energy, the Environment and Water website, Paris Agreement Inventory visualization (2022)	2017	Not specified	524.2 $MtCO_2e$ (total)	Reporting Lag (2)	Non-UNFCCC report is 5.54% smaller than UNFCCC report. Recalculation explained.

Country	Climate Watch Ranking*	UNFCCC designation	UNFCCC Report (Report Year)	UNFCCC GHG Data Year	UNFCCC IPCC Methodology Used?**	UNFCCC GHG Emissions Reported	Non-UNFCCC Source (Report Year)	Non-UNFCCC GHG Data Year	Non-UNFCCC Report IPCC Methodology Used?**	Non-UNFCCC GHG Emissions Reported	Assessment Results	GHG Emissions Percent Difference
South Africa	16	Non-Annex I	NIR (2021)	2017	2006	482 $MtCO_2e$ (net)	South Africa's National GHG Inventory Report (2022)	2017	2006	494.5 $MtCO_2e$ (net)	Reporting Lag (2)	Non-UNFCCC report is 2.56% larger than UNFCCC report. Recalculation explained.
Türkiye	17	Annex I	NIR (2022)	2019	2006	508.1 $MtCO_2e$ (total)	Turkish Ministry of Environment, Urbanization, and Climate Change website (2021)	2019	2006	506.1 $MtCO_2e$ (total)	Reported Discrepancy (1)	Non-UNFCCC report is 0.39% smaller than UNFCCC report.
Pakistan	18	Non-Annex I	BUR1 (2022)	2018	2006	489.87 $MtCO_2e$ (net)	Pakistan's Ministry of Climate Change Year Book Report (2021)	2018	2006	489.87 $MtCO_2e$ (net)	Reported Alignment (3)	—
Viet Nam	19	Non-Annex I	BUR3 (2021)	2016	2006, 2019 Refinement	316.7 $MtCO_2e$ (net)	Vietnamese Ministry of Industry and Trade press release (2022)	2016	Not specified	316.7 $MtCO_2e$ (net)	Reported Alignment (3)	—
Thailand	20	Non-Annex I	BUR4 (2022)	2019	2006	372.7 $MtCO_2e$ (total)	Thai Office of Climate Change Management and Coordination press release (2022)	2019	Not specified	372.7 $MtCO_2e$ (total)	Reported Alignment (3)	—

*** Climate Watch Ranking:**

Countries ranked using Climate Watch methodology for "Total including LUCF" based on 2019 data (Climate Watch 2022)

**** IPCC Methodologies referenced:**

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2006: 2006 IPCC Guidelines for National Greenhouse Gas Inventories

2019 Refinement: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories

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