EPA
United States
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Summary of Expert Review Comments and Responses:
Draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022*

Expert Review Period (Fall 2023)
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U.S. Environmental Protection Agency
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Washington, D.C.

Responses to Comments Received during the Expert Review Period on the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022*

Preface

EPA thanks all commenters for their interest and feedback on the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks. To continue to improve the estimates in the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks, EPA distributed draft chapters of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022* for a preliminary Expert Review of estimates and methodological updates prior to release for Public Review. The Expert Review of sectoral chapters was 30 days and included charge questions to focus review on methodological refinements and other areas identified by EPA as needing a more in-depth review by experts. The goal of the Expert Review is to provide an objective review of the Inventory to ensure that the final Inventory estimates, and document reflect sound technical information and analysis. Conducting a basic expert peer review of all categories before completing the inventory in order to identify potential problems and make corrections where possible is also consistent with IPCC good practice as outlined in Volume 1, Chapter 6 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and its refinement, i.e., 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

EPA received 108 unique comments as part of the Expert Review process. Generally, the verbatim text of each comment extracted from the original comment letters is included in this document, arranged by sectoral chapters. In a few instances, comments and respective footnotes are summarized, in particular where feedback focused on implementing minor editorial revisions to improve clarity of the report narrative. EPA's responses to comments are provided immediately following each comment excerpt. The list of reviewers, dates of review and all charge questions and supplementary technical memos distributed to reviewers are included in the Annex to this document.

Chapters 1. Introduction, 2. Trends, 9. Recalculations and Improvements

Chapters 1, 2 and 9 were not sent out for expert review given they include only summary information and synthesize information from chapters 3-7 rather than presenting or providing underlying technical information.

Chapter 3. Energy

Comment E1: Missing Citations
Page 3-5 lines 2 and 4, page 3-11 line 14, and page 3-12, line 3 are missing citations (EIA 2022a).

Response: That citation has been updated in the Final Report (pg. 3-10) to reference the February 2024 Monthly Energy Review (EIA 2024a) and included in the reference list. EIA (2024a) Monthly Energy Review, February 2024, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035 (2024/02).

Comment E2: Disagreement Regarding Effect on Supply in U.S. Territories
Recalculations Discussion: For the paragraph between lines 21 and 24, our international experts don't believe these changes have affect of product supplied in U.S. Territories. All the petroleum products consumed in the territories are imported and the territories do not have any refinery activities in 2022.

Response: The change to territories petroleum emissions was due to the update to the non-combustion and energy HGL carbon contents that are calculated based on the amounts and types of HGLs used. Since those values were changed to reflect updated methodologies for removing natural gasoline and adjusting the amounts of HGLs used for NEU, the carbon factors changed which impacted territories calculations. This discussion was added to the recalculations text in the Final Report (pg. 3-41) to explain the changes.

Comment E3: Source Improvement
"Woody biomass emissions were estimated by applying two gross heat contents from EIA (Lindstrom 2006) to U.S. consumption data (EIA 2023a)" I may have mentioned this in previous reviews, but I would suggest updating this data source at some point since Perry Lindstrom is no longer with EIA.

Response: EPA continues to evaluate other possible sources of woody biomass heat content and carbon factors for inclusion in future reports.

Comment E4: Sources of U.S. Territory Energy Use Comparable to EIA
Data for energy use in Puerto Rico, U. S. Virgin Islands, and Guam are derived from EIA internal survey of these three territories. America Samoa and Northern Marianna are from UN's Statistic Division. Wake Island has no permanent inhabitants except a U. S. military base with about 100 personnel. The energy use on the base is confidential.

Response: EPA pulls data for American Samoa, Guam, Puerto Rico, U.S. Pacific Islands, U.S. Virgin Islands and Wake Island for use in territories calculations. The EPA uses data from EIA's International

Energy Statistics to collect this information. Aggregated data are used were available for the different territories. See pg. 3-32 of the Final Report also Reference (EIA 2024b), EIA (2024b) International Energy Statistics 1980-2022. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/beta/international/.

Chapter 4. IPPU

Comments on Proposed Methodology for Production of Fluorochemicals other than HCFC-22

Comment I5: Improved Transparency Needed
During our review, transparency was identified as not sufficient. While the document provides a detailed description of the inventorying process for this source, the document does not provide coherent information or include appropriate references and documentation within the methodology. Given the variability of methods applied, different data gaps being addressed, and a large pool of fluorinated compounds, the proposed methodology does not guide the reader through identifying proper source data, assumptions, emission factors, and other relevant parameters on gas-by-gas review. For instance, the section on SF6 emission could be a separate section. The information provided in the methodology is important to explain the trends in SF6 emissions.

Response: In response to the commenter's statement that "transparency was identified as not sufficient," we have clarified in Chapter 4.15 of the Inventory that facility-specific activity (production and transformation) estimates are confidential and therefore cannot be published (p. 4-81). (Facility-specific emission factors are also confidential because production and transformation data could be back-calculated by dividing the provided emissions by any provided emission factor.) We have also provided aggregate total production and transformation estimates (across facilities) for the time series in the Inventory. The Inventory is as transparent as possible given the requirements for protection of confidential activity data or other data that would reveal the activity data.

It is not clear what the commenter means by "the document does not provide coherent information." Both the Proposed Methodology Memorandum and Chapter 4.15 of the Inventory systematically review the data and methods used to estimate facility-specific emissions for facilities that respectively do and do not report their emissions to EPA's Greenhouse Gas Reporting Program, discussing how the methodology changes over the time series. Information on the closure of one SF_6 plant, which did indeed drive SF_6 emissions downward, is included in both the methodology and the trends discussions.

Comment I6: Inconsistency within documentation
There's a formatting inconsistency within the document.

a. For example, the table referred to as "Table A-1", on Page 3, is instead documented in Annex as Table A.1.
b. Other inconsistencies exist in the document. Ensuring proper cross-references in this methodology is critical to facilitate proper review.
c. Additionally, Table 1 is presented in the document twice – with the name Destruction Efficiency Range Values Used to Estimate Pre-Abatement Emissions for Production and Transformation Processes (page 7), and the second time – under the name Preliminary National Fluorinated GHG Emissions Estimates from Production of Fluorinated Gas for 1990 and 2017-2022 (Tg CO2e) (page 12).
d. Table 2 is referred to in the text (page 11), but is not included.
e. In many cases, the graphs and the tables are not included on the pages where they are discussed, which makes the document hard to navigate.

Response: The commenter correctly notes that the table in the Proposed Methodology Memorandum that should have been numbered as Table 2 was incorrectly numbered as a second Table 1. The tables are correctly numbered in Chapter 4.15 of the Inventory. In Chapter 4.15 of the Inventory, we have integrated the tables into the text as far as practicable. Due to the large number of individual compounds emitted from this industry (approximately 200, 47 of which are HFCs, PFCs, SF_6, or NF_3), it is not practicable to include a full listing of emitted compounds in the text. However, Chapter 4.15 of the Inventory includes the most emitted HFCs and PFCs as well as SF_6 and NF_3 (pp. 4-79-80). It also includes the most emitted fluorinated GHGs other than HFCs, PFCs, SF_6, and NF_3 (pp. 4-80-81).The CRTs will include a complete listing of emitted HFCs and PFCs as well as SF_6 and NF_3. Moreover, Tables A-4 and A-5 in the appendix to the Proposed Methodology Memorandum included the most emitted 28 compounds, representing 99 percent of GWP-weighted emissions. (A full list of the emitted compounds was also included as an attachment to the Proposed Methodology Memorandum.)

Comment I7: Missing tabular and numerical information

This methodology attempts to explain complex methodologies that are applied to various types of fluorinated compounds. However, we identify the lack of data in a tabular format and numerical information to significantly decrease the transparency efforts within this report. For example, a table with EFs and other parameters would significantly increase the transparency efforts. Throughout this document, we were unable to easily extract all relevant information for calculation methodologies straightforwardly. Providing proper tables associating information on a by-gas format significantly improves the transparency and consistency of the information being presented. The discussions on uncertainty do not include specific uncertainty values. Activity data values are also not included in the document or the accompanying Excel file.

Response: As noted above, facility-specific activity data and emission factors cannot be provided because they would reveal confidential data. However, both the Proposed Methodology Memorandum and Chapter 4.15 of the Inventory include multiple tables relevant to the methodology, including estimated starting years for emission controls at each fluorinated gas production facility reporting under subpart L of the GHGRP, the destruction and removal efficiency values used to calculate pre-control emissions, a list of the saturated and unsaturated HFCs whose production was estimated using the USEPA Vintaging Model, and default GWPs used under the GHGRP when a compound does not have a chemical-specific GWP.

Comment I8: F-gases memo, question 5-7

[Question 5-7 reads “Where general trend data were not available to back-cast production of fluorinated gases, we have assumed that production of these gases remained constant over time. Should we instead assume that production increased with the U.S. GDP or another common index? If so, please identify the index you recommend.] In the case of fluorinated gases, this assumption may be reasonable. However, it would be recommended to conduct a QA analysis using production data of products that use each fluorinated GHG group. For example, perfluorocyclobutane serves as a deposition gas and etchant in the production of semiconductor materials and devices. This can be used as a common index (e.g., surrogate data) to deduce the production trend of this class of fluorinated gases.

Response: As noted in the both the Proposed Methodology Memorandum and Chapter 4.15 of the Inventory, we assume that production of perfluorocyclobutane has grown with layer-weighted production of semiconductors. See the list of compounds to which we apply Total Manufactured Layer Area (TMLA) growth on page 8 of the Proposed Methodology Memorandum and page 4-87 of Chapter

4.15 of the Inventory. The assumption that production was constant was only applied to fluorinated gases whose primary use lay outside industries for which trend data were available.

Comment I9: F-gases memo, question 5-11
[Question 5-11 reads "Is the method for calculating the estimates clearly explained?"] Partially. The methodology does not explicitly identify and state the calculation methods, and formulas as a first step for the reader. Assumptions are properly and transparently documented; however, information is not logically presented. See additional comments per relevant thematic area identified by reviewers.

Response: EPA notes this feedback but notes no examples were provided to illustrate the potential issues with clarity and transparency so EPA is not fully clear on what the commenter means by "information is not logically presented." As noted above, both the Proposed Methodology Memorandum and the Chapter 4.15 of the Inventory systematically review the data and methods used to estimate facility-specific emissions for facilities that respectively do and do not report their emissions to EPA's Greenhouse Gas Reporting Program, discussing how the methodology changes over the time series. Both documents explain how facility-specific emissions are estimated under the GHGRP and how emissions before and after 2011 (when the GHGRP began to collect data) are estimated. The following two excerpts illustrate this:

> ***For vents that emit 10,000 mtCO2e or more (considering controls) of fluorinated GHGs from continuous processes, facilities [reporting under the GHGRP] must use emissions testing to establish an emission factor at least every ten years, or sooner if the process changes in a way that will significantly affect emissions from the vent. For other process vents, facilities may use emissions testing, engineering calculations, or engineering assessments to establish the emission factor. Facilities then calculate their annual emissions based on the measured or calculated emission factor and related activity data, considering the extent to which the process is controlled and any destruction device or process malfunctions (Proposed Methodology Memorandum, p. 3, Chapter 4.15 of the Inventory, p. 4-82).***
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> ***For the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 1990-2010 emissions are estimated using (1) facility- and chemical-specific emission factors based on the emissions data discussed under "2011-2022 Emissions" above, (2) reported or estimated production and transformation of fluorinated GHGs at each facility in each year, and (3) reported and estimated levels of emissions control at each facility in each year.***
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> ***Facility- and chemical-specific emission factors were developed based on the 2011-2015 emissions reported under the GHGRP (discussed above) and the 2011-2015 production and transformation of fluorinated GHGs reported under the GHGRP. (Production and transformation of CFCs and HCFCs are not reported under the GHGRP.) For each emitted fluorinated GHG at each facility, emissions of the fluorinated GHG were summed over the five-year period. This sum was then divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility over the five-year period. (Proposed Methodology Memorandum, p. 5, Chapter 4.15 of the Inventory has similar text on p. 4-84, but that text also reflects the addition of new data for facilities owned by one company.)***

Comment I10: Rationale for using the 2019 Refinement to the 2006 Guidelines

The 2006 IPCC Guidelines also include methodological guidance on non-HCFC-22 fluorochemical production. As the 2006 IPCC GLs remain the main methodological guidance according to the UNFCCC and the Paris Agreement, it is a reasonable approach to refer to this document first since the 2019 Refinement has not still adopted by COP. The Refinement is noted in SBSTA conclusions but not yet acknowledged by Parties as the resource to use for inventories the 2006 IPCC Guidelines remain the main methodological guidance the countries should use for their national GHG inventories under the UNFCCC and the Paris Agreement. If a country chooses to use a country-specific method or different guidelines (2019 Refinement falls under this category), the choice of methodology needs to be justified. To justify using the 2019 Refinement instead of the 2006 IPCC GLs, a more solid explanation is necessary in Section 2: Methodology.

For instance, countries may justify that the 2006 IPCC Guidelines use total production-related emissions calculations and does not distinguish between the emissions components from process vents and equipment leaks. Because the activity data on both components are available from production facilities (i.e., direct measurements or estimates) and the relevant emission factors have been estimated under the GHGRP, United States chose the 2019 refinement to the 2006 IPCC Guidelines to improve the completeness and transparency of reporting emissions from the fluorochemical production category.

Response: EPA notes the explanation suggested by the commenter, and notes that using updated science and methods, when available, is also considered a good practice. EPA will consider including a justification for international reviewers in the next annual report for additional clarity.

Comment I11: Description of Calculation Method Used

Under Section 2 Methodology, the document does not transparently disclose which specific gases are estimated using in Tier 3 and which ones were estimated using Tier 1 methodologies. Similarly, it is not transparently disclosed the allocation of the methodologies based on data reported under the GHGRP and data estimated using production data from other sources. Additionally, it is not clear if the choice of calculation method is consistent across the time series. This information should be clearly stated in this section. Additionally, section Facility- and Chemical-Specific Emission Factors Reflecting No Emissions Controls provides a verbal description of the calculation steps used to estimate emissions from the uncontrolled processes but does not present the corresponding equations which would have made understanding of the logical path of the calculation much better and improve transparency.

Response: Both Section 2 of the Proposed Methodology Memorandum and Chapter 4.15 of the Inventory are quite explicit and detailed regarding the data and calculation methods used for different facilities and different parts of the time series. (It is important to note that many GHGs, including SF_6, have been emitted from multiple facilities over the time series; thus, there is not a simple correspondence between a particular GHG and a particular method.) Both documents include detailed background regarding the data reported under the GHGRP (including the Tier 3 methods that facilities must use to estimate their emissions), since the GHGRP data is the basis for the estimated emissions over the time series (Proposed Methodology Memorandum, pp. 2 to 4; Chapter 4.15 of the Inventory, p. 4-81 to 4-84). The different parts of the time series are clearly indicated by subheadings with ranges of years, and the methods used for each part of the time series, and for facilities that have or have not reported their emissions under the GHGRP, are described in detail. One way that the discussion could be clarified further would be to briefly summarize the numbers of facilities for which each method was used in each part of the time series. (This is partly, but not completely, done in the existing Chapter 4.15 of the Inventory.)

Regarding the explanation of the methods used to calculate emissions from uncontrolled processes, an equation is provided in both the Proposed Methodology Memorandum and Chapter 4.15 of the Inventory for the Effective Destruction Efficiency or EDE, which shows the relationship between the EDE, controlled emissions, and uncontrolled emissions (Proposed Methodology Memorandum, p. 4; Chapter 4.15 of the Inventory, p. 4-83).

Comment I12: Add Country-specific method Description and Reference
A brief description and a reference for each approach are needed to improve transparency where the method provided is country-specific. According to paragraph 41 of the Decision 24/CP.19, "Annex I Parties that prepare their estimates of emissions and/or removals using higher-tier (tier 3) methods and/or models shall provide in the NIR verification information consistent with the 2006 IPCC Guidelines."

***Response**: As noted above, both the Proposed Methodology Memorandum and Chapter 4.15 of the Inventory systematically review the data and methods used to estimate facility-specific emissions for facilities that respectively do and do not report their emissions to EPA's Greenhouse Gas Reporting Program, discussing how the methodology changes over the time series. Both documents explain how facility-specific emissions are estimated under the GHGRP and how emissions before and after 2011 (when the GHGRP began to collect data) are estimated. In addition, both documents provide an overview of the process of verifying data under the GHGRP. EPA can consider specific comments to enhance clarity and transparency, if provided in future reviews.*

Comment I13: Information Not Broken Down by Gas
Throughout the document, information provided in text format often does not represent information by individual gas. For example, in the section Emissions Reported Under Subpart L of the GHGRP, it is stated that "most emissions are reported by chemical". No further information is provided to identify these chemicals.

Response: Due to the large number of individual compounds emitted from this industry (approximately 200, 47 of which are HFCs, PFCs, SF_6, or NF_3), it is not practicable to include a full listing of emitted compounds in the text. However, Chapter 4.15 of the Inventory includes the most emitted HFCs and PFCs as well as SF_6 and NF_3 (see pp. 4-79-80). It also includes the most emitted fluorinated GHGs other than HFCs, PFCs, SF_6, and NF_3 (see pp. 4-80-81). The CRTs will include a complete listing of emitted HFCs and PFCs as well as SF_6 and NF_3. Moreover, Tables A-4 and A-5 in the appendix to the Proposed Methodology Memorandum included the most emitted 28 compounds, representing 99 percent of GWP-weighted emissions. (A full list of the emitted compounds was also included as an attachment to the Proposed Methodology Memorandum.)

Comment I14: GWP Source Not Found
Table A.1 does not provide the source of GWP, just the value for each gas/group of gases is included in the table. This source of GWP information must be included for transparency and accuracy of calculations of CO2e.

Response: EPA will clarify this in the next Inventory and appropriately reference existing discussions on use of 100-year GWP's from IPCC's Fifth Assessment Report (AR5). AR5 GWPs are used in preparing national inventory estimates as required by the reporting guidelines to ensure comparability in reporting (see discussion included in the Introduction Chapter (p. 1-8, and Annex 6 to the Inventory).

As noted in the Proposed Methodology Memorandum and Chapter 4.15 of the [Inventory](), chemical-specific GWPs are generally used by facilities to calculate the CO_2e emissions they report to the GHGRP by fluorinated GHG group; the default GWPs shown in Table A.1 in the Proposed Methodology Memorandum (Table 4-68 of Chapter 4.15 of the [Inventory]()) are only used for GHGs that lack a chemical-specific GWP. The chemical specific GWPs currently used in the GHGRP are primarily based on the IPCC Fourth Assessment Report (AR4) but also on the IPCC Fifth Assessment Report (i.e., for GHGs that do not have GWPs in AR4). The same is true of the default GWPs.

It is important to note, however, that the same GWPs used to report emissions in metric tons CO2e under the GHGRP are used by EPA to back-calculate estimated emissions in metric tons; thus, the GWP is ultimately cancelled out of the calculation of the metric tons emitted. As for other source categories, GWPs from the IPCC Fifth Assessment Report (AR5) were applied to calculate the CO_2e emissions presented in Chapter 4.15 of the [Inventory]().

Comment I15: F-gases memo, question 5-1
[Question 5-1 reads in part "For all the years from 1990 through 2022, but especially for the years 1990 through 2010, are you aware of data or information that could be used to develop emissions estimates for one or more facilities that are more accurate, precise, or complete than the emissions estimates presented here?"] Arkema has not developed FGHG emission estimates for these date ranges that are better than what has been derived from the data reported per Part 98.

Response: EPA notes this feedback.

Comment I16: F-gases memo, question 5-2
[Question 5-2 reads in part "We are still in the process of developing emissions estimates for facilities that produce fluorinated GHGS but do not report their emissions under subpart L of the GHGRP. We are likely to use the Tier 1 emission factor from the 2019 IPCC Refinement to estimate these emissions. Are you aware of data or information for these facilities that could be used to develop emissions estimates that are more accurate, precise, or complete than emissions that would be calculated for them using the Tier 1 factor?"] No other data is available except for actual production data for HFC-134a (beginning in 1997) and HFC-32 (beginning in 2007) between 1990 and 2010.

Response: EPA has used the information provided by the commenter on Arkema's start dates of production of HFC-134a and HFC-32 in its estimates for Chapter 4.15 of the [Inventory]().

Comment I17: F-gases memo, question 5-3
[Question 5-3 reads "For the years 1990 through 2010, are you aware of general usage or production data for any group of fluorinated GHGs other than the usage/production data discussed in the Methodology section above for HFCs, PFCs, NF3 and SF6? For example, are you aware of usage or production data for fluoropolymers for 1990 through 2010?"] Arkema has production records for HCFCs produced from at least 1998 forward and may have records prior to 1998 that are not readily available. Arkema also has records of PVDF fluoropolymer produced between 1990 and 2010. However, PVDF is not a fluorinated GHG as it is a solid at standard conditions and does not meet the vapor pressure requirement in the definition of a "Fluorinated Greenhouse Gas" listed in 40 CFR 98.6. [Regarding publicly available data,] I have been told IHS Insight provides public data related to production. Beyond that I am not aware of other publicly published data.

Response: EPA notes this feedback and will investigate whether the IHS Insight data may be helpful to estimate emissions before 2010.

Comment I18: F-gases memo, question 5-4
[Question 5-4 reads "Are you aware of fluorochemical production processes that emit fluorinated GHGs but whose emissions are not reported under the GHGRP because the processes are not fluorinated gas production or transformation processes or do not occur at a fluorinated gas production facility?"] No.

Response: EPA notes this feedback.

Comment I19: F-gases memo, question 5-5
[Question 5-5 reads "Were there any fluorinated gas production or transformation processes that were significant contributors to fluorinated GHG emissions at any point between 1990 and 2010 that are not represented in the 2011 through 2015 data?"] No.

Response: EPA notes this feedback.

Comment I20: F-gases memo, question 5-6
[Question 5-6 reads "Are you aware of emission factors for specific fluorinated GHGs from the production or transformation of specific fluorinated gases, including, for example, HFCs, PFCs, CFCs, and HCFCs (other than HCFC-22)?"] Yes, as required by Part 98 Subpart L. Arkema has developed both calculated and stack test-based emission factors in accordance with the requirements of Subpart L. [Regarding publicly available data,] I have been told IHS Insight provides public data related to production. Beyond that I am not aware of other publicly published data.

Response: EPA notes this feedback and will investigate whether the IHS Insight data may be helpful to estimate emissions before 2010.

Comment I21: F-gases memo, question 5-7
[Question 5-7 reads "Where general trend data were not available to back-cast production of fluorinated gases, we have assumed that production of these gases remained constant over time. Should we instead assume that production increased with the U.S. GDP or another common index?"] U.S. GDP would likely be a better predictor of general production than a flat rate of production over many years. Production can vary greatly and is rarely, if ever, flat year over year. Please note, Arkema has not conducted a study of the relationship specifically between its historic production and U.S. GDP and therefore can't comment definitively on the general production of fluorinated gases related to U.S. GDP.

Response: EPA notes this feedback and will consider whether U.S. GDP or another common index can be applied to production data for fluorinated gases whose primary use lies outside industries for which trend data are available.

Comment I22: F-gases memo, question 5-8
[Question 5-8 reads "Are you aware of any fluorinated gas production facilities (other than facilities that produced SF6 or HCFC-22 only) that produced fluorinated gases before 2010 but not during or after 2010? If so, please provide any information you can on the gases produced, production capacity, and emissions or emission rates of these facilities."] No.

Response: EPA notes this feedback.

Comment I23: F-gases memo, question 5-9
[Question 5-9 reads "Are you aware of any fluorinated gas production facilities that produced fluorinated gases during or after 2010 but that did not produce fluorinated gases during the entire period 1990 to 2009? If so, please provide any information you can on which facilities fall into this category and when they began producing fluorinated gases."] No.

Response: ***EPA notes this feedback.***

Comment I24: F-gases memo, question 5-10
[Question 5-10 reads "In general, are you aware of any data that could address or decrease the uncertainties listed in section 4?"] Other than possible production records mentioned in the comments to questions 2 and 3 above, no.

Response: EPA notes this feedback.

Comment I25: F-gases memo, question 5-11
[Question 5-11 reads "Is the method for calculating the estimates clearly explained?"] Yes.

Response: EPA notes this feedback.

Comment I26: F-gases memo, question 5-12
[Question 5-12 reads "Are the shortcomings of available data and estimation approaches clearly articulated?"] Yes.

Response: EPA notes this feedback.

Comment I27: Emission Factors Reflecting Emissions Controls
It seems the Agency is developing an emission intensity factor based on emissions per production. While this approach is understandable given the lack of data for this time period, it should be noted this is not an emission factor per se. The emission factors required to be developed under Subpart L are related to a process activity (e.g., mass flow through a flow meter) that is likely not production. Arkema has no objection to using this approach as long as the Agency understands an emission intensity factor based on production is not the same as an emission factor based on process variables.

Response: EPA notes this feedback.

Comment I28: Estimated production for facilities and fluorinated GHGs for which production data before 2010 were not available (page 9)
"In the absence of production data for years 1990 to 2009, the production data reported to the GHGRP under subpart OO were extrapolated backward based on the industry trends discussed above. For compounds for which industry trend data were unavailable, production was assumed to have remained constant over the time series." This is not an accurate assumption. Arkema's HFC-134a unit did not begin operations until 1997 and its HFC-32 unit did not begin operations until 2007. Accordingly, the emission estimates for Arkema detailed the "F-GHG_emissions_estimates_for_Arkema" spreadsheet can not be accurate. Most of the FGHG emissions estimated back to 1990 would not have been produced by Arkema during many of those years.

Response: The commenter notes that it is inaccurate to assume that production remained constant from 1990 to 2009, citing their growing production of HFC-134a and HFC-32 over this period. However, the assumption that production remained constant only applies to production of fluorinated GHGs for which EPA doesn't have other indices (e.g., the Vintaging Model) for estimating emissions. Both HFC-134a and HFC-32 are included in the Vintaging Model, so EPA currently estimates that production of both compounds increased substantially between 1990 and 2010. The data provided by the commenter on the start dates of their HFC-32 and HFC-134a production enabled EPA to further refine these estimates for the final Inventory (see Chapter 4.15 of the Inventory). However, HFC-134a and HFC-32 are not the only products that drive the commenter's estimated emissions; the commenter also manufactures other fluorinated GHGs. In the current analysis, EPA has not attempted to link emissions of particular F-GHGs to production of particular F-GHGs, but assumes that all production emits all F-GHGs reported under subpart L. While EPA recognizes that this is inaccurate (see the discussion of uncertainties in Chapter 4.15 of the Inventory on page 4-91), EPA does not have an alternative unless the commenter is willing to share the specific compounds that are emitted by each production process. Because EPA assumes that the commenter's production of the other fluorinated GHGs was flat between 1990 and 2010, EPA concludes that the commenter was emitting, during that period, all the HFCs that the commenter later reported emitting under subpart L, but at a rate proportional to total estimated fluorinated gas production and transformation at the time.

Comment I29: F-gases memo, question 5-1

[Question 5-1 reads in part "For all the years from 1990 through 2022, but especially for the years 1990 through 2010, are you aware of data or information that could be used to develop emissions estimates for one or more facilities that are more accurate, precise, or complete than the emissions estimates presented here?"] I know of no further way of driving estimates of the emissions. For Washington Works we have had our Thermal destruction device in operation, largely operating in the same manner, since pre-2000. I have no input for other Chemours sites. Essentially the GHG inventory addresses a set of chemicals that are largely unregulated in other rules. If West Virginia had not established Ozone Depleting Chemicals (ODCs) as a class of regulated chemicals (ODC1 and ODC2) we would not have the records available in the AEI records for WV. Materials like C-318 [Perfluorocyclobutane] are not reportable under any other system other than the GHG inventory so there would be no driving force for tracking the emissions of perfluorinated compounds if they were generated. An additional problem is that, barring legal hold orders or consent decrees Industrial sources generally retain records for production amounts for 3 years after the end of the year. In your explanation you are essentially asking us to report all details without the IVT system of data protection. Most industrial sites will consider the direct reporting of production data to not be in the best interest of the company and that such capacity-related data is considered confidential business information.

Response: EPA notes this feedback.

Comment I30: F-gases memo, question 5-2

[Question 5-2 reads in part "We are still in the process of developing emissions estimates for facilities that produce fluorinated GHGS but do not report their emissions under subpart L of the GHGRP. We are likely to use the Tier 1 emission factor from the 2019 IPCC Refinement to estimate these emissions. Are you aware of data or information for these facilities that could be used to develop emissions estimates that are more accurate, precise, or complete than emissions that would be calculated for them using the Tier 1 factor?"] We already make extensive efforts to maintain and correct the data associated with emissions estimates. I would expect that most people are not as complicated as Chemours at

Washington Works – but you are asking for essentially a peak at the yield and performance of processes. We use the Subpart L IVT form to submit the data and it is already very detailed and time consuming to generate the report. But without the IVT protection would be arguing that the data request infringes on confidential information that is protected to ensure economic viability of the process.

Response: EPA notes this feedback. Note that question 2 concerned emissions from facilities that do not report their emissions under subpart L of the GHGRP. Because the commenter's facility reports their emissions under subpart L, we were not requesting this information for the commenter's facility.

Comment I31: F-gases memo, question 5-3
[Question 5-3 reads "For the years 1990 through 2010, are you aware of general usage or production data for any group of fluorinated GHGs other than the usage/production data discussed in the Methodology section above for HFCs, PFCs, NF3 and SF6? For example, are you aware of usage or production data for fluoropolymers for 1990 through 2010?"] We routinely use the production data for fluoropolymers as part of the Subpart L form reporting. We use all forms of the polymers produced to generate the emissions associated with the production. So, yes we have such data and it has been used to generate the appropriate reports – during the time periods the data was retained.

Response: In question 5-3, we had intended to specify that we were asking whether commenters knew of any PUBLIC fluorinated gas usage or production data (e.g., on fluoropolymer production). We followed up with the commenter to clarify this but did not receive a response.

Comment I32: F-gases memo, question 5-4
[Question 5-4 reads "Are you aware of fluorochemical production processes that emit fluorinated GHGs but whose emissions are not reported under the GHGRP because the processes are not fluorinated gas production or transformation processes or do not occur at a fluorinated gas production facility?"] Processes that generated fluorinated GHG but are not a fluorinated gas production unit would be any process that uses fluorine to enhance the physical properties of a material. We run fluorination processes in association with some of our transformation units and they generate small amounts of NF3 – which we report. Similar processes where direct fluorination of non-fluorinated substrates may be a potential source of further GHG emissions not currently captured.

Response: EPA notes this feedback.

Comment I33: F-gases memo, question 5-5
[Question 5-5 reads "Were there any fluorinated gas production or transformation processes that were significant contributors to fluorinated GHG emissions at any point between 1990 and 2010 that are not represented in the 2011 through 2015 data?"] For Chemours I believe that we have captured a majority of the emissions at our sites although we continue to review testing results, with improved analytical capabilities, to determine if we have materials not being accounted for in the inventory. While you as about the time period 2011 through 2015, I feel a better picture could be developed for the earlier dated by looking at the emissions from the units in the 2018 – 2019 time frame when industrial awareness of the complexity of the GHG emissions was starting to dawn.

Response: EPA notes this feedback.

Comment I34: F-gases memo, question 5-6

[Question 5-6 reads "Are you aware of emission factors for specific fluorinated GHGs from the production or transformation of specific fluorinated gases, including, for example, HFCs, PFCs, CFCs, and HCFCs (other than HCFC-22)?"] We have our specific emission factors for unsaturated perfluorinated materials that are our products from our monomer unit. These emission factors are monitored as part of the yield and utility calculation of the affected processes and are considered confidential business information. Yields in general would be advantageous to EPA for production data if the industrial participants could be cajoled into revealing them. Yield is generally a finished product / raw material calculation that expresses how much of the raw materials were converted to finished product. It is a direct handle that would reflect how much of the process was directed to control devices or transformed into "other" non-product forms.

Response: EPA notes this feedback. In question 5-6, we had intended to specify that we were asking whether commenters knew of any PUBLIC emission factor data.

Comment I35: F-gases memo, question 5-7
[Question 5-7 reads "Where general trend data were not available to back-cast production of fluorinated gases, we have assumed that production of these gases remained constant over time. Should we instead assume that production increased with the U.S. GDP or another common index?"] We have found that Fluoromonomer gases that we manufacture and then either sell or convert to polymers has tracked the electronics industry activities for chip manufacturing in the past. However, with the development of new types of batteries, we are seeing the production of material change it's basis. It really depends on the market the individual business services or has a goal of servicing as a source of supply of fluoropolymers and fluoromonomers.

Response: EPA notes this feedback.

Comment I36: F-gases memo, question 5-8
[Question 5-8 reads "Are you aware of any fluorinated gas production facilities (other than facilities that produced SF6 or HCFC-22 only) that produced fluorinated gases before 2010 but not during or after 2010? If so, please provide any information you can on the gases produced, production capacity, and emissions or emission rates of these facilities."] No, I am not aware of any production facilities that would have produced material prior to 2010 by ceased production since then. Have you cross referenced with changes in the various refrigerant gases as they move out of the production [phase and into increased production controls to restrict manufacturing. I would anticipate that refrigerant gases would have had the potential to generate GHG gases during the manufacture of HCFCs, CFCs or HFCs.

Response: EPA notes this feedback. The Inventory currently includes, in a separate section, emissions of HFC-23 from production of HCFC-22, which was historically used as a refrigerant and is currently used as a feedstock (Chapter 4.15 of the Inventory, pp. 4-74 to 4-76). We may consider including emissions from production of other HCFCs and also CFCs if activity data and emission factors are available to support estimates.

Comment I37: F-gases memo, question 5-9
[Question 5-9 reads "Are you aware of any fluorinated gas production facilities that produced fluorinated gases during or after 2010 but that did not produce fluorinated gases during the entire period 1990 to 2009? If so, please provide any information you can on which facilities fall into this category and when they began producing fluorinated gases."] No, I am not aware of any specific processes that produced GHG materials after 2010 but did not in the years prior to that date. Again, I

would recommend review of Refrigerant gas production and specifically the introduction of new refrigerants during the period starting in 2010 and continuing on. Production of new refrigerants would be marked by permitting activity and advertising as well as obtaining approval for a substitute refrigerant gas for other more destructive refrigerant gases.

Response: EPA notes this feedback.

Comment I38: F-gases memo, question 5-10
[Question 5-10 reads "In general, are you aware of any data that could address or decrease the uncertainties listed in section 4?"] No, You are dealing with a slippery subject. Fluoronated materials are generally produced into a market that has a specific need for the fluorinated materials. Rocket motors use fluorinated materials (Solid fuel units may be largely composed of fluoropolymer with additional gas generating agents added to it.) But there is no direct way to address the size of the market, how it changes or who sells into that market. The same for fluoropolymer wire insulation, used in fine connections in computers. Fluoropolymers have a high-value-in-use and this means that small are used to keep the cost of the final product down. Fluoropolymers are used when other materials do deliver on product characteristics such a longer life span, greater reliability, or because of functional requirements.

As I have mentioned several times in discussions with you on GHG emissions – the current inventory appears to assume that we make about the same amounts from year-to-year. We do not. Production lines may have product wheels that affect the total production of the unit. The monomer supply may have periodic shutdowns for maintenance that may be annual, bi-annual of even longer between shutdowns. The length of the shutdown is also important as well as the ability to easily restart the plant [NOT a sure bet!]. We easily exceed the GHG inventory change flags based on the subjects above, and based on 2023 we will also trigger then again.

Response: The commenter appears to be using the term "inventory" to describe GHGRP data verification algorithms. Chapter 4.15 of the Inventory reflects the emissions reported by the commenter since 2011, including the year-to-year fluctuations highlighted by the commenter.

Comment I39: F-gases memo, question 5-11
[Question 5-11 reads "Is the method for calculating the estimates clearly explained?"] Yes.

Response: EPA notes this feedback.

Comment I40: F-gases memo, question 5-12
[Question 5-12 reads "Are the shortcomings of available data and estimation approaches clearly articulated?"] Yes, they're articulated well and are specific in stipulated your concerns.

Response: EPA notes this feedback.

Comments on Proposed Methodology Refinements for Iron and Steel Production

Comment I41: Dramatic Variation in GHG Inventory and GHGRP for 2011-2019

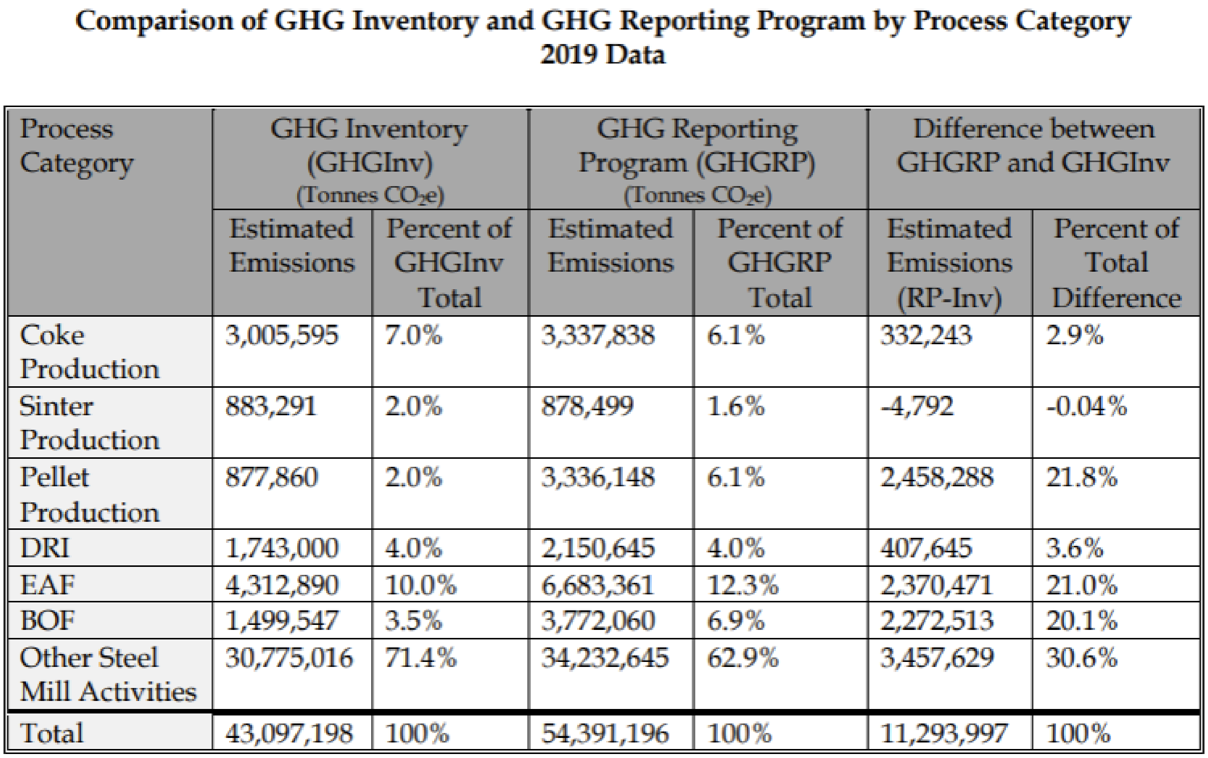
In reviewing the GHG Inventory estimates compared to GHGRP data presented in the GHG Inventory: I&S, the total estimates for the industry by year (page 18-19) vary significantly over the 2011-2019 period examined. The most dramatic variation between the two approaches falls in 2017 (as shown in Table 14, page 19). In that year, the GHGRP total estimate is 30 percent higher than the GHG Inventory estimate. The annual variation over the nine-year period, however, does not demonstrate a discernible pattern that would provide insight into potential causes.

GHG Inventory and GHGRP totals over the nine-year timeframe examined, but along with the year 2017, the years 2012 and 2013 show fairly substantial variation between annual estimates. Additionally, the variation across specific process categories (e.g., Coke, Sinter, Pellet, etc.) for given year comparisons fluctuates significantly (as shown in Table 15 and Figure 8, page 19). In the years 2016, 2017 and 2019, the Other Steel Mill Activities category shows substantial variation between estimates. However, in the years 2018 and 2015 the Other Steel Mill Activities category reflects little variation between GHGRP and GHG Inventory estimates. Alternatively, the annual variation between the GHG Inventory and GHGRP estimates for the Pellets process category is very consistent for all nine years from 2011-2019.

Additional insights may be found from examining specific year comparisons in greater detail. The table below looks more closely at the comparison of GHG Inventory and GHGRP for the year 2019. For this year, the Other Steel Mill Activities category makes up over 70 percent of the total GHG Inventory estimate and almost 63 percent of the total GHGRP estimate. Almost one third (30.6 percent) of the variation between the two approaches is associated with the Other Steel Mill Activities category.

Based on the above comparisons, AISI suggests the following avenues for further consideration [see comments 142-145 below].

Table 1: Supplement to Comment I41



Comparison of GHG Inventory and GHG Reporting Program by Process Category
2019 Data

Process Category	GHG Inventory (GHGInv) (Tonnes CO$_2$e)		GHG Reporting Program (GHGRP) (Tonnes CO$_2$e)		Difference between GHGRP and GHGInv	
	Estimated Emissions	Percent of GHGInv Total	Estimated Emissions	Percent of GHGRP Total	Estimated Emissions (RP-Inv)	Percent of Total Difference
Coke Production	3,005,595	7.0%	3,337,838	6.1%	332,243	2.9%
Sinter Production	883,291	2.0%	878,499	1.6%	-4,792	-0.04%
Pellet Production	877,860	2.0%	3,336,148	6.1%	2,458,288	21.8%
DRI	1,743,000	4.0%	2,150,645	4.0%	407,645	3.6%
EAF	4,312,890	10.0%	6,683,361	12.3%	2,370,471	21.0%
BOF	1,499,547	3.5%	3,772,060	6.9%	2,272,513	20.1%
Other Steel Mill Activities	30,775,016	71.4%	34,232,645	62.9%	3,457,629	30.6%
Total	43,097,198	100%	54,391,196	100%	11,293,997	100%

Response: The EPA continues to examine the differences between the GHGRP reported data for I&S and the existing calculations in the Inventory. As noted, the Other Still Mill Activities constitutes the biggest source of emissions and one of the biggest discrepancies in the GHGRP and current Inventory emissions data. That will be an area of specific consideration including breaking it out into more detail in terms of blast furnace emissions and emissions by fuel type. More information will be provided as part of projected updates in a future report. Sufficient review will be available before any updates to the Inventory I&S emission estimation methodology is made.

Comment I42: Compare GHGI and GHGRP Methodologies for Other Steel Mill Activities
Perform a closer comparison between the GHG Inventory and GHGRP methodologies for the Other Steel Mill Activities category. Even though the variation for given years is not as great across the full 2011-2019 period comparison, the Other Steel Mill Activities category represents the largest share of the GHG emissions for both approaches each year.

Response: As noted, the Other Still Mill Activities constitutes the biggest source of emissions and one of the digest discrepancies in the GHGRP and current Inventory emissions data. That will be an area of specific consideration including breaking it out into more detail in terms of blast furnace emissions and emissions by fuel type.

Comment I43: Clarify Methodology for Blast Furnace

Table 1 on page 4 of the GHG Inventory: I&S document portrays the process category breakdown for the GHG Inventory and the GHGRP. In this breakdown, “Blast Furnace, including Pig Iron Production” is listed as one of the eight categories for each estimation approach. However, in the comparison of the estimation methodologies by category that follows, that category is the only category that does not receive its own separate treatment. It would be helpful to better understand the methodology related to the assessment of GHG emissions for this process category.

Response: Blast Furnace, including Pig Iron Production is not a category specifically reported under through the GHGRP. It is included as part of subpart C reporting for I&S facilities. Information, where available, is included as part of the Other Still Mill Activities reported above. This is an area of further research and EPA will provide more information regarding this assessment as part of any updates to a future report.

Comment I44: Potential Activity Data Source
In its review of the GHG Inventory and GHGRP comparison, on page 19, EPA suggests that a potential reason for the higher estimates associated with the GHGRP could relate to the division between process emissions and fuel use. One possible resource that may be useful in considering this question is the Department of Energy’s Manufacturing Energy Consumption Survey (MECS) Steel Industry Analysis. MECS is a national sample survey that annually collects information on the U.S. manufacturing establishment, their energy-related building characteristics, and their energy consumption and expenditures.

Response: EPA is looking into the use of MECS data as a means for separating out fuel use and process emissions from the GHGRP I&S emissions estimates. This will be useful for avoiding double counting between I&S reported emissions and emissions calculated as part of fossil fuel combustion emissions in the Energy sector.

Comment I45: Compare Emission Factors within GHGI and GHGRP
Compare the emission factors employed within the GHG Inventory and GHGRP emission estimation methodologies. The difference between GHG Inventory’s use of 2006 IPCC Guidelines emission factors and the GHGRP facility specific emission factors may be an underlying cause of the difference.

Response: EPA is continuing to look into the differences between the GHGRP I&S emissions and those reported under the current Inventory approach. The emission factors are one area of consideration, especially considering areas where IPCC Tier 1 emission factors are used. The GHGRP methodologies do not rely on emissions factors so much as on the mass and carbon balances of the process involved.

Comment I46: New Data Source for Steel
AISI would also highlight for EPA’s consideration a new source of data currently under development. At the request of the U.S. Trade Representative, the International Trade Commission (ITC) is currently undertaking an investigation of greenhouse gas intensities of the U.S. steel industry. This investigation will involve steel company responses to a detailed questionnaire on GHG intensities at the product level. The resulting database is due to be completed by early 2025 and will reflect 2022 GHG emissions data for the industry. While many of the details of the database format and contents are not yet known at this time, this database may be a useful source of information for EPA’s work on the GHG Inventory.

Response: EPA is aware of the ITC data collection effort and understands it may be a useful source of data for estimating I&S sector emissions. It is unclear how much of the data collected will be publicly

available, but EPA will continue to monitor the effort and examine how any available data could be used to help improve or update the I&S emission calculations in the Inventory.

Comment I47: Concern about Data Bias
Be very aware when using AISI or any other trade association's data. Sometimes their data are biased because there is a tendency to only collect/report data from their members and not from the entire population.

Response: The current Inventory methodology for estimating I&S emissions relies in large part on data from AISI. However, estimates are also based on other industry data including from USGS and other sources. EPA is continuing to examine other data sources including MECS and GHGRP data to help update our methodology. Whatever approach is used will have to be able to be used across the historic timeframe of emissions from 1990 thru the current reporting year.

Comment I48: Source Recommendation: Manufacturing Consumption Survey (MECS)
I'm surprised that there was no data used and referenced about the iron and steel industry from the MECS. There's numerous data—total, fuel, feedstock, and end uses to name a few— about the iron and steel industry in the MECS data tables. The iron and steel industry are broken out from Primary Metals in the tables because it is so energy-intensive. The MECS data online also goes back to 1991. Here's the most recent MECS data if you want to take a closer look at it. The one drawback about the MECS data is it's only conducted and published once every four years. [Link to MECS data.]

Response: EPA is looking into the use of MECS data as a means for separating out fuel use and process emissions from the GHGRP I&S emissions estimates. This will be useful for avoiding double counting between I&S reported emissions and emissions calculated as part of fossil fuel combustion emissions in the Energy sector.

Chapter 5. Agriculture

Comment A49: Citation Availability
In general, none of the ERG and ICF references are publicly available—or at least easily accessible. These are key references to core parts of the report, the CEFM model and uncertainty calculations. Furthermore, there are multiple references to personal communications instead of published reports and peer-reviewed studies.

Response: EPA notes the commenter's comments and agrees that transparency is important and will work to improve the transparency of references, including non-literature references such as personnel communications where information is not considered confidential. For example, in many cases, farm-specific information cannot be shared due to confidential information.

Comment A50: Formatting
5-2, Line 23, Table 5 should be Table 5-2.

Response: Table references have been updated.

Comment A51: Footnote Recommendation
5-5, Lines 1-2, "The diet characteristics for dairy cattle were based on Donovan (1999) and an extensive review of nearly 20 years of literature from 1990 through 2009." It would be helpful to add a footnote that says that there is more detailed information located in Annex 3.10 (A-61 to A-68).

Response: EPA notes the commenter's comment and further notes that a reference to Annex 3.10 is provided in the Inventory. EPA will continue to review the methodology discussion and work to identify areas of improvement for the transparency of the Inventory.

Comment A52: References Unavailable
5-5, the following references are not publicly available and/or personal communications (listed in order of appearance). Donovan (1999), Johnson (1999), Johnson (2002), ERG (2016), Archibeque (2011), Enns (2008).

Response: EPA has revised to the text to address the reviewer's comments. A new citation was added for Donovan and Baldwin (1999).

Comment A53: Citation Needed
5-5, Lines 15-16 "weight gains for cattle were estimated from …. and expert opinion". As written, "expert opinion" is not very transparent. There should be a citation, more information given related the expert opinions, or the words "expert opinion" should be omitted if significant value is not added for the reader considering the long list of references stated in Lines 15-16.

Response: EPA continues to improve its documentation and transparency. These instances are noted and plan to be addressed in future versions of the report.

Comment A54: Reference Unavailable
5-6, Lines 19-20, the ICF (2003) reference for the Monte Carlo Stochastic Simulation technique is not publicly available. While there is a detailed text description of how the uncertainty analysis was

performed, the analysis is difficult to understand without figures, data, or more information on the methodology which could be consulted if ICF (2003) was a publicly available reference.

Response: EPA will consider how to improve the description of the steps to develop the uncertainty analysis, along with including additional documentation in the annexes to the inventory to enhance transparency of the uncertainty analysis. This feedback is noted and useful for addressing incrementally in the next and forthcoming versions of the report. See also response to comment A55 with regards to updates underway.

Comment A55: Uncertainty Ranges in Enteric Fermentation
5-7, Table 5-3, would it be possible to give the uncertainty ranges for each animal category similar to Table 5-1 and Table 5-2? It should not add too much more space to the report. It would also be helpful to include uncertainties for cattle subcategories either in this section or in Annex 3.10. The uncertainty for individual cattle sub-source categories is currently discussed on 5-6, but the statements are relatively qualitative and would be much clearer if presented in table form consistent with Table 5-1 and 5-2. There are comprehensive tables for emissions by state and by cattle subcategory in Annex 3.10, A-70 to A-83, but there is no discussion of uncertainty by cattle subcategory or state. If possible, it would also be interesting to report which parameters currently introduce the largest uncertainties into the outputs of the CEFM. A potential research direction would be to address the uncertainties of these key parameters.

Response: EPA is working to update the uncertainty for this source and will consider this feedback and for presenting the updated uncertainty analysis when complete.

Comment A56: Progress on Planned Improvements
5-8, Planned Improvements, these improvements haven't changed in the last few years. Would it be possible to discuss which of the listed improvements were worked on in the last year and what the progress is?

Response: EPA notes the suggestion from the commenter. EPA is currently working on a number of Enteric Fermentation improvements and plans to provide more details on progress of improvement implementation in the next Inventory for this category similar to the information provided on improvement implementation progress for Manure Management on pg. 5-20 and 5-21.

Comment A57: Formatting
5-33, Lines 1-2, there is a line missing between IPCC (2019) and Johnson (2002); with the current formatting, the two references look like they are 1 reference instead of 2 references.

Response: EPA has updated references and corrected the formatting in the text to address the reviewer's comment.

Comment A58: Reference Clarification
A-62, Lines 12,14,24,27, it is unclear if there is a difference between Donovan (1999) and Donovan and Baldwin (1999). I think that is assumed that the two are the same, but it is confusing to switch between the two, and it would be clearer if a separate reference were added for Donovan and Baldwin (1999). Baldwin is currently not listed in the references for both Annex 3.10 and page 5-32.

Response: EPA has updated the reference list for Chapter 5 to reflect both references as they are two distinct references, see page 10-52 of the final Inventory. EPA is updating the references in Chapter 5.1 in the next Inventory. We are reviewing the in-report citations and will update in the next Inventory with other annual updates. .

Comment A59: Transparency
There is very detailed information in this report, but I would argue that it is lacking in transparency. One could define transparency in the following manner, "Transparency refers to the quality of being clear, open, and easily understandable. It implies that information is readily available and accessible, without obfuscation or hidden agendas. Transparency means conveying information in a straightforward and uncomplicated manner. Transparent information is user-friendly and understandable, with clear documentation, such that complex processes are visible and comprehensible to users." Many of the cited references in this report are not publicly available, and this contributes to a lack of transparency that makes it more difficult for readers to understand how the US EPA GHG inventory was constructed. The lack of transparency also makes it more difficult for third parties to evaluate results and methods. I do not expect all the cited references to be publicly available for the 2023 report, but if the EPA would like to be more transparent, I would recommend for more of the references to be published online over time. A second solution would be to cite sources that are publicly available or to point readers to specific sections of the Annexes. It could be that content from the references that are not publicly available has been adapted and incorporated into the Annexes. However, even for an expert reviewer, it is not clear whether the Annexes contain information from the references that are not publicly available. Perhaps it would be clearer to refer readers to specific pages or tables of the Annexes rather than to simply refer readers to entire sections of the Annexes.

Response: EPA continues to improve its documentation and transparency. These instances are noted and plan to be addressed in future versions of the report.

Comment A60: Enteric Fermentation Methodology
The methodology was presented clearly and is easy to understand.

Response: EPA notes the commenter understood the methodology applied to estimate emissions from enteric fermentation.

Comment A61: Manure Management Memo
The methodology was presented clearly and is easy to understand. I appreciated the list of sources used upfront in the section and the list of improvements and what they will achieve at the end.

Response: EPA notes this feedback.

Comment A62: Agricultural Soil Management
The methodology was presented clearly and is easy to understand.

Response: EPA notes this feedback.

Comment A63: Urea Fertilization
The methodology was presented clearly and is easy to understand.

Response: EPA notes this feedback.

Comment A64: Accuracy of Industry Description for Manure Management
To my knowledge, the current state of the industry is accurately described. I am not aware of any additional technologies, practices, and trends that should be considered.

Response: EPA notes this feedback.

Comment A65: Uncertainties
Yes, the parameters and discussion of uncertainty within the Manure Management source category estimates adequately reflect all uncertainties from the industry.

Response: EPA notes this feedback.

Comment A66: Accuracy of Industry Description for Enteric Fermentation
To my knowledge, the current state of the industry is accurately described. I am not aware of any additional technologies, practices, and trends that should be considered.

Response: EPA notes this feedback.

Comment A67: Regional Designations of U.S. States for Cattle Diet Characterization
In most cases, the regional designations of the U.S. states used to characterize the diets of foraging cattle is appropriate. However, I noticed that in the West region, the states grouped together are different in terms of foraging from cattle. While Arizona, Nevada, and New Mexico are similar in terms of being "desert" states, I feel like these states are different to Alaska, Hawaii, Idaho, Oregon, Utah, and Washington. It is possible that foraging diet in these "desert" states could be different to the foraging diet in the remaining states in the West region.

Response: EPA appreciates the reviewer's "on the ground" perspective and agrees there are likely differences in forage available. The regions were created based on available data and EPA continues to investigate new or updated data sources. If the reviewer knows of a desert state data source, EPA encourages the reviewer to provide the source information.

Comment A68: Citation Recommendation
5-3, Lines 18-19: "based on an analysis of more than 350 dairy cow diets used by producers across the United States". It would be better to provide a citation for this analysis, for example, A-62 in Annex 3.10. However, on page A-62, Line 16, it says that "nearly 250 diets were analyzed". It is unclear how many diets were analyzed.

Response: EPA is reviewing this analysis and will provide more clarity in the next Inventory.

Chapter 6. LULUCF

Comment L69: General, Transparency
Overall, I have found the Chapter very interesting and dense of information. In some sections it would have been useful to include cross-references to go back and check the data (e.g. p.6-2, end of second paragraph, add reference to Table 6-3).

Response: EPA notes this feedback and will consider how to improve readability and cross-references within the chapter.

Comment L70: General, Completeness and Accuracy
P. 6-3 dominant land uses vary due to […] (add “the economy”.

Response: The final Inventory (page 6-10) reflects this suggestion.

Comment L71: General, Completeness and Accuracy
In Table 6-2, add a note with the description of the acronyms (FF, CF, ..).

Response: The final Inventory (Table 6-5, page 6-12) reflects this suggestion.

Comment L72: General, Completeness and Accuracy
P. 6-6: provide a reference supporting the use of the 20-year period to define land use change.

Response: The final Inventory (page 6-14) reflects this suggestion.

Comment L73: General, Completeness and Accuracy
Table 6-3: Will it be possible to include the current data in order to compare different sources? Are sources used different from the 2023 GHGI or the same?

Response: The final Inventory reflects this suggestion, please see the respective category sections and descriptions of data (pages 6-17 through 6-19) for information on sources.

Comment L74: General, Completeness and Accuracy
P. 6-20: the new estimates of forest carbon flux are significantly different from the previous GHGI because of new estimates of forest carbon density. The report should expand the discussion of the new estimates and why they do diverge relative to the previous report. As far as I understand, the previous report used a generic value to convert biomass to carbon while in this new Report used forest-specific estimates for different components. Are these new estimates taking into account changes in natural forest productivity from CO2 fertilization?

Response: The final Inventory reflects this suggestion, including an expanded Recalculations discussion in 6.2 Forest Land Remaining Forest Land starting on page 6-39.

Comment L75: General, Completeness and Accuracy
Table 6-6 provides the values in Table 6-5 in C instead of MMT CO2, I will consider the option of moving the tables in MMT C in the Appendix since they do not provide different estimates but just converted the values (same for Table 6-20 vs 6-21, 6-47 vs 6-48).

Response: This suggestion will be considered for future inventories.

Comment L76: General, Completeness and Accuracy
p. 6-25: please provide reference(s) for the “carbon estimation factors”.

Response: More information is available in Annex 3.13.

Comment L77: General, Completeness and Accuracy
P. 6-26: first sentence, last paragraph is unclear, please rephrase.

Response: EPA will assess how to update the chapter text descriptions for a future inventory.

Comment L78: General, Completeness and Accuracy
P. 6-59: “Country-specific carbon stock change factors” -> does this imply one single factor for the US?

Response: Details on the emission factors are found in Annex 3.12 of the Inventory. Country-specific carbon loss rates are shown in Table A-188 and include factors for each major U.S. region (e.g., Cold Temperate, Dry & Cold Temperate, Moist).

Comment L79: General, Completeness and Accuracy
P. 6-60, 4th paragraph: what could explain the variation in soil organic carbon stock?

Response: EPA continues to improve its documentation and transparency and will consider text updates to better explain uncertainties for future inventories.

Comment L80: General, Completeness and Accuracy
P. 6-63, 4th paragraph: please provide a percentage value of Alaska cropland area as a reference of 28,700 ha, like below 0.1% of the U.S. total area.

Response: EPA will consider including the suggested additional contextual information for future inventories.

Comment L81: General, Completeness and Accuracy
P. 6-67, 6th paragraph: the whole paragraph is redundant, please rephrase it and provide a reference to the section “Cropland remaining Cropland”.

Response: EPA will consider refining the description and using cross-references as applicable in the next and future inventories.

Comment L82: General, Completeness and Accuracy
It will be useful to add a table where the Tier methods are explained.

Response: EPA will consider how best to incorporate this information for future inventories.

Chapter 7. Waste

Comment W83: Landfills
EPA states that "[n]ationally, there are significantly less industrial waste landfills (hundreds) compared to MSW landfills (thousands), which contributes to the lower national estimate of CH_4 emissions for industrial waste landfills" but later in that same paragraph includes a statement that "the WBJ database includes approximately 1,200 landfills accepting industrial and/or construction and demolition debris for 2016 (WBJ 2016)." Is this because the construction and demolition debris landfills are not considered industrial landfills and thus when subtracted from the 1,200 reduces the number of industrial landfills to "hundreds"?

EPA includes a statement that "[l]arger landfills may have deeper cells where a greater amount of area will be anaerobic (more CH_4 is generated in anaerobic versus aerobic areas) and larger landfills tend to generate more CH_4 compared to a smaller landfill (assuming the same waste composition and age of waste)." While larger landfills may generate more methane on a per landfilled ton basis, this does not necessarily mean that a larger landfill will emit methane on a per landfilled ton basis because larger landfills may also recover more methane than smaller landfills. We suggest removing this statement or qualifying it to remove any suggestion that larger landfills emit more methane per landfilled ton.

Response: EPA removed the statements about there being thousands of MSW landfills versus hundreds of industrial waste landfills (p. 7-6). We also updated the estimated count of industrial or C&D landfills utilizing the WBJ 2021 reference (p. 7-6). For the comment about larger landfills generating more methane, we find this text on generation is appropriate for the paragraph it is in, which discusses trends in number and size of MSW landfills in the United States. There is an earlier paragraph (p. 7-5) that describes the various factors that determine how much methane is emitted from a landfill.

Comment W84: Landfills
We find the new level of detail to be readable.

Response: EPA notes the commenters feedback on clarity and transparency.

Comment W85: Landfills
NWRA is aware of ongoing research of remote sensing data that is being led by the Environmental Research and Education Foundation. This research consists of a known amount of methane released for multiple different technologies to detect. The release and the remote sensing technologies were all deployed simultaneously At a landfill in Canada in November 2023. Results of the study are pending.

Response: EPA will review the study when completed and published.

Comment W86: Other
In addition, NWRA is working with its members and consultants to update the SWICS methodology to incorporate a methodology to estimate emissions from landfills without a landfill gas collection system. We anticipate submitting something for EPA's consideration in early 2024.

Response: EPA will review this methodology when completed.

Comment W87: Other
Finally, as stated in prior years' submissions on the GHG Inventory, we encourage EPA to review the DOC and k values for both the 1990 to 2004 Inventory series and for 2005 to the present. We also are pleased that EPA is investigating k values for different climate types, comparing this information with new data and other landfill gas models, and assessing the uncertainty factor applied to these k values in the Waste Model. We offer our support to EPA in collecting and evaluating this information.

Response: EPA notes the offer to support collection and evaluation of information and will reach out to commenter to work on these changes.

Comment W88: Factors Affecting N2O Emissions from Wastewater Treatment
Until industry-specific information is developed for N2O emissions from pulp and paper mill wastewater treatment facilities, NCASI recommends using a default emission factor of 0.0 kg N2O -N/kg total nitrogen. This recommendation is based upon prevalent wastewater treatment designs within the pulp and paper sector and the relatively low concentrations of nitrogen in pulp and paper wastewaters. Based upon predominant wastewater treatment designs and operations, and the low level of nitrogen in untreated pulp and paper wastewaters, it is expected that N2O emissions from pulp and paper wastewater treatment systems will be negligible.

Untreated municipal wastewaters typically have nitrogen contents of 20-70 mg/L total nitrogen (Metcalf and Eddy 2014; Doorn et al. 1997). Most of the influent nitrogen to municipal wastewater treatment is in the form of ammonia nitrogen (Metcalf and Eddy 2014; Doorn et al. 1997). Table 3 [in the reviewer's comment] compares influent and effluent information from municipal wastewaters to pulp and paper wastewaters, as well as information from a detailed, long-term study of N2O emissions from a full-scale domestic wastewater treatment system (van Dijk et. al 2021). Ranges for municipal influent are provided in Metcalf and Eddy (2014), while typical removal information is provided in van Dijk et al. (2021). Pulp and paper influents tend to have higher concentrations of organics than municipal wastewaters and much lower nutrient concentrations. In addition, pulp and paper influents have a higher proportion of organic nitrogen contributing to the nitrogen load compared to untreated municipal wastewater, which has high levels of ammonia nitrogen. Untreated pulp and paper wastewaters are often nutrient deficient and supplemental nitrogen and phosphorus may be added to promote biological activity for organics removal in wastewater treatment (NCASI 2007).

Pulp and paper ASB or AST wastewater treatment designs do not include biological nutrient removal (BNR) systems so would not be expected to have pathways for N2O production and emissions like those expected for municipal wastewater treatment designs incorporating. Most untreated pulp and paper wastewaters are very low in nitrogen, and with effective nutrient management practices put in place, there is typically little need for nitrogen removal add-ons to conventional pulp and paper wastewater treatment systems.

Based upon predominant wastewater treatment designs and operations (i.e., denitrification is rare within pulp and paper wastewater treatment), and the low level of nitrogen in untreated pulp and paper wastewaters, it is expected that N2O emissions from pulp and paper wastewater treatment systems will be negligible.

Response: EPA notes the references and influent and effluent data provided by the commenter. EPA is interested in reviewing this information to see if it provides a sound scientific basis to justify replacing

the defaults currently being used. EPA requested copies of some of the references cited which are publicly unavailable and will review once provided.

Comment W89: Factors Affecting N2O Emissions from Wastewater Treatment
NCASI is not aware of any published data on N2O emissions from pulp and paper industry wastewater treatment operations. Calculation of greenhouse gas emissions, including N2O, from pulp and paper wastewater treatment systems, are provided in a series of papers and a PhD dissertation by Ashrafi and co-authors (Ashrafi 2012; Ashrafi et al. 2013a; Ashrafi et al. 2013b; Ashrafi et al. 2015), but no measurements were taken from operating pulp and paper wastewater treatment systems in their work. To characterize emissions of N2O for pulp and paper wastewater treatment, the authors assume nitrification/denitrification was actively occurring and that the IPCC emission factor information for domestic wastewater treatment was applicable for estimating N2O emissions as a function of total Page 6 of 7nitrogen in untreated pulp and paper wastewaters. Both assumptions may not be appropriate for typical wastewater treatment systems in the pulp and paper sector.

Response: EPA notes the references provided by the commenter. EPA has previously reviewed most of these references and concluded the same, that no actual measurements were provided from a pulp and paper operation. Without the data, it is not possible to create an industry/country-specific emission factor. In absence of that emission factor, it is considered best practice to continue to use the IPCC (2019) emission factor.

Comment W90: General, Transparency, Accuracy and Completeness
Inclusion of more citations from actual measurements. They are sparse throughout the document, though helpful when they're there (e.g. Foley et al. 2015 regarding CH_4 formation in sewage collection systems) – to this end, I have laid out a few categories and citations for inclusion at your discretion.

Response: EPA notes the citations mentioned by the reviewer and will review the citations provided for inclusion in potentially the next or future annual inventories.

Comment W91: General, Transparency, Accuracy and Completeness
Regarding the assumed values, I consistently find myself searching for the assumed values used in the equations. For instance, US pop is discussed, along with the sources, but the values are not in Table 7-10. Sometimes these values are in the text following the equations, other times they are in other Tables, and other times they are in the Table itself following the description (I think when it's a single value). I eventually find them but itis inconsistent. Perhaps another column can be added to the Table that discusses the variables that either has the value used, or points to specific lines/locations/Table number where the values are presented in the chapter. Alternatively, one could have a location for all assumed values following the equation. Perhaps right after the description of the variable, rather than at the end of the chapter (e.g. Table 7-34 which gives values that are used well above the chapter and are alluded to in Table 7-28).

Response: EPA notes the reviewer's suggestions for the organization of the chapter from an inventory user perspective. EPA is planning to review and improve the presentation of methodological information in the report, for this source category to improve consistency, transparency, and clarity of the inputs and steps. Where feasible, EPA will aim to incorporate these suggested approaches.

Comment W92: Wastewater Treatment and Discharge
Suggest continuing to seek US-specific emission factors, whenever possible (like that of N2O from aerobic systems). A body of research shows immense disparity between countries. There are also stark differences observed between emissions from countries that are targeting decarbonization at wastewater and biogas facilities (e.g. European Union) and those that aren't (China, US, South America).Often, measurements (from which international guidelines are developed) are at low-emitting facilities and may not be representative of other facilities, especially outside of that country. I realize there is a paucity of data, but I am just stressing the importance.

Response: EPA notes the reviewer's concern regarding on variability in emissions at the plant or facility-level and potential biases in available emission factors. EPA agrees with the commentor to continue efforts to identify improved data sets and studies, noting it strives to continually update the inventory methodology to be representative of U.S. systems and conditions based on available data and reduce uncertainties.

Comment W93: Wastewater Treatment and Discharge, Q-1a
This is probably the number one concern I have with the inventory of wastewater treatment emissions. Since we don't have good accounting of treatment processes at specific sites (largely since 2004), we are unable to attribute current measurements (e.g. Moore et al. 2023 CH_4 measurements across 63 plants, N2O measurements Ahn et al. 2010) to specific processes to recommend mitigation strategies, or even determine driving factors of emissions from these facilities. Of course, the recommendation would be to reincarnate the CWNS or a version of it for this purpose, but of course I realize this is a large undertaking. An alternative would be to require reporting as a part of the DMR for these facilities – again a political undertaking and likely outside the jurisdiction of this committee. Failing a new, more comprehensive CWNS, data mining techniques could be used to scrape facility websites and state-wide databases (e.g. NYC wastewater treatment facility documents) to build a partial database much cheaper timely than a full survey.

Response: EPA agrees with the commenter. EPA has conducted a new CWNS in 2022, but the data have not yet been released and may not provide data as comprehensive as the 2004 survey. When available, EPA will review if the data can be used to improve the accounting of treatment processes in use and will continue to conduct literature reviews for any nation-wide sources as they are available and consider potential approaches to supplementing gaps in the anticipated survey.

Comment W94: Wastewater Treatment and Discharge, Q-1b
Barring any substantial advancements in reporting of treatment processes, nutrient loading, etc. I think an approach like Song et al (Env. Sci. Tech. 2023 DOI: https://doi.org/10.1021/acs.est.2c04388) could be used, which incorporated all known values of EFs throughout the literature and applied them using knowledge from the CWNS about treatment processes in the US. This accounts for observed differences between different combinations (i.e. sludge and water) of treatment types.

Response: EPA notes the reference provided by the commenter and plans to review for potential inclusion in future annual GHG inventories.

Comment W95: Wastewater Treatment and Discharge, Q-1c
Also needed, but no knowledge of [biogas generation and recovery options] existence. Perhaps there are widespread biogas generation companies that would be willing to share when/where units were installed?

Response: EPA agrees this is a gap and area where data is limited. EPA is aware of some regional data from the Water Environment Federation but has not been successful in finding national data. EPA plans to conduct some additional outreach in preparing for the next GHG inventory cycle, e.g., the American Biogas Council or other industry stakeholders to discuss available data.

Comment W96: Wastewater Treatment and Discharge, Q-1d
Are the differences in overall emissions large depending on method? Could this be incorporated into uncertainty? I would always err on the side of measurements, so NPDES would be my suggestion – however many N species are not required to be reported and there are clerical errors throughout. However, across the entire time series, most facilities should have at least some data that can be used. Where possible, population served can be used to extrapolate N or BOD from a point in time onward, assuming a linear relationship, where data were but are no longer available. Additionally, perhaps where one value (e.g. BOD) is reported to NPDES, the ratio given by Metcalf & Eddy (2013, Table 3-18) between TN and BOD (35:200) can be used as an estimator with perhaps a 30% uncertainty.

Response: EPA has not compared the differences in emissions between the two methods (BOD and N discharge data from ICIS-NPDES versus average values removed by system type) but agrees this analysis is useful for QA/QC of the current approach. The findings and differences can inform uncertainty assumptions, ensuring it accurately reflects any variability in methods. EPA has previously investigated use of EPA's Water Pollutant Loading Tool to evaluate the data on N-species discharged and found what the commenter noted, that N species are not required to be reported (in addition to clerical data entry errors). Recognizing this limitation, EPA plans to continue investigate the differences between reported data and the current method. EPA also notes the commenter's observation about the ratio given in Metcalf & Eddy and expert judgment on uncertainty. EPA will review and confirm that this ratio is appropriate for domestic discharges.

Comment W97: Wastewater Treatment and Discharge, Q-1e
I am unaware of anything US-specific.

Response: ***EPA notes the commenter's confirmation on lack of available data for this parameter.***

Comment W98: Wastewater Treatment and Discharge, Q-1f
I don't see where the N-content of sludge is discussed – apologies if I missed it (very likely).

Response: EPA notes that the N content of sludge is no longer explicitly used in the calculations for wastewater treatment and sludge, but the value of 3.9% is taken from McFarland, 2001. These data are used to estimate the amount of N that may be transferred to other sectors, e.g., land application, incineration.

Comment W99: Wastewater Treatment and Discharge, Q-1g

I'm not aware, but it seems it could be a trivial GIS project – using the FRS database and a basic water body layer, you could simply characterize each facility by the nearest water body and assume (with uncertainty) that the nearest water body (river/lake/reservoir/bay) is the location discharge? This way you could then attribute the flow from each facility to a body of water and scale up to the nation that way. Of course, care would be needed to avoid counting facilities that are no longer working, etc. but I must assume these data can also be joined to the FRS database.

Response: EPA's current method is similar to this suggestion, i.e., the NPDES permit numbers are matched with the available in the ICIS-NPDES dataset and the ATTAINS dataset (which houses both waterbody characterizations and impairments). EPA has considered the commenter's suggested method, or similarly trying to base the discharge off reported coordinates, but due to the known data entry errors noted and the known uncertainties in assuming that the nearest body of water is the location of discharge, EPA has not pursued this approach. In addition, there is still the lack of data on whether the waterbody is nutrient-impacted. EPA may explore the use of a GIS waterbody layer to see if the current method can be supplemented.

Comment W100: General, Transparency, Accuracy and Completeness
7-1, line 15, Figures 7-1 and 7-2: Use one consistent format, either use a Bar chart or Column chart for ease of comprehension.

Response: EPA notes the commenter's feedback for improving visualizations included in the report and will consider the suggestions for the next Inventory.

Comment W101: General, Transparency, Accuracy and Completeness
7-1, lines 29-32: Present as a pie chart to support discussion of percent emissions attributed by each type of waste method.

Response: EPA notes the commenter's feedback for improving visualizations included in the report.

Comment W102: General, Transparency, Accuracy and Completeness
7-3, lines 2-4: Waste-To-Energy or treatment of municipal solid waste via combustion with material and energy recovery should be included in the Waste Sector. Use of any type of waste material for claiming energy or materials benefits should be equally attributed to the Waste Sector. When such benefits from one waste management method are discussed in a separate context such as Energy Sector the significance and positive impact of essential services of managing waste in an environmentally beneficial manner go unrecognized. This lack of recognition excludes the Waste Sector as a significant contributor in climate change mitigation through avoidance of GHG particularly when forty two percent of GHG emissions are attributed to the provision of goods and food from a full lifecycle perspective, as identified by the EPA. WTE facilities are widely recognized as a source of greenhouse gas (GHG) mitigation, including by the U.S. EPA; Columbia University scientists, U.S. EPA scientists; the Intergovernmental Panel on Climate Change ("IPCC");. the World Economic Forum; the European Union; CalRecycle; California Air Resources Board; and the Joint Institute for Strategic Energy Analysis (NREL). WTE facilities reduce GHG emissions, even after consideration of stack emissions from combustion, by:

a) Diverting post-recycled solid waste from landfills, where it would have emi2ed the potent GHG methane for decades, even when factoring in landfill gas collection
b) Generating energy that otherwise would have been produced by GHG-emitting fossil fuel power plants, and

c) Recovering metals for recycling, thereby avoiding GHGs and energy associated with the production of products and materials from virgin inputs.

In United States today, waste materials have only two options at scale, landfilling and WTE. And of the two, WTE is the only technology that can readily divert and beneficially treat waste while avoiding the greenhouse gas methane, recover metals for recycling and generate energy. The waste sector receives waste materials from municipal, commercial and industrial sectors. To conserve resources keeping materials circulating in the economy impacts the Waste Sector the most. To accelerate the movement towards a net-zero transition, Waste-to-Energy (combustion with material and energy recovery) must be discussed alongside other waste management methods to equally discuss opportunities and tradeoffs associated with each method. The rapid decarbonization of the MSW system may provide short-term relief for negotiations to cut emissions from hard-to-abate sectors including heavy-duty transport (e.g., aviation, shipping, and trucking) and heavy industries (e.g., chemical, cement, and steel manufacturing) through material and energy recovery.

Response: EPA will consider additions to the Waste Chapter introduction to note the amount of MSW treated at WTE facilities. In preparing the Inventory, EPA follows IPCC guidance to account for emissions from waste incineration in the Energy Sector. Additionally, the avoidance of emissions by WTE, or any other waste management option, are not accounted for in the Inventory as comparison against a baseline is out of scope.

Comment W103: General, Transparency, Accuracy and Completeness
7-5, 14-16: Similarly net carbon dioxide flux from carbon stock of biogenic materials in landfills should be included to provide a complete picture to present all the Waste Sector. Consider clearly identifying insignificant sources of GHG emissions listed in one box.

Response: Net carbon dioxide flux from carbon stock changes of materials of biogenic origin in landfills are estimated and reported under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (see Chapter 6).

Comment W104: General, Transparency, Accuracy and Completeness
Globally municipal solid waste (MSW)–related emissions are anticipated to nearly double by 2050 compared with 2016 in a business-as-usual scenario. Given that the United States currently landfills most of its municipal solid waste, implementing decisions using the latest information available is key to handle solid waste from separation to collection and treatment, as each of these have direct implications to curbing climate change. Therefore, a separate section should be considered that brings together emission pathways of the current MSW systems in the United States.

Response: Inclusion of information on scenarios for potential mitigation measures and related impacts on emissions is beyond the scope of the Inventory report.

Comment W105: Landfills
The EPA should reevaluate the proposed changes to degradable organic carbon and decay rates (kvalues) in alignment with actual measurements of landfill GHG emissions. While WTE facilities utilize direct measurement to quantify their emissions, landfills utilize models. The EPA is proposing changes to the default values for degradable organic carbon (“DOC”) content in municipal solid waste managed at landfills, as well as the default values for decay rate (kvalues) from the 2022 Data Quality Improvements Proposal. As the EPA acknowledges, changing the DOC/k-value defaults to the proposed values will

reduce the cumulative emissions reported by landfills over their reporting lifetime. This resultant impact will not only decrease the accuracy of emissions reported from landfills but would starkly contrast research showing that actual measured emissions from landfills are higher than those reported.

In its effort to improve landfill modeling accuracy, we believe the EPA should reconsider the current collection efficiency defaults to help bring modeled emissions into better alignment with actual measurements of landfill GHG emissions.

Response: This is a planned improvement (see p. 7-15 of Chapter 7 - Waste https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-chapter-7-waste_04-17-2024.pdf).

Comment W106: Landfills

The EPA should consider actual emissions measurement methods and the most recent available data to adjust collection efficiency models. New measurement techniques and studies have added significantly to our understanding of landfill emissions since the defaults for landfill gas collection efficiency were adopted in 2009; however, this new body of research has not been reflected in updated efficiency values. Recent studies have found that over the life of waste in a landfill, the lifetime gas collection efficiency is estimated to only be 35%-70%, which is far below the current GHGRP defaults. Similarly, the EPA's own two-year study of measured methane emissions in 2012 did "not support the use of collection efficiency values of 90% or greater" as is currently allowed for landfills with final cover. xxiv Current defaults do not account for landfill gas escaping through cracks and imperfections in the surface cap, around wells and penetrations, through leachate collection systems, and through the cap itself which result in lower collection efficiencies and higher measured landfill emissions compared to what is reported. In fact, a series of studies employing direct measurement of methane plumes via aircraft downwind of several U.S. landfills found that actual measured landfill emissions were on average double the amount reported in GHG inventories. The specific studies are summarized as follows:

Table 2: Supplement to Comment W106

Scope	LF-Specific Reported Value (Gg CH_4/y)	Inventory Source	LF-specific Measured Value (Gg CH_4/y)	Difference Factor
SoCAB (L.A.) [xxvi]	17.84	EPA GHGRP	24.1 – 43.9	1.9x
California [xxvii]	312	CARB (2010)	840	2.7x
Indianapolis [xxviii]	13.93	EPA GHGRP	22.5	1.6x
Indiana [xxix]	3.73	EPA GHGRP	4 – 6.6	1.4x
Baltimore/DC [xxx]	19.68	EPA-GHGRP	47.3	2.4x
San Francisco Bay [xxxi]	61.5	BAAQMD	88.5 – 143.8	1.9x
				2.0x

a. To increase accuracy, we recommend that the EPA utilize alternative measurement techniques to determine default collection efficiencies. Flux chamber data largely informs the current defaults utilized by the GHGRP despite several recent studies finding that flux chambers underestimate emissions.

b. A 2020 study in California found that flux chamber measurements indicated significantly higher collection efficiency estimates than aerial measurements, which have the capability to measure an entire landfill's methane plume.
c. Utilizing the inflated collection efficiency estimates will result in current landfill modeling to underreport methane emissions. As the Executive Director of UNEP, Inger Andersen, stated in the recent Global Methane Assessment, methane is "the strongest lever we have to slow climate change over the next 25 years;" thus, it is imperative that landfill methane reporting is accurate.
d. As a result, we ask the EPA to validate its emissions models against landfill emission data collected using more representative measurement technologies and to propose appropriate changes to the landfill gas collection efficiency defaults to ensure that emissions modeling better aligns with the current data on landfill methane emissions.

Response: EPA will review these reports and studies along with other recent remote sensing studies to evaluate feasibility of integrating findings or data into the MSW landfill methodology.

Comment W107: Landfills
The EPA should explore alternative measurement technologies that more accurately measure landfill GHG emissions. In another effort to improve the accuracy of GHG emissions data, the EPA has proposed new guidelines to expand the number of landfills that can report emissions by monitoring surface concentrations of methane utilizing portable monitors. However, to ensure these measurements best represent actual emissions, we encourage the EPA to explore alternative technologies less susceptible to spatial and temporal variability. Data from portable surface monitors is greatly affected by the specific device utilized, the soil characteristics and vegetation of the landfill as well as atmospheric conditions, resulting in data variability depending on the measuring time and location. Monster et al. 2019 explain that these portable devices may be helpful in landfill maintenance, for example locating landfill hotspots or checking the integrity of cover materials, but recommends they be used in combination with another quantitative technique which is representative of the entire landfill's plume for reporting purposes such as radial plume mapping, gas dispersion, or aerial inverse modeling.

The literature referenced by the EPA in relation to surface monitoring is only one part of the larger body of research which demonstrates the strengths of alternative direct measurement techniques. The Duren et al. article cited in the proposal utilizes aerial methods to conclude that California landfill methane emissions may be considerably higher than those quantified under subpart HH. Similarly, several other studies agree that landfill operators derive the most representative measurements downwind of a landfill using aerial or ground plume techniques, which have the capacity to measure an entire landfill's methane plume.

Response: EPA notes the comments are beyond the scope of the Inventory. The comments have been shared with EPA's Greenhouse Gas Reporting Program.

Comment W108: Landfills
The EPA should incorporate the latest science in assessing the climate impacts of methane. The EPA should reconsider its use of the 100-year global warming potential (GWP) for methane, considering the pressing need to reduce methane emissions over the next several decades to avoid the most significant impacts of climate change. This change would be in alignment with California, New York, and New Jersey who have all adopted time frames where methane is 84-86 times more potent than carbon dioxide over a 20 year period. As stated in a joint press release with the European Union announcing the Global

Methane Pledge, the Biden administration noted that "rapidly reducing methane emissions… is regarded as the single most effective strategy to reduce global warming in the near term and keep the goal of limiting warming to 1.5 degrees Celsius temperature limit." Thus, considering the shrinking timeline to combat global warming, there is an increase in the relative importance of accurate methane and SLCP GWP measurements.

There is no scientific reasoning for selecting the 100-year GWP compared to other metrics; it depends solely on the policy objectives one has in mind. As reiterated above, because of the temperature time constraint and the fact that SLCPs contribute over 40% to current anthropogenic global radiative forces, policy objectives should emphasize decreasing SLCP emissions. Literature since Assessment Report 5 (AR5) has concluded that the 100-year GWP is not well-suited to represent the warming effect at specific points in time from sustained SLCFs. Instead, studies find that the 20- year GWP provides the most accurate perspective on the speed at which SLCP emissions will impact the atmosphere and, thus, the effectiveness of SLCP emission controls. Hence, the use of the 20-year GWP best captures the importance of SLCPs and would provide policymakers with the most accurate information when considering climate policies with the potential to make the most considerable impact in the near future.

Response: EPA uses 100-year Global Warming Potentials (GWP) from IPCC's Fifth Assessment Report to calculate CO_2 equivalent emissions as required for reporting annual inventories to the UNFCCC and the Paris Agreement. This is required to ensure that national GHG Inventories reported by all nations are comparable. See decision 7/CP. 27 available online at https://unfccc.int/sites/default/files/resource/cp2022_10a01_adv.pdf for more information and paragraph 37 of the Annex to decision 18/CMA.1 available online at https://unfccc.int/sites/default/files/resource/cp2022_10a01_E.pdf.

The U.S. Inventory also includes unweighted estimates in kilotons (see Table 2-2 of the Trends chapter) and stakeholder/researchers can and have used these values to apply other metrics. Further, Annex 6 of the Inventory includes information on effects to inventory estimates in shifting to AR5 and AR6 100-year GWPs. The U.S. Inventory report website is available at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

More information on GWPs is available on the IPCC's Working Group 1 website for AR5 (Chapter 8) and for AR6 (Chapter 7) online at https://www.ipcc.ch/working-group/wg1/.

Appendix A: List of Reviewers and Commenters

EPA distributed the expert review chapters of the draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022* to a list of 265 expert reviewers across all sectors of the Inventory. The list below includes names of those expert reviewers who submitted comments as part of the Expert Review Period.

- Jessica Wood – Arizona Department of Environmental Quality (ADEQ)
- Alice Favero – Research Triangle Institute (RTI International)
- Anne M. Germain – National Waste & Recycling Association (NWRA)
- Nathan P. Li – Princeton University
- Kevin Nakolan – Energy Information Administration (EIA)
- Olia Glade – Greenhouse Gas Management Institute (GHGMI)
- Alissa Benchimol – Greenhouse Gas Management Institute (GHGMI)
- Greg Watson – Arkema
- John Mentink – Chemours's Washington Works
- Paul Balserak – American Iron and Steel Institute (AISI)
- Tom Lorenz – Energy Information Administration (EIA)
- Jyoti T. Agarwal – Covanta
- Daniel Moore – Environmental Engineering Princeton University
- Barry Malmberg – NCASI

Note: Names of commenters are listed in no particular order.

Appendix B: Dates of Review

- Energy: October 25, 2023 – November 27, 2023
- Industrial Processes and Product Use (IPPU): November 9, 2023 – December 11, 2023
- Agriculture: November 9, 2023 – December 11, 2023
- Land Use, Land Use Change and Forestry (LULUCF): November 21, 2023 – December 21, 2023
- Waste: October 25, 2023 – November 27, 2023

Appendix C: EPA Charge Questions to Expert Reviewers

To facilitate expert review and indicate where input would be helpful, the EPA included charge questions for the Expert Review Period of the draft *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022* report. EPA also noted to expert reviewers that while these charge questions were designed to assist in conducting a more targeted expert review, comments outside of the charge questions were also welcome. Included below is a list of the charge questions by Inventory chapter.

Chapter 3. Energy

Requests for Expert Feedback for the 1990-2022 Energy Chapter

General Questions:

1. Please provide your overall impressions of the clarity and transparency of the Energy chapter.
2. Please provide any recommendations that EPA can consider for improving the completeness and/or accuracy of the Energy chapter.
3. Please provide any information on data sources available with regional or other disaggregated information on energy use or emissions.

Fossil Fuel Combustion: CO_2 from Fossil Fuel Combustion

1. Please provide your overall impressions of the clarity of the discussion of trends in CO_2 emissions from fossil fuel combustion. Please provide recommendations for any information that could be added to the discussion to provide additional transparency and clarity.
2. Data for energy use in U.S. Territories comes from updated International Energy Statistics provided by EIA. Do they compare to any other sources of U.S. Territory energy use that could be used?
3. Facility-level combustion emissions data from EPA's GHGRP are currently used to help describe the changes in the industrial sector. Are there other ways in which the GHGRP data could be used to help better characterize the industrial sector's energy use? Are there ways the industrial sector's emissions could be better classified by industrial economic activity type? Please provide your overall impressions of the clarity of the discussion of trends in CO_2 emissions from fossil fuel combustion. Please provide recommendations for any information that could be added to the discussion to provide additional transparency and clarity.

Fossil Fuel Combustion: CH_4 and N_2O from Stationary Combustion

1. The CH_4 and N_2O emission factors for the electric power sector are based on a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology. For all other stationary sectors, the emission factors used in Tier 1 methods are primarily taken from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Are there other more U.S.-specific CH_4 and N_2O emission factor data sources that could be utilized, especially for natural gas combustion sources?

Carbon Emitted from Non-Energy Uses of Fossil Fuels

1. Please provide your overall impressions of the clarity of the discussion of Carbon Emitted from Non-Energy Uses of Fossil Fuels. Please provide recommendations for any information that could be added to the discussion to provide additional transparency and clarity, especially in relation to linkages with the estimates in the IPPU chapter.

Incorporating CCS Data

1. See forthcoming memo for questions and feedback on including Carbon Dioxide Transport, Injection, and Geologic Storage in the Inventory. [Note this memo was distributed following publication of the national GHG inventory, so will be incorporated in the forthcoming expert review of the next national inventory (i.e. for publication in April 2025)].

Chapter 4. Industrial Processes and Product Use (IPPU)

Requests for Expert Feedback for the 1990-2022 IPPU

General Questions:

1. Please provide your overall impressions of the transparency of the IPPU chapter.
2. For the source categories included in the expert review draft, is the state of the industry current and accurately described? Are there technologies, practices, or trends that EPA should consider?

Source-Specific Questions:

Minerals

1. **Other Process Uses of Carbonates – Ceramics Production** – See pg. 5 of attached supporting technical memo on the proposed methodology titled "6. Ceramics_Production_Improvement_Memo_1990-2022"
2. **Other Process Uses of Carbonates – Non-Metallurgical Magnesia Production** – See pg. 4 of attached supporting technical memo on the proposed methodology titled "7. Non Metallurgical_Magnesia_Production_Improvement_Memo_1990-2022"

Chemicals

3. **Glyoxal and Glyoxylic Acid Production** – Please provide feedback or information:
    - Based on data reported to EPA for TSCA, it appears that glyoxal may be produced domestically at up to 4 facilities and that all glyoxylic acid used in the U.S. may be imported. Please share any information about these facilities, including whether they use gas-phase catalytic oxidation of ethylene glycol with air in the presence of a silver or copper catalyst (the LaPorte process) or liquid-phase oxidation of acetaldehyde with nitric acid.
    - Please provide feedback on production data and/or information on data sources of glyoxal and glyoxylic acid, nationally and disaggregated by state for 1990-2022.
4. **Calcium Carbide Production** - Please provide information on availability of data on calcium carbide production or petroleum coke used in calcium carbide production, and on calcium carbide used in the production of acetylene used for welding applications for 1990-2022.
5. **Phosphoric Acid Production** - Please provide feedback on data sources and assumptions, including:
    - The use of regional production capacity from 2005 to 2016 and from 2017 to 2020 to estimate regional production for those respective years, 2005 to 2016 and from 2017 to 2020.

   - The carbonate composition of phosphate rock and how it varies depending upon where the material is mined and over time.
   - The disposition of the organic carbon content of the phosphate rock and the assumption that it remains in the phosphoric acid product and is not released as CO_2. This includes feedback on the assumption that all domestically produced phosphate rock is used in phosphoric acid production, and it is used without first being calcined.
6. **Petrochemical Production** – See pg. 4 of the attached supporting technical memo on the proposed methodology updates titled "4. Petrochemical_Production_Improvement_Memo_1990-2022" for questions specific to the methanol production proposed updates.
7. **Fluorochemical Production** – Production of Fluorochemicals other than HCFC-22— See forthcoming technical memo on the proposed methodology titled "5. Fluorochemical_Production_Improvement_Memo_1990-2022" For specific questions (will be shared in a follow-up email).

Metal Production

1. **Iron and Steel Production** - See pg. XX of the attached supporting technical memo on the proposed methodology updates titled "3. Iron_and_Steel_Procution_Improvement_Memo_2023" for questions specific to the proposed methodology updates.
2. **Ferroalloy Production** - Please provide feedback on data sources and assumptions, including:
   - The use of 2010 national production ratios for ferrosilicon 25-55% Si, ferrosilicon 56-95% Si, silicon metals, and miscellaneous alloys 32-65% Si to determine the ratio of national ferroalloy production by type for 2011 through 2020.
   - Data and/or information on data sources on production of ferroalloys by state for 1990-2020.
3. **Lead Production** – Please provide data and/or information on data sources on primary and secondary production of lead by state for 1990-2020.

Other IPPU Categories

4. **ODS Substitutes** - The EPA seeks feedback on possible sources of hydrofluorocarbon (HFC) use that are not reflected, or whose use is modeled lower than actual, as evident from a comparison of the underlying model with data reported under EPA's GHGRP.
5. **Nitrous Oxide from Product Uses** - Please provide feedback or data and/or information on data sources on nitrous oxide production, market share of end uses, and the emission factors for each end use for 1990-2022, nationally and by state.
6. **Use of SF_6 and PFCs in other products** – EPA seeks feedback on the methodologies proposed for both military applications and scientific / industrial emission estimates for this category, including feedback on the following:
   - The use of reported emissions in 2008-2012 to estimate emissions prior to 2008 for emissions military applications and reported emissions for 2010-2014 to estimate emissions prior to 2010 for emissions from U.S. Government particle accelerators and other scientific applications. Please provide information on other data sources that may be available for this time period that could be used to refine estimates of historical emissions, including availability of activity data (e.g., number of AWACS or sorties).
   - The methodology for allocating SF6 from military applications to emissions from AWACS

and emissions from other military applications.

Chapter 5. Agriculture

Requests for Expert Feedback for the 1990-2022 Agriculture Chapter

General Questions:

1. Provide your overall impressions of the clarity and transparency of the Agriculture chapter.
2. Provide feedback on the methodologies, assumptions and activity data used to estimate emissions for categories within the Agriculture chapter. In particular, provide feedback on sources of activity data for U.S. states or territories.

Source Specific Questions:

1. For the Manure Management source category, is the state of the industry current and accurately described? Are there other technologies, practices, trends that we should consider?
2. Are the parameters and discussion of uncertainty within the Manure Management source category estimates adequately reflecting all uncertainties from this industry and the data EPA is currently using?
3. The Manure Management source category relies on national/regional livestock production and management data for calculating emissions estimates from USDA APHIS and NASS. Are there other/newer data sources that EPA should be aware of and consider in the calculating these emissions? Especially for:
    - Waste management system data, particularly seasonal changes in emissions from different WMS;
    - Maximum methane producing capacity;
    - Volatile solids and nitrogen excretion rates;
    - Measured emission estimates (by waste management system) to help refine estimates of methane conversion factors.
4. See also pg. 11 of the attached supporting technical memo - **3. Manure Management-ER Memo_1990-2022** - that describes proposed improvements for estimating greenhouse gas emissions from manure management and includes additional questions where EPA is requesting feedback.
5. For the Enteric Fermentation source category, is the state of the industry current and accurately described? Are there other technologies, practices, trends that we should consider?
6. The Enteric Fermentation source category relies on national/regional livestock production, diet and management data for calculating emissions estimates. Are there other/newer data sources or methods that EPA should be aware of and consider in the calculating these emissions? Especially for:
    - Dry matter/gross energy intake;
    - Annual data for the DE, Y_m, and crude protein values of specific diet and feed components for foraging and feedlot animals;
    - Monthly beef births and beef cow lactation rates;
    - Weights and weight gains for beef and dairy cattle.

Chapter 6. Land Use, Land-Use Change, and Forestry (LULUCF)

Requests for Expert Feedback for the 1990-2022 LULUCF Chapter

General Questions:

1. Provide your overall impressions of the clarity and transparency of the categories provided in the attached draft LULUCF chapter.
2. Provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the attached draft LULUCF chapter.
3. Provide feedback on the methodologies and activity data used to estimate emissions for categories within the attached draft LULUCF chapter.

Category-Specific Questions:

1. For *Forest Land and Land Converted to Forest Land*, see questions on page 4 of the attached supplemental memo (Attachment 3, Summary of Improvements to Forest Carbon Estimates Using National Scale Volume and Biomass Estimators) describing the new NSVB approach and underlying methodology for estimating volume and biomass to inform estimation of carbon stocks in forests.
2. EPA and USDA-USFS is interested in uses of remote sensing data that can be used to identify areas for improving the forest carbon estimates in the *Inventory*, including refinement of methods in the national emissions estimates. EPA requests information on relevant methods, papers, or ongoing research.
3. Are there nationally consistent, long-term data available on agroforestry practices on croplands or other data on living biomass in perennial crops that would allow for the estimation of carbon stock changes using Tier 1 methods and default data?
4. For the *Yard Trimmings and Food Scraps* category, is the state of the sector current and accurately described? Are there other technologies, practices, trends that we should consider?
5. For the *Yard Trimmings and Food Scraps* category, are there other data sources that EPA should be aware of and consider in the calculating these emissions? Especially for:
    - C storage, decay rates, etc. for yard trimmings and food scraps
    - Decay rates of food scraps, leaves, grass, and branches
    - National yard waste compositions
    - Precipitation range percentages for populations for the decay rate sensitivity analysis
    - Is there any available data source for the above at the state level?
6. For *Peatlands*, are there data sources on the application/consumption of peat by U.S. state that could help refine estimates?
7. For *Flooded Lands Remaining Flooded Lands* and *Lands Converted to Flooded Lands*, the primary data source for flooded land surface area has been updated to the National Wetlands Inventory. A review of the data and methods would be appreciated.

Chapter 7. Waste

Requests for Expert Feedback for the 1990-2022 Waste Chapter

General

1. Please provide your overall impressions of the clarity and transparency of the Waste chapter. Do you have suggestions for improving the discussion of our methodology? Is there any additional information that should be included to provide additional transparency? Are there any presentation changes that would help clarify methodologies or activity data used?.
2. Please provide any recommendations that EPA can consider to improve the completeness and/or accuracy of the Waste chapter (see subsector specific questions below as well).

Source-Specific Questions

Wastewater Treatment and Discharge

1. For **domestic wastewater** emissions, please provide input on:
    a. National level data on the type of wastewater treatment systems in operation,
    b. Whether the state of domestic wastewater treatment is current and accurately described,
    c. National level data on the biogas generation and recovery operations,
    d. Whether the estimate of BOD and N discharged in effluent should be estimated using limited data from ICIS-NPDES rather than average values of the percent of BOD or N removed by aerobic, anaerobic, and other treatment systems,
    e. The revision of the non-consumed protein factor ($F_{NON\text{-}CON}$) for centralized treatment to the default IPCC (2019) factor, and whether there are any sources to create a U.S.-specific factor,
    f. Any additional sources for the N content of sludge, amount of sludge produced, and sludge disposal practices, and
    g. Any additional sources for estimating the wastewater volume discharged to the type of aquatic environment for the time series.
2. For **industrial wastewater** emissions, please provide input on:
    a. Any measurement data on nitrous oxide emissions from industrial wastewater treatment systems,
    b. Any additional sources of wastewater outflow, BOD generation, N entering treatment, BOD discharged, or N discharged for industries included in the inventory, to capture any changes over the time series,
    c. National or state level production data for industries included in the inventory,
        i. In particular, do the data sources for fruits and vegetables processing encompass all U.S. food processing production? Are there data sources other than USDA NASS that would provide a more complete and consistent basis of production over the time series?
    d. Whether the state of industrial wastewater treatment is current and accurately described,
    e. National level data for biogas generation and recovery operations for industries included in the inventory, and
    f. Any sources for estimating the wastewater volume discharged by type of aquatic environment for the time series.
3. Are there additional industries that are sources of methane or nitrous oxide emissions that should be included in the wastewater emission estimates? Are there available sources of national-level data for these industries (e.g., wastewater volume, treatment systems, wastewater discharge location information, production data, BOD production, BOD or N removal, N entering treatment)? Are there available sources of state-level data for these industries?

Landfills

1. EPA has removed some portions of text from the methodology section this year, to improve

readability. These details are already covered in Annex 3.14 to the report. Please comment if this new level of detail on the methods is sufficient and readable for balancing information within the main report and methodological annex.

2. EPA is interested in uses of landfill remote sensing data that can be used to identify areas for improving the Inventory, including refinement of methods in the national landfill emissions estimates. EPA requests information on relevant methods, papers, or ongoing research. For example, the EPA is interested in information that might improve our scale-up factor methodology, which accounts for MSW landfills that do not report to the Greenhouse Gas Reporting Program (GHGRP). Additionally, any studies that compare reported annual emissions to measured emissions from various methane detection technologies would be valuable. This would be a long-term improvement to the Inventory and may need to be complementary to the GHGRP.

Composting

1. Please comments on datasets available on industrial composting facilities located in the U.S. territories of Puerto Rico, Guam, U.S. Virgin Islands, Northern Mariana Islands, and American Samoa. We are aware of composting facilities in Puerto Rico. In order to accurately estimate GHG emissions from these facilities, data is needed on the first year of operation, approximate annual quantities processed and/or number of households serviced, and whether the amount of waste composted is consistent from year to year. Additional improvements could be made to the Inventory if type of composting method (e.g., windrow, aerated static pile) is available for facilities, with amount of waste processed by facility.

Anaerobic Digestion at Biogas Facilities

1. Please comment on potential facility-specific data sources we could use to fill data gaps on the quantity of waste processed by stand-alone digesters for any and all years of the 1990-2020 time series.
2. EPA has simplified the methodology for developing emission estimates from AD at biogas facilities. The changes are described in the methodology and recalculations sections. Please comment on:
    a. How appropriate is the assumed leakage rate of 5% of all methane generated?
    b. Similarly, are there any data or studies on typical CH_4 generation at AD facilities or typical gas utilization amounts to support 95% utilization?
3. EPA is investigating the emission factor recommended by IPCC guidance (IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. *Volume 5: Waste, Chapter 4: Biological Treatment of Solid Waste, Table 4.1.).* Please note any feedback or recommendations you have for utilizing this default.

Appendix D: Supplemental Technical Memos to Expert Reviewers for Energy, IPPU, and Waste Sectors

1) Attachment 3 Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Summary of Improvements to Forest Carbon Estimates Using National Scale Volume and Biomass Estimator.
2) A National-Scale Tree Volume, Biomass, and Carbon Modeling System for the United States.
3) Updates on Proposed Methodology for Petrochemicals Production.
4) Updates on Methodological Refinements for Iron and Steel and Metallurgical Coke Production
5) Improvements to Manure Management Estimates
6) Proposed Methodology for Production of Fluorochemicals other than HCFC-22.
7) Updates on Proposed Methodology for Ceramics Production.
8) Proposed Methodology for the Addition of Non-Metallurgical Magnesia Production.

Attachment 3
Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Summary of Improvements to Forest Carbon Estimates Using National Scale Volume and Biomass Estimators

1 Introduction

The U.S. Department of Agriculture – U.S. Forest Service (Forest Service) Forest Inventory and Analysis (FIA) program published a new modeling system in September 2023 for predicting tree cubic-foot volume, biomass, and carbon attributes on the basis of measured tree data. While the Intergovernmental Panel on Climate Change (IPCC) methodology serving as the basis of the forest carbon estimates has not changed, we are proposing a significant update to the approach used to quantify volume and biomass from FIA plot data. This system, termed 'National Scale Volume and Biomass Estimators' (NSVB), provides a more consistent and accurate accounting of structural components of trees across the U.S. for total tree cubic-foot volume, biomass, and carbon. This improvement has been outlined through Forest Service research efforts , noted below, and has been underway for the past decade. This system has been implemented to generate the estimates contained in the current Expert Review draft of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* ("*Inventory*") report.

2 Previous Method

From 2012 through to the previous *Inventory*, the component ratio method (CRM) (Heath et al., 2009; Woodall et al., 2011) was used to develop nationally consistent biomass estimates for live and standing dead trees in the FIA Database (FIADB).

As described in Woodall et al. (2011), the CRM entails 1) measuring attributes of the tree in the field; 2) applying those tree measurements to the applicable volume model to compute both gross cubic-foot volume and sound cubic-foot volume of wood in the bole; 3) converting the sound cubic-foot volume of wood in the bole to mass and estimating bark biomass using compiled sets of specific gravity; 4) calculating the biomass of tops and limbs as a proportion of the bole based on component proportions from Jenkins et al. (2003); 5) calculating stump volume based on models in Raile (1982) and converting to biomass, and 6) summing all aboveground components for a total aboveground biomass estimate. The CRM approach for estimating the biomass of non-merchantable portions of a tree was based on estimates of the merchantable bole of the tree and applying a ratio. The CRM approach was an advancement from prior methods and was the first attempt to utilize local tree volume/biomass information within a consistent, national approach (Woodall et al., 2011).

However, this compilation had limitations with estimating different tree attributes (e.g., volume and carbon) that are additive among individual tree components and consistent across diverse forest conditions at a national scale. Specifically, FIA units were potentially using different volume models which resulted in estimates that were not considered nationally consistent (i.e., biomass of the same diameter and tree species would differ between regions due to the use of potentially varying assumptions or the use of different models). At the time of publication of the CRM approach, the Forest Service acknowledged that future research should be focused on developing consistent national-scale individual tree volume, biomass, carbon models that accommodate the diversity of tree habitats and conditions (Woodall et al., 2011).

See the 1990-2021 *Inventory*, Annex 3.13, or Woodall et al. (2011) for more details.

3 Current Approach/Improvements

The Forest Inventory and Analysis program and collaborators from universities and industry have been developing a new national methodology for the prediction of individual-tree volume, biomass, and carbon content. Implementation of this new approach completes a Forest Service goal of the 2015 FIA Strategic Plan. The resulting methodology is referred to as the National-Scale Volume and Biomass (NSVB) framework. The following is a summary of the updates, and reviewers should also refer to the Forest Service General Technical Report for more details (Westfall et al., 2023) attached to the expert review email sharing this memo but also available online at: https://www.fs.usda.gov/research/publications/gtr/gtr_wo104.pdf.

The overall approach of compiling the 1990-2022 Expert Review draft *Inventory* (stock-difference method) remains largely the same (see additional updates in the Recalculations Discussion section, Chapter 6.2, of the draft *Inventory*). The update of the NSVB addresses the quantification of live and standing dead tree volume and biomass.

The NSVB framework improves upon the CRM methodology. For example, previously tree biomass was based on the volume predicted by regional models that were not nationally consistent and tree carbon was assumed to be 50 percent of biomass (carbon conversion factor of 0.5), regardless of species. NSVB provides a nationally consistent methodology for compatible predictions of tree volume, biomass, and carbon content (Westfall et al., 2023).

The new modeling framework is based on whole-stem volume models. These models include stump, merchantable bole, and non-merchantable top components. To get to total aboveground biomass estimates, these referenced components in addition to tree branches, are summed.

The NSVB models were developed from detailed tree measurements and empirical data, allowing for a more representative quantification of uncertainty and estimation of tree components (Westfall et al., 2023). As noted by the Forest Service, the new models are based on measurements from over 232,000 sampled trees, of which FIA felled and analyzed over 3,000 trees for this work. For non-merchantable portions of the trees, in particular, this was an improvement to how those components were modeled and estimated. Non-merchantable portions of trees include branches/limbs and non-merchantable stem.

The NSVB approach utilizes ecological divisions, rather than the CRM approach of using administrative boundaries. Utilizing these new boundaries better reflects environmental drivers of tree size, form, and growth (e.g., temperature and moisture (climate), soil conditions, light). Previously, the CRM use of administrative boundaries could result in arbitrary changes of tree species characterization (that were in the same ecological zone) depending on choice of model.

Lastly, the new NSVB approach updates the previous CRM standard 0.5 biomass to carbon conversion factor across all tree species. The NSVB now utilizes tree species-specific carbon conversion factors.

During the United Nations Framework Convention on Climate Change (UNFCCC) review of the *Inventory* submitted in April 2018 (covering 1990 through 2016), the Expert Review Team (ERT) recommended that the *Inventory* utilize country-specific values or values in line with the 2006 IPCC Guidelines (UNFCCC 2019). Updating the carbon conversion factors to be species-specific improves the accuracy of the estimates and also addresses this ERT recommendation. On average, the carbon fraction is 0.477 across all species, with a minimum value of 0.420 and a maximum value of 0.538 (Westfall et al., 2023).

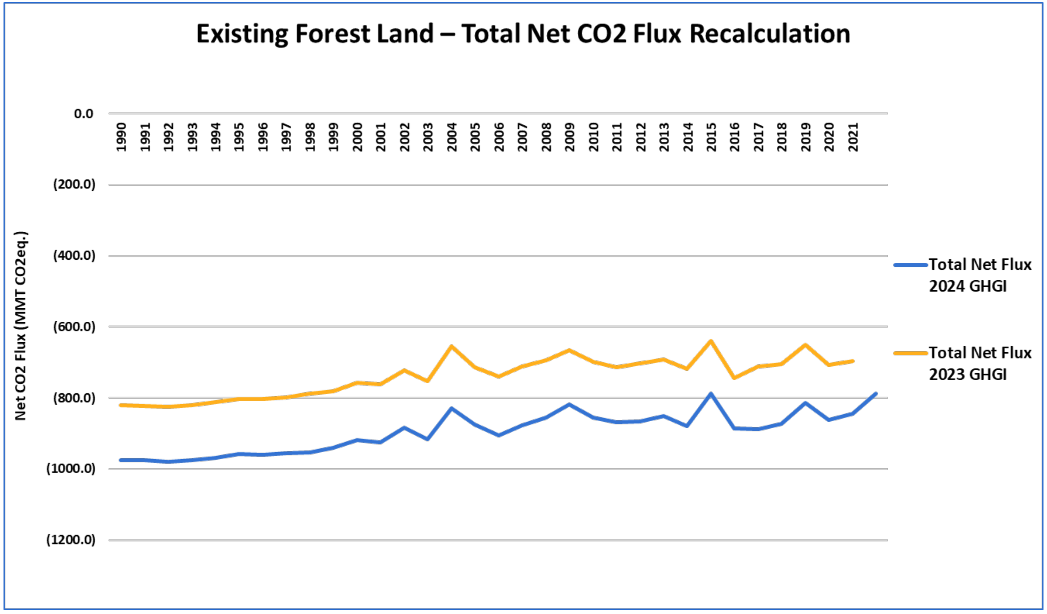
Other updates are described in the current Expert Review draft of the *Inventory* report, Section 6.2.

4 Impacts on National GHG Emissions Estimates

This section summarizes some of the main impacts of these improvements for the national GHG *Inventory*. For more details on the results of the *Inventory*, please see the Recalculations Discussion section, Chapter 6.2 of the Expert Review draft *Inventory* which also includes detailed comparison tables with the previous Inventory. As noted in the draft *Inventory*, there are other updates and improvements made to the forest carbon estimates but those are not detailed in this memo. For more details on the technical basis of this change, please see (Westfall et al., 2023).

- Forest Carbon Stock: Regarding recalculations to the year 2021 (EPA, 2023), there was an increase to the total forest carbon stock by 8.63 percent (7.90 percent on average across time-series), primarily attributed to an 11.01 percent increase in aboveground biomass (9.23 percent increase across the time-series).
    - While there was also a large increase to mineral and organic soil carbon stocks, there was little stock change from these carbon pools.
    - While the increase in aboveground biomass carbon stocks is smaller than that of the soil carbon stocks, aboveground biomass makes up roughly 66 percent (on average) of the forest ecosystem carbon stock change each year, resulting in large carbon stock change estimates this *Inventory* (see below).
- Forest Ecosystem Carbon: An average of -159.4 MMT CO_2eq. change (i.e., increase carbon sink) to net carbon stock change estimates across the time series. Average change of 25 percent across time series.
- Total Forest Carbon Stock Change: In total (Harvested Wood Products (HWP) and Forest Ecosystem Carbon), 2021 recalculation was -148.8 MMT CO_2eq. (increase to forest carbon sink), or a 21.4 percent change, see Figure 1.

Figure 1. Forest Land Remaining Forest Land Net CO_2 Flux Recalculation and Trends



Marco Trends:

- Using the Expert Review draft *Inventory* estimates, the total LULUCF carbon stock change estimates offset approximately 14.5 percent of gross U.S. emissions
- Annual and long-term trends remain the same

As described throughout the Expert Review draft Inventory Land Use, Land Use Change and Forestry Chapter, this NSVB update also resulted in recalculations to other source categories related to the conversion of forest land to a different land type (e.g., forest land converted to grass land). Please see the respective Recalculations Discussion sections of those categories in the attached draft chapter for the specific impacts.

5 Charge Questions

1) Is the basis for the update transparently described in the Expert Review draft *Inventory*?
2) Does the new NSVB approach and underlying methodology for estimating volume and biomass to inform estimation of carbon stocks in forests reflect sound science?
3) Does this update represent an improvement in estimating carbon stocks on forested lands?
4) Are the shortcomings of available data and estimation approaches clearly articulated in the Expert Review draft *Inventory*?

6 References

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Forest Service
U.S. DEPARTMENT OF AGRICULTURE

October 2023

A National-Scale Tree Volume, Biomass, and Carbon Modeling System for the United States

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Abstract

The Forest Inventory and Analysis (FIA) Program of the U.S. Department of Agriculture, Forest Service conducts the national forest inventory of the United States. Although FIA assembles a myriad of forest resource information, many analyses rely on the fundamental attributes of tree volume, biomass, and carbon content. Due to the chronological development of the FIA Program, numerous models and methods are currently used across the country, contingent upon the tree species and geographic location. Thus, an effort to develop nationally consistent methods for prediction of tree volume, biomass, and carbon content was undertaken. A key component of this study was amassing existing data in conjunction with collection of new data to fill information gaps related to tree size and species frequency and spatial distributions. These data were used in a modeling framework that provides compatible predictions of tree volume, biomass, and carbon content across the entire United States. National-scale comparisons to currently used methods show that only a small increase in volume occurs, but substantial increases in biomass and carbon are realized due to relatively large increases in predicted tree top/limbs biomass and carbon. Changes in tree carbon were also affected by use of newly developed species carbon fractions instead of the current constant conversion factor of 0.5. Examples of the calculations required to predict tree volume, biomass, and carbon content for commonly encountered tree conditions provide step-by-step implementation details. An appendix lists supplemental data tables of values needed to calculate results, which are available as comma-separated values (CSV) files at https://doi.org/10.2737/WO-GTR-104-Supp1.

Keywords: carbon fraction, ecodivision, forest inventory, specific gravity, volume ratio, whole stem

CONTENTS

INTRODUCTION

The practice of forestry in the United States has a long history of quantifying individual tree volume to characterize the amount and type of wood resources. Because obtaining direct, exact measurements of tree volume is impractical, various methods for estimating volumes of standing trees have been developed. Pioneering efforts to predict tree volume included freehand curves (Mulloy and Beale 1937) and statistical models (Schumacher and Hall 1933). Regardless of the underlying method, it was common to develop volume tables for ease of application (Gevorkiantz and Olsen 1955, Mesavage and Girard 1946). Eventually, the direct use of prediction models became more favorable than the use of tabular methods (Avery and Burkhart 1983). Increases in computer usage, software capability, and advancements in statistical methods led to more sophisticated and flexible modeling approaches (Max and Burkhart 1976, Van Deusen et al. 1981). This trend continued to evolve as data and statistical capabilities increased (Burkhart and Tomé 2012, Garber and Maguire 2003, Gregoire and Schabenberger 1996, Zhao et al. 2019).

The appearance of corresponding tables and statistical models to directly assess tree weight or biomass began decades later (Schlaegel 1975, Wiant et al. 1977). Subsequently, many studies on tree biomass prediction appeared in the scientific literature (Baldwin 1987, Smith 1985, Tritton 1982), including national-scale tree biomass models for the United States (Jenkins et al. 2003). As with tree volume, tree biomass modeling has continually evolved and has become a focal point for quantifying tree carbon storage and sequestration (Hoover and Smith 2021, McRoberts et al. 2018, Temesgen et al. 2015).

The progression of volume and biomass prediction methods has been an important facet of the national forest inventory of the United States, which began with the passage of the McNary-McSweeney Act (P.L. 70–466) in 1928. At that time, the Forest Inventory and Analysis (FIA) Program of the U.S. Department of Agriculture, Forest Service originated, with the primary emphasis being on quantifying timber volume. Because the work was initially done sporadically and primarily on a State-by-State basis, tree volumes were usually obtained from available sources of information for species common to the area being inventoried (Cowlin and Moravets 1938, Flanary et al. 2016). As FIA became more geographically diverse and eventually nationwide, tree volume and biomass predictions across the country arose from numerous unrelated studies (Woodall et al. 2011). Nonetheless, use of these diverse models allowed for the compilation of forest resource assessments at State, regional, and national scales. This capability was highly relevant for FIA to fulfill its mission, meet reporting requirements, and accommodate a large and diverse user community that conducts independent analyses via online availability of data and analytical software. However, models were often developed from small and geographically limited data sets using a variety of model forms and predictor variables (Temesgen et al. 2015, Weiskittel et al. 2015). Due to the wide-ranging uses of FIA data and the need to improve consistency across the country, a standard method for calculating tree biomass and carbon was adopted nationally circa 2010 (Woodall et al. 2011). While the method was nationally consistent, the underlying basis relied on the numerous regional volume models still in use. Further, the spatial application of volume models was often defined by administrative boundaries instead of any meaningful ecological basis. For tree biomass prediction, the accuracy and precision of models were essentially unknown due to the pseudo-data approach used in the original research. Thus, efforts were undertaken to develop a national methodology for compatible predictions of tree volume, biomass, and carbon content (Radtke et al. 2015, 2017; Weiskittel et al. 2015) for species commonly occurring on U.S. forest land. Specifically, the targeted species are inclusive of those identified by FIA species code (*SPCD*) ≤999, except for those designated as woodland species (USDA Forest Service 2022). The resulting methodology is hereafter referred to as the national-scale volume and biomass (NSVB) framework. This document serves as the primary reference for the outcome of those efforts and describes all the relevant aspects of the data, statistical modeling methods, and results.

METHODS

Data

In the NSVB study, two primary efforts were undertaken to maximize data availability: (1) engage in felled-tree work to fill information gaps in tree species, size, and location, and (2) find existing data from previous studies, convert the data into electronic format (if necessary), and assimilate the data into a common database structure. Several universities were engaged in the felled-tree data collection effort, where tree volume, biomass, and wood density information were measured on over 3,000 trees nationally. The primary emphasis for this effort was to target the top 20 species (by cubic-foot volume) in the Eastern United States and top 10 species (by cubic-foot volume) in the Western United States, which represented 67 and 81 percent of total live tree volume, respectively. These studies encompassed measuring diameter of inside and outside bark along boles, obtaining branch weights, cutting wood disks from bole sections and branches to examine wood properties, and collecting foliage for biomass analysis. The focus was on cubic-foot volume, so no effort was made to quantify volume in board-foot units. Protocols were modified as necessary to accommodate landowner requirements (e.g., keeping merchantable log lengths intact). Substantial effort was also invested in obtaining legacy data from numerous sources, including peer-reviewed journal articles, M.S. theses, Ph.D. dissertations, Forest Service publications and field surveys, forest industry studies, and other miscellaneous origins. This effort compiled records from nearly 280,000 trees—most destructively sampled—for use in this study, and data are available at www.legacytreedata.org (also see Radtke et al. 2023). Construction of the database entailed standardization of tree component definitions for compatibility across studies (i.e., total stem was defined as groundline to tree tip; merchantable cubic volume was from a 1-foot stump height to a 4.0-inch top diameter outside bark). The minimum criteria for inclusion of a tree record in the modeling dataset were measurements of diameter at breast height, total height, and one or more measurements of tree taper or biomass components. The actual model fitting data consisted of 234,823 destructively sampled trees from 339 species across 23 ecodivisions (Cleland et al. 2007). These data are available in a permanent open repository (Radtke et al. 2023), with the exception of some confidential proprietary data. Supplemental data tables of values needed to calculate results are available as comma-separated values (CSV) files and are listed in the appendix.

Model Development

Due to the wide range of species and ecological conditions, it was assumed a single model form may not deliver optimal predictions for all trees in the fitting dataset. Four candidate allometric models were initially considered for evaluation:

Schumacher-Hall model

$$y_i = a * D_i^b * H_i^c + \varepsilon_i \tag{1}$$

Segmented model

$$y_i = \begin{cases} a * D_i^b * H_i^c + \varepsilon_i ; D_i < k \\ a * k^{(b-b_1)} * D_i^{b_1} * H_i^c + \varepsilon_i ; D_i \geq k \end{cases} \tag{2}$$

Continuously Variable model

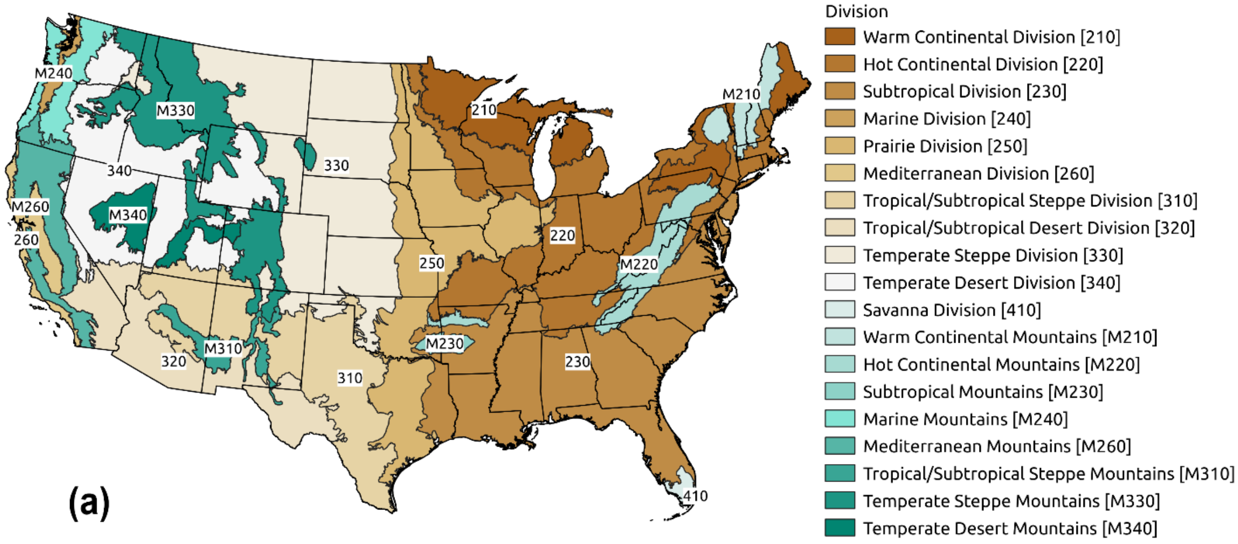
$$y_i = a * D_i^{a_1 * \left(1-exp^{(-b * D_i)}\right)^{c_1}} * H_i^c + \varepsilon_i \tag{3}$$

Modified Wiley model

$$y_i = a * D_i^b * H_i^c * exp^{(-(b_1 * D_i))} + \varepsilon_i \tag{4}$$

where for each tree *i*, y_i is the observed value of the component to be estimated (weight or volume), D_i = diameter (inches) at breast height (4.5 feet), H_i = total tree height (feet), *k* is a set segmentation point that is 9 inches for softwoods (*SPCD* <300) and 11 inches for hardwoods (*SPCD* ≥300), *exp* is the base of the natural logarithm, ε_i is a random residual error, and all other variables are coefficients estimated from regression. Note here that the models were fit to various assemblages of species and spatial domain as needed. Also, for slash pine (*Pinus elliottii*) (*SPCD* = 111) and loblolly pine (*P*. *taeda*) (*SPCD* = 131), planted (stand origin code (*STDORGCD*) = 1) and natural (*STDORGCD* = 0) stand origins may be fitted separately. While all candidate models were evaluated, the Schumacher-Hall model was considered the default formulation due to the parsimonious formulation and consistency in performance across a wide range of data sources. A different equation was chosen only if the Akaike information criteria (AIC) score (Akaike 1974) was lower and all estimated coefficients were significant at the α = 0.05 level.

Preliminary investigations showed that the relationship between tree size and volume (or biomass) within a species or species group frequently varied across ecodivisions. Therefore, models were fit for species and species groups by ecodivision (fig. 1). Within-division biomass models (total aboveground, stem wood, stem bark, branch, foliage) were developed for any species groups with at least 50 trees. Within-division volume models (stem wood, stem bark, volume ratio) were developed for species groups with at least 80 trees. These thresholds were chosen to balance the tradeoff between the number of species-specific models that could be presented while maintaining a sufficient number of observations (n) for those species. (Note: large samples are often described as *n* >30). The threshold was higher for volume models due to the relatively larger number of trees in the database having volume information. Species-level models were also fit across divisions because the FIA database (hereafter FIADB, with documentation by Burrill et al. 2021) contained species and division combinations that were not represented in the fitting dataset.



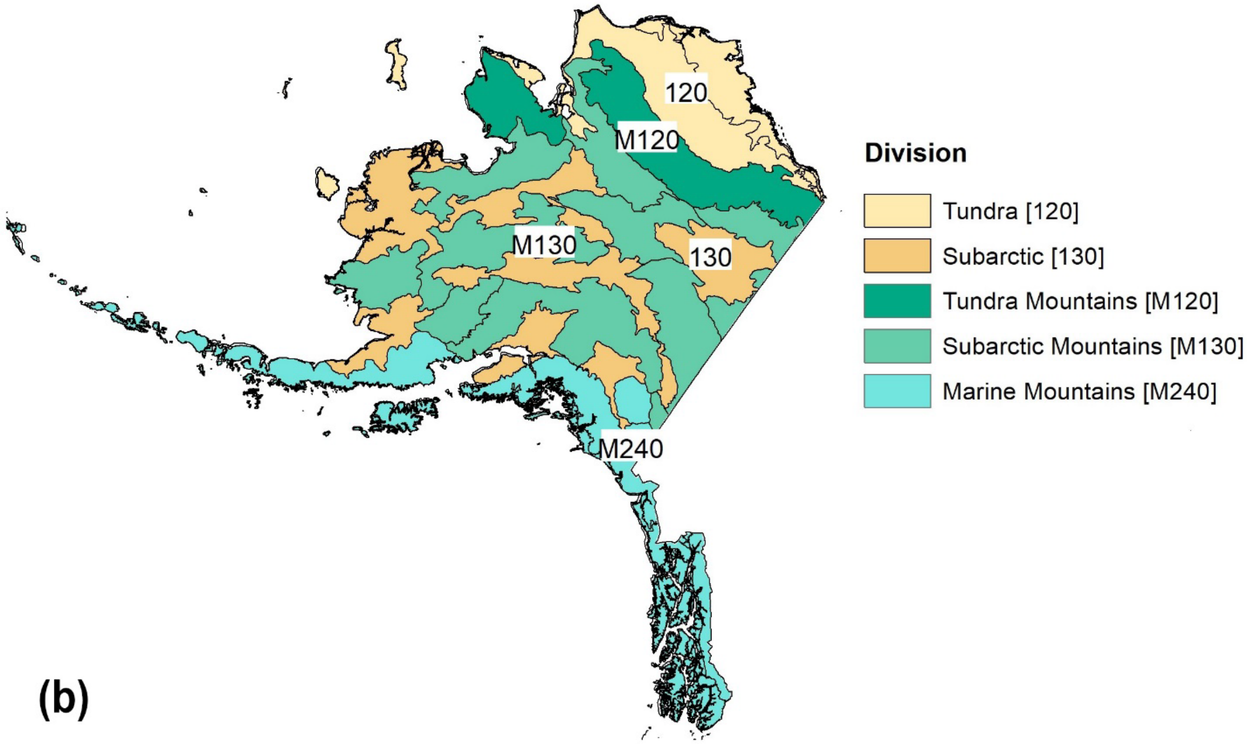


Figure 1.—Ecodivisions used by Forest Inventory and Analysis for (a) 48 of the 50 United States (Source: Cleland et al. 2007) and (b) Alaska (Source: Nowacki and Brock 1995).

The species-level models, either within divisions or across divisions, accounted for 89 percent of standing volume in the FIADB and 72 percent of standing aboveground biomass. To produce estimates for the remaining species in the FIADB, models were also estimated for the species groups described in Jenkins et al. (2003). The Jenkins groups are already in use by FIA and consist of species assemblages based on phylogenetic relationships and wood specific gravity. Models were estimated for 8 of the 10 Jenkins groups. Two Jenkins groups, Douglas-fir (because it was a single species) and woodland groups (due to lack of data), were excluded from this study. For species with fewer than five trees, model 5 that incorporates published species-level wood specific gravity (*WDSG*) values (Miles and Smith 2009) was estimated for total aboveground and branch biomass by Jenkins group:

Modified Schumacher-Hall model

$$y_i = a * D_i^b * H_i^c * WDSG_i + \varepsilon_i \tag{5}$$

For species with between 5 and 50 biomass trees (or 80 volume trees), mixed-effects model techniques were used at the Jenkins group level to fit model 1 for bark and foliage biomass and the modified version of the Schumacher-Hall model 5 for total aboveground and branch biomass. For these models, species was used as a random effect to account for differences among species within a given Jenkins group. The random effect was associated with the *b* parameter, i.e., the coefficient is a mixed parameter ($b + \theta$) where θ is the random species effect.

Allometric models were developed for the following volume and biomass: total stem wood volume, total stem bark volume, total branch wood and bark biomass, total aboveground biomass (without foliage), and total foliage biomass. Additionally, inside- and outside-bark volume ratio models were estimated to predict the proportion of volume to any height along the stem for all possible species and Jenkins groups:

Volume Ratio model

$$R_i = \left(1 - \left(1 - \frac{h_i}{H_i}\right)^{\alpha}\right)^{\beta} + \varepsilon_i \qquad (6)$$

where R_i is the proportion of total stem volume from groundline to h_i as a height along the stem with α and β as estimated parameters. Although no formal statistical tests were performed, heteroscedastic residual patterns were visually apparent in initial modeling analyses. Subsequent weighting of observations by $1/D_i^2$ for models 1–5 and $1/(\frac{h_i}{H_i} \times \left(1 - \frac{h_i}{H_i}\right))$ for model 6 displayed satisfying homoscedastic residual behaviors that were deemed to sufficiently address the assumption of constant error variance (Crow and Laidly 1980).

Model 6 can also be combined with model 1 to estimate the height h_i to any diameter d_i. This is accomplished by recognizing that the stem volume or biomass from groundline to h_i can be constructed as the product of a total volume model and a volume ratio model:

$$y_i = a * D_i^b * H_i^c * \left(1 - \left(1 - \frac{h_i}{H_i}\right)^{\alpha}\right)^{\beta}$$

The implied taper function is then specified as (Zhao et al. 2019):

$$d_i^2 = a \times D_i^b * H_i^c / 0.005454154 / H_i \times \alpha \times \beta \times \left(1 - \frac{h_i}{H_i}\right)^{(\alpha-1)} \times \left(1 - \left(1 - \frac{h_i}{H_i}\right)^{\alpha}\right)^{(\beta-1)}$$

The height along the stem (h_i) at a specified diameter on the stem (d_i) can be obtained by iteratively solving (i.e., numeric optimization or minimization, Nocedal and Wright 2006) equation 7 for h_i:

$$d_i - (a \times D_i^b * H_i^c / 0.005454154 / H_i \times \alpha \times \beta \times \left(1 - \frac{h_i}{H_i}\right)^{(\alpha-1)} \times \left(1 - \left(1 - \frac{h_i}{H_i}\right)^{\alpha}\right)^{(\beta-1)})^{0.5} \qquad (7)$$

where d_i is the desired top diameter; h_i is the height to desired top diameter; a, b, and c are coefficients from the outside bark volume coefficient table (table S3); and α and β are coefficients from the outside bark volume ratio coefficient table (table S4).

Modifications for standing dead trees to wood density and for bark and branch losses based on the observed level of decay as indicated by the FIA decay class code (*DECAYCD*) variable (Burrill et al. 2021) and hardwood or softwood species designation are incorporated into the NSVB framework by adopting the findings of Harmon et al. (2011) as shown in table 1. (Note, these values account for differences between hardwood and softwood species, unlike the values presented in Domke et al. (2011)). The values for wood density proportion for *DECAYCD* = 3 are also used to account for the fact that rotten wood cull still maintains a weight greater than zero even though rotten cull is entirely deducted to obtain sound cubic volume amounts. In this case, the observed cull is assumed to be entirely rotten wood, and the density of that wood is reduced accordingly. In addition, a standardized approach is implemented to estimate volume and biomass reductions from missing stem tops using model 6. Belowground coarse root biomass is calculated using the approach described in Heath et al. (2009) but by using merchantable stem wood volume as calculated here and applying the wood density proportions from table 1 for standing dead trees.

Table 1.—Wood density proportions and remaining bark and branch proportions for dead trees by species hardwood/softwood designation and Forest Inventory and Analysis (FIA) decay code (*DECAYCD*) classification.

Hardwood/softwood species	**FIA decay code (*DECAYCD*)**	**Wood density proportion**	**Remaining bark proportion**	**Remaining branch proportion**
H	1	0.99	1	1
H	2	0.8	0.8	0.5
H	3	0.54	0.5	0.1
H	4	0.43[a]	0.2	0
H	5	0.43[a]	0	0
S	1	0.97	1	1
S	2	1	0.8	0.5
S	3	0.92	0.5	0.1
S	4	0.55[a]	0.2	0
S	5	0.55[a]	0	0

[a] Decay class 4 values from Harmon et al. (2011) are used for FIA *DECAYCD* = 4 and 5.

RESULTS

Due to the large number of species and ecodivision combinations, along with the numerous volume and biomass models required, tables of coefficients are provided to address the prediction requirements for all species included in the study (tables S1–S9 in the appendix). Consulting these tables reveals two basic types, i.e., those having either a “spcd” or “jenkins” name suffix. Tables with the spcd suffix provide the models 1–4 form and associated coefficients for species/ecodivision/stand origin combinations. If a species occurs in an ecodivision not explicitly listed, the entry having no ecodivision noted is used. For species not included in the spcd tables, the jenkins suffix tables are used with model 5 and associated coefficients for the Jenkins group associated with the species of interest. Species assignments to Jenkins groups are in FIADB table REF_SPECIES as variable name *JENKINS_SPGRPCD*. Note that Jenkins group coefficients incorporate the predicted random effect into the reported coefficients, i.e., in some cases the value is a sum of the fixed and random effects. Also included are associated tables of coefficients for predicting volume ratios (model 6). New carbon content fractions based on Doraisami et al. (2022) are provided in table S10, where species-specific values are given for live trees and values for dead trees are based on hardwood/softwood classification and level of wood decay (*DECAYCD*) (Martin et al. 2021). Mean crown ratios of live trees based on FIA data are provided in table S11 for making branch and foliage weight deductions for dead trees with broken tops. Example 3 in the Results section provides additional information on using table S11.

In addition to the tables needed for calculations, key modeling statistics such as sample sizes (*n*), tree diameter distributions (minimum, mean, and maximum), fit index (*FI*; analogous to R^2), root mean squared error (*RMSE*), prediction error mean (*Mean(PE))* and standard deviation (*SD(PE*)), percent prediction error mean (*Mean(PE%)*) and standard deviation (*SD(PE%)*), absolute prediction error mean (*Mean(APE)*) and percent (*Mean(APE%)*), and diameter at breast height-weighted prediction error variability (*Sigma*) may be of primary interest to inventory practitioners and data users. These statistics are defined as follows:

$$FI = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}$$

$$Mean(PE) = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n} = \bar{\varepsilon}$$

$$SD(PE) = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - \bar{\varepsilon})^2}{n-1}}$$

$$Mean(PE\%) = \frac{1}{n}\sum_{i=1}^{n}\frac{(y_i - \hat{y}_i)}{y_i}100 = \frac{1}{n}\sum_{i=1}^{n_j} PE_i\% = \bar{\varepsilon}\%$$

$$SD(PE\%) = \sqrt{\frac{\sum_{i=1}^{n}(PE_i\% - \bar{\varepsilon}\%)^2}{n-1}}$$

$$Mean(APE) = \frac{\sum_{i=1}^{n}|y_i - \hat{y}_i|}{n}$$

$$Mean(APE\%) = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{(y_i - \hat{y}_i)}{y_i}\right|100$$

$$Sigma = \sqrt{\frac{\sum_{i=1}^{n}[(y_i - \hat{y}_i)^2(1/D_i^2)]}{n-1}}$$

where $\hat{y}_i$ is the predicted value of the weight or volume component to be estimated for tree *i*, $\bar{y}$ is the mean of the y_i, and *n* is the sample size. Supplemental tables listed in the appendix report the relevant statistics for the entire suite of models 1–5. For example, supplemental tables S12–S20 provide statistics for various aggregations of ecodivision, species, FIA region, State, and national perspectives. As expected, various outcomes were realized across attributes (volume or biomass) and the attribute components (e.g., wood, bark, branches). Readers are encouraged to consult the tables for their specific ecodivisions and species of interest.

Typically, biomass conversion to carbon is performed using a carbon fraction value. In the past, FIA has used the generic approximation of 0.5 as the ratio of carbon to dry wood weight for all species. For the species addressed in this study, the NSVB framework introduces more rigorous carbon content predictions via species-specific carbon fractions (a) developed for 100 species using the Global Woody Tissue Carbon Concentration Database (GLOWCAD; Doraisami et al. 2022), and (b) established for the remaining 321 species as a linear model prediction based on specific gravity (Martin et al. 2018). On average, the carbon fraction is 0.477 across all species, with a minimum value of 0.420 and a maximum value of 0.538. Thus, there will be a general expectation that carbon content will decline for a given amount of biomass because the overall average is less than the previous carbon fraction of 0.5. However, realized differences in carbon amounts will depend on various interrelated factors, including changes in the tree biomass basis, species composition, and tree size distributions for a specified area of interest.

Examples of Tree-Level Calculations

A number of calculations are required to obtain the full suite of volume and biomass components for each tree. An outline of the necessary calculations is provided here to familiarize readers with the general conceptual approach, followed by a series of examples. The general approach requires the following steps:

1. Predict gross total stem wood volume as a function of diameter at breast height (*D*) and total height (*H*).
2. Predict gross total stem bark volume as a function of *D* and *H*.
3. Obtain gross total stem outside-bark volume as the sum of wood and bark gross volumes.
4. Estimate heights to merchantable (4.0-inch) top diameter and, if present, sawlog top diameter (7 inches for softwoods (*SPCD* <300) and 9 inches for hardwoods (*SPCD* ≥300)). Make adjustments to these values as needed for trees with a broken top.
5. Estimate stem component gross volumes (stump; merchantable stem; sawlog, if present; and stem top) using a ratio function.
6. Estimate stem component sound volumes to account for any cull present or dead tree density reductions.
7. Convert total stem wood gross volume to biomass weight using published wood density values (Miles and Smith 2009). Reduce stem wood weight due to broken top, cull deductions (accounting for nonzero weight of cull), and dead tree wood density reduction.
8. Predict total stem bark biomass as a function of *D* and *H*. Reduce the prediction if necessary for missing bark due to a broken top or dead tree structural loss if either is present.
9. Predict total branch biomass as a function of *D* and *H*. Reduce the prediction if necessary for missing branches due to a broken top or dead tree wood density reduction and structural loss, if present.
10. Predict total aboveground biomass as a function of *D* and *H*. Reduce the prediction if necessary using the overall proportional reduction obtained from the stem wood, bark, and branch component reductions. This biomass value is considered the “optimal” biomass estimate.
11. Sum total stem wood biomass, total stem bark biomass, and total branch biomass (with each component reduced for broken tops, cull, and dead tree density loss as appropriate) to obtain a second total aboveground biomass.
12. Proportionally distribute the difference between the directly predicted total biomass and the total from the component estimates across total stem wood, total stem bark, and total branch weights to create an adjusted total stem wood weight, an adjusted total stem bark weight, and an adjusted total branch weight.

13. Calculate an adjusted wood density by dividing the adjusted total stem wood weight by the predicted total stem wood volume. This adjusted wood density can be used to convert any subsection of the main stem wood volume to biomass.
14. Calculate an adjusted bark density by dividing the adjusted total stem bark weight by the predicted total stem bark volume. This value can be used to convert any subsection of the main stem bark volume to biomass.
15. Directly predict total foliage dry weight as a function of *D* and *H*.
16. Estimate total aboveground carbon using total aboveground biomass (excluding foliage) and the species-specific carbon fraction.

In the following examples, the model forms are referred to by the number listed in the Methods section. For all examples, units for volume and biomass predictions are cubic feet and pounds, respectively. The calculations retain many digits only to minimize the compounding of rounding error effects throughout the prediction system. This is not intended to imply a level of accuracy in the predictions, and users can choose to round the final predictions for their attributes of interest to the extent desired.

Example 1

Assume the following measurements were taken for a Douglas-fir (*SPCD* = 202) tree having *D* = 20.0 inches and *H* = 110 feet with no cull growing in the Marine Division (*DIVISION* = 240). The first step is to predict total stem wood volume in cubic feet using the appropriate model form and coefficients. The inside-bark wood volume coefficient table (table S1) indicates trees in the group 202/240 (i.e., *SPCD* = 202 and *DIVISION* = 240) use model 2 with the appropriate coefficients:

$$Vtot_{ib}Gross = a_0 \times k^{(b0-b1)} \times D^{b_1} \times H^c$$

$$Vtot_{ib}Gross = 0.001929099661 \times 9^{(2.162413104203-1.690400253097)} \times 20^{1.690400253097} \times 110^{0.985444005253} = 88.452275544288$$

Total bark volume is predicted next. Consulting the bark volume coefficient table (table S2) indicates the use of model 1 with the appropriate coefficients:

$$Vtot_{bk}Gross = a \times D^b \times H^c$$

$$Vtot_{bk}Gross = 0.000031886237 \times 20^{1.21260513951} \times 110^{1.978577263767} = 13.191436232306$$

Total outside bark volume is then calculated via addition:

$$Vtot_{ob}Gross = Vtot_{ib}Gross + Vtot_{bk}Gross$$

$$Vtot_{ob}Gross = 88.452275544288 + 13.191436232306 = 101.643711776594$$

Note that table S3 provides the information needed to directly obtain model predictions of $Vtot_{ob}Gross$. However, this table is not intended to be used in this manner as it does not facilitate maintaining additive properties nor enable proper treatment of the stem wood and bark components in terms of reductions for wood cull or dead tree decay and loss. The primary use of table S3 is for calculating merchantable and sawlog stem volumes. Merchantable volumes are defined as the volume from a 1-foot stump to a 4.0-inch outside-bark top diameter. Sawlog volumes are defined as being between a 1-foot stump and a 7.0-inch top diameter for softwood species (D ≥9.0 inches) and 9.0-inch top diameter for hardwood species (D ≥11 inches). Equation 7 can be used to find the height (h_{ij}) to any top diameter (d_{ij}); however, it cannot be inverted or algebraically rearranged to be solved directly. Therefore, iterative methods must be used (i.e., numerical optimization or minimization). For the merchantable height to a 4.0-inch top (h_m), inserting the correct coefficient values for a, b, and c from the outside-bark volume coefficient table (table S3) and values for α and β from the outside-bark volume ratio coefficient table (table S4) results in the following calculation:

$$|4 - (0.002916157874 \times 20^{1.778795704183} \times 110^{1.085526548472}/0.005454154)/110 \times 2.386864288974 \times 0.907607415992\times (1 - h_m/110)^{(2.386864288974-1)} \times (1 - (1 - h_m/110)^{2.386864288974})^{(0.907607415992-1)})^{0.5}|$$

Iterative minimization results in $h_m = 98.28126765402$. To determine merchantable volume, use model 6 and the coefficients from the inside-bark volume ratio table (table S5) to find the proportion of total stem volume for both the 1-foot stump height and the 4.0-inch top diameter height:

$$R_1 = (1 - (1 - h_1/H)^{\alpha})^{\beta}$$
$$R_1 = (1 - (1 - 1/110)^{2.220714200464})^{0.952218706779} = 0.024198309503$$

$$R_m = (1 - (1 - h_m/H)^{\alpha})^{\beta}$$
$$R_m = (1 - (1 - 98.28126765402/110)^{2.220714200464})^{0.952218706779} = 0.993406175350$$

where h_1 is stump height (1 foot), h_m is the merchantable height, R_1 is the proportion of volume to 1 foot and R_m is the proportion of volume to the merchantable height.

Then, multiply the ratios by the already estimated total stem wood volume and subtract the stump volume to obtain the merchantable stem inside-bark volume:

$$Vmer_{ib}Gross = (R_m \times Vtot_{ib}Gross) - (R_1 \times Vtot_{ib}Gross)$$
$$Vmer_{ib}Gross = (0.993406175350 \times 88.452275544288) - (0.024198309503 \times 88.452275544288) = 85.728641209612$$

The same procedure can be used to estimate the merchantable stem outside-bark volume:

$$Vmer_{ob}Gross = (R_m \times V\ tot_{ob}Gross) - (R_1 \times V\ tot_{ob}Gross)$$
$$Vmer_{ob}Gross = (0.99340617535 \times 101.643711776594) - (0.024198309503 \times 101.643711776594) = 98.513884967785$$

Note that the same volume ratio coefficients are used for both inside-bark and outside-bark ratios to ensure consistency. Merchantable stem bark volume is then calculated via subtraction:

$$Vmer_{bk}Gross = Vmer_{ob}Gross - Vmer_{ib}Gross$$
$$Vmer_{bk}Gross = 98.513884967785 - 85.728641209612 = 12.785243758174$$

Calculating cubic-foot volume in the sawlog portion of the stem (1-foot stump height to 7.0-inch top diameter for softwoods ($SPCD$ <300; D ≥9.0 inches) and 9.0-inch top diameter for hardwoods ($SPCD$ ≥300; D ≥11.0 inches)) proceeds similarly, with sawlog height (h_s) being obtained from the following calculation:

$$|7 - (0.002916157874 \times 20^{1.778795704183} \times 110^{1.085526548472}/0.005454154)/110 \times 2.386864288974 \times 0.907607415992 \times (1 - h_s/110)^{(2.386864288974-1)} \times (1 - (1 - h_s/110)^{2.386864288974})^{(0.907607415992-1)})\ 0.5|$$

Iterative minimization results in $h_s = 83.785181046$. To determine sawlog volume, use model 6 and the coefficients from the inside-bark volume ratio table (table S5) to find the proportion of total stem volume for both the 1-foot stump height and the 7.0-inch top diameter height (R_s):

$$R_1 = (1 - (1 - h_1/H)^{\alpha})^{\beta}$$
$$R_1 = (1 - (1 – 1/110)^{2.220714200464})^{0.952218706779} = 0.024198309503$$

$$R_s = (1 - (1 - h_s/H)^{\alpha})^{\beta}$$
$$R_s = (1 - (1 - 83.785181046/110)^{2.220714200464})^{0.952218706779} = 0.960553392655$$

where h_1 is stump height (1 foot), h_s is the sawlog height, R_1 is the proportion of volume to 1 foot and R_s is the proportion of volume to the sawlog height.

Then, multiply the ratios by the already estimated total stem wood volume and subtract:

$$Vsaw_{ib}Gross = (R_s \times Vtot_{ib}Gross) - (R_1 \times Vtot_{ib}Gross)$$

$$Vsaw_{ib}Gross = (0.960553392655 \times 88.452275544288) - (0.024198309503 \times 88.452275544288) = 82.822737822255$$

The same procedure can be used to estimate the sawlog outside-bark volume:

$$Vsaw_{ob}Gross = (R_s \times Vtot_{ob}Gross) - (R_1 \times Vtot_{ob}Gross)$$

$$Vsaw_{ob}Gross = (0.960553392655 \times 101.643711776594) - (0.024198309503 \times 101.643711776594) = 95.174606192451$$

Sawlog stem bark volume is then calculated via subtraction:

$$Vsaw_{bk}Gross = Vsaw_{ob}Gross - Vsaw_{ib}Gross$$

$$Vsaw_{bk}Gross = 95.174606192451 - 82.822737822255 = 12.351868370196$$

Stump wood and bark volumes are estimated using the same volume ratio approach:

$$Vstump_{ob}Gross = (R_1 \times Vtot_{ob}Gross)$$
$$Vstump_{ob}Gross = (0.024198309503 \times 101.643711776594) = 2.459605996608$$

$$Vstump_{ib}Gross = (R_1 \times Vtot_{ib}Gross)$$
$$Vstump_{ib}Gross = (0.024198309503 \times 88.452275544288) = 2.140395539869$$

$$Vstump_{bk}Gross = Vstump_{ob}Gross - Vstump_{ib}Gross$$
$$Vstump_{bk}Gross = 2.459605996608 - 2.140395539869 = 0.319210456739$$

Finally, stem-top volumes are calculated by subtracting the other stem volume subcomponents:

$$Vtop_{ob}Gross = Vtot_{ob}Gross - Vmer_{ob}Gross - Vstump_{ob}Gross$$
$$Vtop_{ob}Gross = 101.643711776594 - 98.513884967785 - 2.459605996608 = 0.670220812201$$

$Vtop_{ib}Gross = Vtot_{ib}Gross - Vmer_{ib}Gross - Vstump_{ib}Gross$
$Vtop_{ib}Gross = 88.452275544288 - 85.728641209612 - 2.140395539869 = 0.583238794807$

$Vtop_{bk}Gross = Vtop_{ob}Gross - Vtop_{ib}Gross$
$Vtop_{bk}Gross = 0.670220812201 - 0.583238794807 = 0.086982017394$

The same ratio procedure can be used to estimate outside- or inside-bark volume between any heights and can be used to estimate many product classes (i.e., sawlog volumes). Additionally, if bark volumes are desired, predict for both outside- and inside-bark volumes and then subtract (i.e., $V_{bk} = V_{ob} - V_{ib}$).

Associated sound wood and bark attributes are also needed to account for any rotten/missing cull wood, along with any decay reductions that are specified for dead trees. Notationally, values designated as "Sound" hereafter refer to values occurring after considering any deductions due to cull, broken top, or dead tree density reductions. Although the tree in this example has *CULL* = 0, it is shown how cull would be applied to any inside-bark volumes at this point:

$Vtot_{ib}Sound = Vtot_{ib}Gross \times (1 - CULL/100)$
$Vtot_{ib}Sound = 88.452275544288 \times (1 - 0/100) = 88.452275544288$

where *CULL* is the percentage of rotten/missing wood in the main stem below any missing top (i.e., to *ACTUALHT*). For the example tree used here, all sound attributes are equal to their gross counterparts due to the tree being alive with no cull.

An outside-bark volume that includes wood cull (note that bark volume predictions are unaffected by the *CULL* value) can be determined by adding the appropriate bark volume to the sound wood volume estimates:

$Vtot_{ob}Sound = Vtot_{ib}Sound + Vtot_{bk}Sound$
$Vtot_{ob}Sound = 88.452275544288 + 13.191436232306 = 101.643711776594$

Total stem wood volume is converted to total stem wood dry weight in pounds (lb) using the wood density (specific gravity) value from the REF_SPECIES table, which is 0.45 for *SPCD* = 202. To convert to weight multiple this value by the weight of a cubic foot of water (62.4 lb/ft^3):

$Wtot_{ib} = Vtot_{ib}Gross \times WDSG \times 62.4$

$Wtot_{ib} = 88.452275544288 \times 0.45 \times 62.4 = 2483.739897283610$

It is considered that most cull material will be rotten wood, which would still contribute to the stem weight. As such, it is assumed the density of cull wood is reduced by the proportion for *DECAYCD* = 3 (table 1; *DensProp* = 0.54 for hardwood species, 0.92 for softwood species) as reported by Harmon et al. (2011) to obtain the reduced weight due to cull. In this example, *CULL* = 0, so no reduction in weight is incurred:

$Wtot_{ib}red = Vtot_{ib}Gross \times (1 - CULL/100 \times (1 - DensProp)) \times WDSG \times 62.4$
$Wtot_{ib}red = 88.452275544288 \times (1 - 0/100 \times (1 - 0.54)) \times 0.45 \times 62.4 = 2483.739897283610$

Next, total stem bark weight can be estimated using the appropriate model form and coefficients. Consulting the stem bark weight coefficient table (table S6), use model 1 with the appropriate coefficients:

$Wtot_{bk} = a \times D^b \times H^c$
$Wtot_{bk} = 0.009106538193 \times 20^{1.4378944424586} \times 110^{1.336514272981} = 361.782496100100$

Total branch weight can then be estimated using the appropriate model form and coefficients. Consulting the branch weight coefficient table (table S7), use model 1 with the appropriate coefficients:

$Wbranch = a \times D^b \times H^c$
$Wbranch = 9.521330809106 \times 20^{1.762316117442} \times 110^{-0.40574259177} = 277.487756904646$

Reductions to bark and branch weights are only considered for dead trees and trees with broken tops. As neither of these conditions is present in the current example, $Wtot_{bk}red = Wtot_{bk}$ and $Wbranchred = Wbranch$.

Now, total aboveground biomass (AGB) can be estimated using the appropriate equation form and coefficients. The total biomass coefficient table (table S8) prescribes the use of model 1 with the appropriate coefficients:

$AGB_{Predicted} = a \times D^b \times H^c$
$AGB_{Predicted} = 0.135206506787 \times 20^{1.713527048035} \times 110^{1.047613377046} = 3154.5539926725$

The next series of steps are designed to ensure consistent estimates between the three independently estimated components (total stem wood weight, total stem bark weight, and branch weight) and the predicted total aboveground biomass ($AGB_{Predicted}$). First, estimate a second total aboveground biomass by summing the three components and then calculate the difference between the two *AGB* estimates:

$AGB_{Component}red = Wtot_{ib}red + Wtot_{bk}red + Wbranchred$
$AGB_{Component}red = 2483.739897283610 + 361.782496100100 + 277.487756904646 = 3123.010150288360$

A reduction factor is now calculated to modify $AGB_{Predicted}$ to account for any component rot or loss (none in this case):

$AGB_{Reduce} = AGB_{Component}red / (Wtot_{ib} + Wtot_{bk} + Wbranch)$
$AGB_{Reduce} = 3123.010150288360/(2483.739897283610 + 361.782496100100 + 277.487756904646) = 1.000000000000$

$AGB_{Predicted}red = AGB_{Predicted} \times AGB_{Reduce}$
$AGB_{Predicted}red = 3154.5539926725 \times 1.000000000000 = 3154.5539926725$

$AGB_{Diff} = AGB_{Predicted}red - AGB_{Component}red$
$AGB_{Diff} = 3154.5539926725 - 3123.0101502883 = 31.543842384153$

Next, to harmonize the three components with the predicted total aboveground biomass, proportionally distribute AGB_{Diff} across the components. Mathematically, this can be accomplished with the following calculations:

$Wood_{Harmonized} = AGB_{Predicted}red \times (Wtot_{ib}red/AGB_{Component}red)$
$Wood_{Harmonized} = 3154.5539926725 \times (2483.7398972836/3123.01015028834) = 2508.826815376370$

$Bark_{Harmonized} = AGB_{Predicted}red \times (Wtot_{bk}red/AGB_{Component}red)$
$Bark_{Harmonized} = 3154.5539926725 \times (361.7824961001/3123.01015028834) = 365.436666110811$

$Branch_{Harmonized} = AGB_{Predicted}red \times (Wbranchred/AGB_{Component}red)$
$Branch_{Harmonized} = 3154.5539926725 \times (277.487756904647/3123.01015028834) = 280.290511185328$

At this point, all the individual tree components have been harmonized and are additive with the predicted total aboveground biomass estimate. The final biomass component that can be predicted is foliage weight. Consulting the foliage weight coefficient table (table S9) indicates the use of model 2 with the appropriate coefficients:

$$Wfoliage = a_0 \times k^{(b0-b1)} \times D^{b1} \times H^{c}$$
$$Wfoliage = 0.477184595914 \times 9^{(2.592670351881-1.249237428914)} \times 20^{1.249237428914} \times 110^{-0.325050455055} = 83.634788855934$$

Reductions to foliage weight are only considered for live trees with a broken top. As no broken top is present in the current example, *Wfoliagered = Wfoliage*. Foliage biomass is kept separate from total biomass values, which consist of wood, bark, and branch mass.

Finally, calculate a new adjusted wood density using the harmonized total stem wood weight and the predicted total stem wood volume. Careful attention is needed for this calculation because cull is treated differently for volume vs. biomass in the NSVB framework. The wood volume basis does not include a deduction for cull but does include deductions for missing wood (i.e., broken top). In this example, no cull nor broken top is present such that $Vtot_{ib}Gross$ and $Vtot_{bk}Gross$ are representative of the actual existing wood and bark volume, respectively:

$$WDSG_{Adj} = Wood_{Harmonized}/Vtot_{ib}Gross/62.4$$
$$WDSG_{Adj} = 2508.826815376370/88.452275544288/62.4 = 0.454545207473$$

Similarly, an adjusted bark density is calculated using the harmonized total stem bark weight and the predicted total stem bark volume:

$$BKSG_{Adj} = Bark_{Harmonized}/Vtot_{bk}Gross/62.4$$
$$BKSG_{Adj} = 365.436666110811/13.191436232306/62.4 = 0.4439514186$$

The adjusted wood density can convert any stem wood volume subcomponents (e.g., merchantable or sawlog portion of the stem) to weights compatible with the harmonized total stem wood weight. The adjusted bark density can similarly be used to convert any stem bark volume subcomponents to weights compatible with the harmonized total stem bark weight. Merchantable stem wood and bark weights can be determined using the same volume basis (e.g., *Gross*) as above for the adjusted specific gravity calculations:

$$Wmer_{ib} = Vmer_{ib}Gross \times WDSG_{Adj} \times 62.4$$

$Wmer_{ib} = 85.728641209612 \times 0.454545207473 \times 62.4 = 2431.57468351127$

$Wmer_{bk} = Vmer_{bk}Gross \times BKSG_{Adj} \times 62.4$
$Wmer_{bk} = 12.785243758174 \times 0.4439514186 \times 62.4 = 354.184091263592$

The merchantable stem outside-bark weight is then calculated via addition:

$Wmer_{ob} = Wmer_{ib} + Wmer_{bk}$
$Wmer_{ob} = 2431.57468351127 + 354.184091263592 = 2785.75877477486$

$Wmer_{ob}$ is equivalent in definition to the FIADB variable DRYBIO_BOLE (dry biomass in the merchantable bole). Similarly, stump weights are calculated as follows:

$Wstump_{ib} = Vstump_{ib}Gross \times WDSG_{Adj} \times 62.4$
$Wstump_{ib} = 2.140395539869 \times 0.454545207473 \times 62.4 = 60.709367768006$

$Wstump_{bk} = Vstump_{bk}Gross \times BKSG_{Adj} \times 62.4$
$Wstump_{bk} = 0.319210456739 \times 0.4439514186 \times 62.4 = 8.842949550309$

$Wstump_{ob} = Wstump_{ib} + Wstump_{bk}$
$Wstump_{bk} = 60.709367768006 + 8.842949550309 = 69.552317318315$

$Wstump_{ob}$ is equivalent in definition to the FIADB variable DRYBIO_STUMP (dry biomass in the tree stump).

The NSVB component analogous to the current FIADB component DRYBIO_TOP (dry biomass in the top and branches of the tree) is the total AGB minus the stump and merchantable stem components:

$DRYBIO\_TOP = AGB_{Predicted}red - Wmer_{ob} - Wstump_{ob}$

$DRYBIO\_TOP = 3154.5539926725 - 2785.75877477486 - 69.552317318315 = 299.242900579325$

As the sum of the biomass components is equal to $AGB_{Predicted}red$, the carbon content (C) of the stem and branches (but not foliage) is obtained via multiplication by the appropriate C fraction for $SPCD = 202$ (table S10):

$C = AGB_{Predicted}red \times CF$
$C = 3154.5539926725 \times 0.515595833333 = 1626.474894645920$

Example 2

Assume a red maple (*SPCD* = 316) tree with *D* = 11.1 inch, *H* = 38 feet, and *CULL* = 3 percent growing in the Warm Continental Division - Mountain (*DIVISION* = M210). The first step is to predict total stem wood volume using the appropriate equation form and coefficients. Consulting the inside-bark wood volume coefficient table (table S1), there are no coefficients for the *SPCD/DIVISION* combination of 316/M210. Therefore, the species-level coefficients are to be used. Use model 1 with the appropriate coefficients:

$$Vtot_{ib}Gross = a \times D^{b} \times H^{c}$$

$$Vtot_{ib}Gross = 0.001983918881 \times 11.1^{1.810559393287} \times 38^{1.129417635145} = 9.427112777611$$

Next, total bark volume will be predicted. Consulting the bark volume coefficient table (table S2), use model 2 with the appropriate coefficients:

$$Vtot_{bk}Gross = a_0 \times k^{(b0-b1)} \times D^{b1} \times H^{c}$$

$$Vtot_{bk}Gross = 0.003743084443 \times 11^{(2.226890355309-1.685993125661)} \times 11.1^{1.685993125661} \times 38^{0.275066356213} = 2.155106401987$$

Outside-bark volume is then calculated via addition:

$$Vtot_{ob}Gross = Vtot_{ib}Gross + Vtot_{bk}Gross$$

$$Vtot_{ob}Gross = 9.427112777611 + 2.155106401987 = 11.582219179599$$

Merchantable and sawlog stem volumes are calculated next using equation 7, which can be minimized to estimate the height to any top diameter. For the height to a 4.0-inch top diameter (h_m), inserting the correct coefficients from tables S3 and S4 results in the following:

$$|4 - (0.003068676884 \times 11.1^{1.811800477506} \times 38^{1.054949234246}/0.005454154/38 \times 2.500241064397 \times 0.88374141693 \times (1 - h_m/38)^{(2.500241064397-1)} \times (1 - (1 - h_m/38)^{2.500241064397})^{(0.88374141693-1))})^{0.5}|$$

Iterative minimization results in h_m = 28.047839250135. To determine merchantable volume, use model 6 and the coefficients from the inside-bark volume ratio table (table S5) to find the proportion of total stem volume from the 1-foot stump to the 4.0-inch top:

$$R_1 = (1 - (1 - h_1/H)^{\alpha})^{\beta}$$

$$R_1 = (1 - (1 - 1/38)^{2.533953226865})^{0.8781223155} = 0.091117585499$$

$$R_m = (1 - (1 - h_m/H)^{\alpha})^{\beta}$$

$$R_m = (1 - (1 - 28.047839250135/38)^{2.533953226865})^{0.8781223155} = 0.970485778632$$

Then, multiply the ratios by the already estimated total inside-bark stem wood volume and subtract the 1-foot stump volume from the 4.0-inch top volume:

$$Vmer_{ib}Gross = (R_m \times Vtot_{ib}Gross) - (R_1 \times V\ tot_{ib}Gross)$$

$$Vmer_{ib}Gross = (0.970485778632 \times 9.427112777611) - (0.091117585499 \times 9.427112777611) = 8.289903129704$$

The same procedure can be used to estimate the merchantable outside-bark volume:

$$Vmer_{ob}Gross = (R_m \times Vtot_{ob}Gross) - (R_1 \times Vtot_{ob}Gross)$$

$$Vmer_{ob}Gross = (0.970485778632 \times 11.582219179599) - (0.091117585499 \times 11.582219179599) = 10.185035152427$$

Merchantable stem bark volume is then calculated via subtraction:

$$Vmer_{bk}Gross = Vmer_{ob}Gross - Vmer_{ib}Gross$$

$$Vmer_{bk}Gross = 10.185035152427 - 8.289903129704 = 1.895132022724$$

Calculation of cubic-foot volume in the sawlog portion of the stem (1-foot stump height to 7.0-inch top diameter for softwoods ($SPCD$ <300; D ≥9.0 inches) or 9.0-inch top diameter for hardwoods ($SPCD$ ≥300; D ≥11.0 inches)) proceeds similarly, with sawlog height (h_s) being obtained from the following calculation:

$$|9 - (0.003068676884 \times 11.1^{1.811800477506} \times 38^{1.054949234246}/0.005454154/38 \times 2.500241064397 \times 0.88374141693 \times (1 - h_s/38)^{(2.500241064397-1)} \times (1 - (1 - h_s/38)^{2.500241064397})^{(0.88374141693-1)})^{0.5}|$$

Iterative minimization results in $h_s = 9.98078332380462$. To determine sawlog volume, use model 6 and the coefficients from the inside-bark volume ratio table (table S5) to find the proportion of total stem volume for both the 1-foot stump height and the 9.0-

inch top diameter height (R_s):

$R_1 = (1 - (1 - h_1/H)^{\alpha})^{\beta}$

$R_1 = (1 - (1 - 1/38)^{2.533953226865})^{0.8781223155} = 0.091117585499$

$R_s = (1 - (1 - h_s/H)^{\alpha})^{\beta}$

$R_s = (1 - (1 - 9.98078332380462/38)^{2.533953226865})^{0.8781223155} = 0.580175217851$

Then, multiply the ratios by the already estimated total inside-bark stem wood volume and subtract:

$VsawibGross = (R_s \times VtotibGross) - (R_1 \times VtotibGross)$

$Vsaw_{ib}Gross = (0.580175217851 \times 9.427112777611) - (0.091117585499 \times 9.427112777611) = 4.610401454934$

The same procedure can be used to estimate the sawlog outside-bark volume:

$Vsaw_{ob}Gross = (R_s \times Vtot_{ob}Gross) - (R_1 \times Vtot_{ob}Gross)$

$Vsaw_{ob}Gross = (0.580175217851 \times 11.582219179599) - (0.091117585499 \times 11.582219179599) = 5.664372689357$

Sawlog stem bark volume is then calculated via subtraction:

$Vsaw_{bk}Gross = Vsaw_{ob}Gross - Vsaw_{ib}Gross$

$Vsaw_{bk}Gross = 5.664372689357 - 4.610401454934 = 1.053971234423$

Stump volumes are estimated using the same volume ratio approach as previously used:

$Vstump_{ob}Gross = (R_1 \times Vtot_{ob}Gross)$

$Vstump_{ob}Gross = (0.091117585499 \times 11.582219179599) = 1.055343846369$

$Vstump_{ib}Gross = (R_1 \times Vtot_{ib}Gross)$

$Vstump_{ib}Gross = (0.091117585499 \times 9.427112777611) = 0.858975754526$

$Vstump_{bk}Gross = Vstump_{ob}Gross - Vstump_{ib}Gross$

$Vstump_{bk}Gross = 1.055343846369 - 0.858975754526 = 0.196368091843$

Finally, stem-top volumes are calculated by subtracting the other stem volume subcomponents:

$$Vtop_{ob}Gross = Vtot_{ob}Gross - Vmer_{ob}Gross - Vstump_{ob}Gross$$

$$Vtop_{ob}Gross = 11.582219179599 - 10.185035152427 - 1.055343846369 = 0.341840180802$$

$$Vtop_{ib}Gross = Vtot_{ib}Gross - Vmer_{ib}Gross - Vstump_{ib}Gross$$

$$Vtop_{ib}Gross = 9.427112777611 - 8.289903129704 - 0.858975754526 = 0.278233893382$$

$$Vtop_{bk}Gross = Vtop_{ob}Gross - Vtop_{ib}Gross$$

$$Vtop_{bk}Gross = 0.341840180802 - 0.278233893382 = 0.06360628742$$

Cull is applied to any inside-bark stem volumes at this point to obtain estimates of sound volume:

$$Vtot_{ib}Sound = Vtot_{ib}Gross \times (1 - CULL/100)$$

$$Vtot_{ib}Sound = 9.427112777611 \times (1 - 3/100) = 9.144299394283$$

Because cull deductions only apply to inside-bark wood and no adjustments to bark are needed to account for a broken top or dead tree decay, $Vtot_{bk}Sound = Vtot_{bk}Gross$. An outside-bark volume that includes cull can be determined by adding the appropriate bark volume to the sound wood volume estimates:

$$Vtot_{ob}Sound = Vtot_{ib}Sound + Vtot_{bk}Sound$$

$$Vtot_{ob}Sound = 9.144299394283 + 2.155106401987 = 11.299405796270$$

Distribution of sound volume into stump, merchantable stem, and top components is accomplished using the same ratios as gross volume.

Total stem wood volume is converted to total stem wood dry weight using the correct value from the wood density table (REF_SPECIES) in conjunction with the weight of one cubic foot of water (62.4 lb). Also it is considered that most cull will be rotten wood, which would still contribute to the stem weight. As such, it is assumed the density of cull wood is reduced by the proportion for *DECAYCD* = 3 (table 1; *DensProp*

= 0.54 for hardwood species and 0.92 for softwood species) as reported by Harmon et al. (2011) to obtain the reduced weight due to cull:

$Wtot_{ib} = Vtot_{ib}Gross \times WDSG \times 62.4$
$Wtot_{ib} = 9.427112777611 \times 0.49 \times 62.4 = 288.243400288234$

$Wtot_{ib}red = Vtot_{ib}Gross \times (1 - CULL/100 \times (1 - DensProp)) \times WDSG \times 62.4$
$Wtot_{ib}red = 9.427112777611 \times (1 - 3/100 \times (1 - 0.54)) \times 0.49 \times 62.4 =$
284.265641364256

Total stem bark weight can be estimated by consulting the stem bark weight coefficient table (table S6), which indicates the use of model 1 with the appropriate coefficients. For live trees with intact tops, no bark deductions are incurred:

$Wtot_{bk} = a * D^{b} * H^{c}$

$Wtot_{bk} = 0.061595466174 \times 11.11.818642599217 \times 380.654020672095 =$
52.945466015848

$Wtot_{bk}red = Wtot_{bk} = 52.945466015848$

The total stem weight considering the cull deduction is calculated as follows:

$Wtot_{ob}red = Wtot_{ib}red + Wtot_{bk}red$
$Wtot_{ob}red = 284.265641364256 + 52.945466015848 = 337.211107380104$

Total branch weight can then be estimated by consulting the branch weight coefficient table (table S7), where the use of model 1 with the appropriate coefficients is indicated. For live trees with intact tops, no branch deductions are incurred:

$Wbranch = a \times D^{b} \times H^{c}$

$Wbranch = 0.011144618401 \times 11.1^{3.269520661293} \times 38^{0.421304343724} =$
135.001927997271

$Wbranchred = Wbranch = 135.001927997271$

Total aboveground biomass can be estimated by consulting the total biomass coefficient table (table S8) that stipulates the use of model 4 with the appropriate coefficients:

$AGB_{Predicted} = a \times D^{b} \times H^{c} \times exp^{(-(b2\times D))}$

$AGB_{Predicted} = 0.31573027567 \times 11.1^{1.853839844372} \times 38^{0.740557378679} \times exp^{(-(-0.024745684975\times 11.1))} = 532.584798820042$

Next, the three independently estimated components (stem wood weight, stem bark weight, and branch weight) need to be harmonized with the predicted total aboveground biomass. First, estimate an alternative total aboveground biomass by summing the three components:

$AGB_{Component}red = Wtot_{ib}red + Wtot_{bk}red + Wbranchred$

$AGB_{Component}red = 284.265641364256 + 52.945466015848 + 135.001927997271 = 472.213035377375$

Subsequently, $AGB_{Predicted}$ needs to be reduced to account for component rot and loss by calculating a reduction factor. For harmonization purposes, determine the difference between the reduced predicted and component-based values:

$AGB_{Reduce} = AGB_{Component}red / (Wtot_{ib} + Wtot_{bk} + Wbranch)$

$AGB_{Reduce} = 472.213035377375/(288.243400288234 + 52.945466015848 + 135.001927997271) = 0.991646711840$

$AGB_{Predicted}red = AGB_{Predicted} \times AGB_{Reduce}$

$AGB_{Predicted}red = 532.584798820042 \times 0.991646711840 = 528.135964525863$

$AGB_{Diff} = AGB_{Predicted}red - AGB_{Component}red$

$AGB_{Diff} = 528.135964525863 - 472.213035377375 = 55.922929148488$

Next, proportionally distribute AGB_{Diff} across the components:

$Wood_{Harmonized} = AGB_{Predicted}red \times (Wtot_{ib}red/AGB_{Component}red)$

$Wood_{Harmonized} = 528.135964525863 \times (284.265641364256/472.213035377375) = 317.930462388645$

$Bark_{Harmonized} = AGB_{Predicted}red \times (Wtot_{bk}red/AGB_{Component}red)$

$Bark_{Harmonized} = 528.135964525863 \times (52.945466015848/472.213035377375) = 59.215656211618$

$Branch_{Harmonized} = AGB_{Predicted}red \times (Wbranchred/AGB_{Component}red)$
$Branch_{Harmonized} = 528.135964525863 \times (135.001927997271/472.213035377375)$
$= 150.989845925600$

Foliage weight can be estimated using the foliage weight coefficient table (table S9), which prescribes the use of model 1 with the appropriate coefficients:

$Wfoliage = a \times D^b \times H^c$

$Wfoliage = 0.850316556558 \times 11.1^{1.998961809584} \times 38^{-0.418446486365} = 22.807960563788$

Reductions to foliage weight are only considered for live trees having a broken top. As no broken top is present in the current example, *Wfoliagered = Wfoliage*.

At this point, calculate a new adjusted wood density using the harmonized total stem wood weight and the predicted total stem wood volume. As noted in the previous example, it is important that the volume basis used here does not include any cull deduction but does account for missing wood and bark. Thus, $Vtot_{ib}Gross$ and $Vtot_{bk}Gross$ again provide the appropriate volume bases:

$WDSG_{Adj} = Wood_{Harmonized}/ Vtot_{ib}Gross /62.4$
$WDSG_{Adj} = 317.930462388645/9.427112777611/62.4 = 0.540466586276$

Similarly, calculate an adjusted bark density using the harmonized total stem bark weight and the predicted total stem bark volume:

$BKSG_{Adj} = Bark_{Harmonized}/Vtot_{bk}Gross/62.4$
$BKSG_{Adj} = 59.215656211618/2.155106401987/62.4 = 0.440335033421$

Merchantable stem wood and bark weights can be determined as follows:

$Wmer_{ib} = Vtot_{ib}Gross \times (R_m - R_1) \times WDSG_{Adj} \times 62.4$
$Wmer_{ib} = 9.427112777611 \times (0.970485778632 - 0.091117585499) \times 0.540466586276 \times 62.4 = 279.577936252521$

$Wmer_{bk} = Vmer_{bk}Gross \times BKSG_{Adj} \times 62.4$
$Wmer_{bk} = 1.895132022724 \times 0.440335033421 \times 62.4 = 52.072364607955$

Merchantable stem outside bark weight is then calculated via addition:

$Wmer_{ob} = Wmer_{ib} + Wmer_{bk}$

$Wmer_{ob} = 279.577936252521 + 52.072364607955 = 331.650300860476$

Similarly, stump weights are calculated as follows:

$Wstump_{ib} = Vstump_{ib}Gross \times WDSG_{Adj} \times 62.4$

$Wstump_{ib} = 0.858975754526 \times 0.540466586276 \times 62.4 = 28.969056089533$

$Wstump_{bk} = Vstump_{bk}Gross \times BKSG_{Adj} \times 62.4$

$Wstump_{bk} = 0.196368091843 \times 0.440335033421 \times 62.4 = 5.395587617753$

$Wstump_{ob} = Wstump_{ib} + Wstump_{bk}$

$Wstump_{ob} = 28.969056089533 + 5.395587617753 = 34.364643707286$

The component DRYBIO_TOP (dry biomass in the top and branches of the tree) is the sum of the branches and the nonmerchantable top:

$DRYBIO\_TOP = AGB_{Predicted}red - Wmer_{ob} - Wstump_{ob}$

$DRYBIO\_TOP = 528.135964525863 - 331.650300860476 - 34.364643707286 = 162.121019958101$

The carbon content (*C*) of the tree is obtained via multiplication by the appropriate C fraction for *SPCD* = 316 (table S10):

$C = AGB_{predicted}red \times CF$

$C = 528.135964525863 \times 0.485733333333 = 256.533242502186$

Example 3

Assume the following measurements were taken for a dead (*DECAYCD* = 2) tanoak (*SPCD* = 631) tree having *D* = 11.3 inch, *H* = 28 feet, and a broken top (actual height *AH* = 21 feet) with *CULL* = 10 percent growing in the Marine Division - Mountain (*DIVISION* = 240).

The first step is to predict total stem wood volume using the inside-bark wood volume coefficient table (table S1). There are no coefficients for the *SPCD/DIVISION* combination of 631/210 nor any species-level coefficients. Therefore, the appropriate

Jenkins Group (*JENKINS_SPGRPCD*) coefficients are to be used. Tanoak is in the Other hardwoods group (*JENKINS_SPGRPCD* = 8 as shown in the REF_SPECIES table). Use model 1 with the appropriate coefficients:

$$Vtot_{ib}Gross = a \times D^{b} \times H^{c}$$

$$Vtot_{ib}Gross = 0.002340041369 \times 11.3^{1.89458735401} \times 28^{1.035094060155} = 7.283117547652$$

Total bark volume is predicted by consulting the bark volume coefficient table (table S2), which indicates the use of model 1 with the appropriate coefficients:

$$Vtot_{bk}Gross = a \times D^{b} \times H^{c}$$

$$Vtot_{bk}Gross = 0.001879520673 \times 11.3^{1.721074101914} \times 28^{0.825002196089} = 1.907136145131$$

Outside bark volume is then calculated via addition:

$$Vtot_{ob}Gross = Vtot_{ib}Gross + Vtot_{bk}Gross$$

$$Vtot_{ob}Gross = 7.283117547652 + 1.907136145131 = 9.190253692783$$

Merchantable and sawlog stem volumes are calculated next by minimizing equation 7 to estimate the height to any top diameter. For the merchantable height to a 4.0-inch top (h_m), insert the correct coefficients from tables S3 and S4 to produce the following:

$$|4 - (0.00334258499 \times 11.3^{1.861924531448} \times 28^{1.015964521941} / 0.005454154 / 28 \times 2.317280548447 \times 0.846218848701 \times (1 - h_m/28)^{(2.317280548447-1)} \times (1 - (1 - h_m/28)^{2.317280548447})^{(0.846218848701-1)})^{0.5}|$$

Iterative minimization results in $h_m = 21.790361419761$. To determine merchantable volume, use model 6 and the coefficients from the inside-bark volume ratio table (table S5) to find the proportion of total stem volume to the 1-foot stump and the 4.0-inch top diameter height:

$$R_1 = (1 - (1 - h_1/H)^{\alpha})^{\beta}$$

$$R_1 = (1 - (1 - 1/28)^{2.353772358051})^{0.831640004254} = 0.124985332188$$

$$R_m = (1 - (1 - h_m/H)^{\alpha})^{\beta}$$

$$R_m = (1 - (1 - 21.790361419761/28)^{2.353772358051})^{0.831640004254} = 0.975933190572$$

Then, multiply the ratios by the already estimated total inside-bark stem wood volume and subtract:

$$Vmer_{ib}Gross = (R_m \times Vtot_{ib}Gross) - (R_1 \times Vtot_{ib}Gross)$$

$$Vmer_{ib}Gross = (0.975933190572 \times 7.283117547652) - (0.124985332188 \times 7.283117547652) = 6.197553279533$$

The same procedure can be used to estimate the merchantable outside-bark volume:

$$Vmer_{ob}Gross = (R_m \times Vtot_{ob}Gross) - (R_1 \times Vtot_{ob}Gross)$$

$$Vmer_{ob}Gross = (0.975933190572 \times 9.190253692783) - (0.124985332188 \times 9.190253692783) = 7.820426697879$$

Merchantable stem bark volume is then calculated via subtraction:

$$Vmer_{bk}Gross = Vmer_{ob}Gross - Vmer_{ib}Gross$$

$$Vmer_{bk}Gross = 7.820426697879 - 6.197553279533 = 1.622873418346$$

Calculation of cubic-foot volume in the sawlog portion of the stem (1-foot stump height to 7.0-inch top diameter for softwoods (*SPCD* <300; *D* ≥9.0 inches) or 9.0-inch top diameter for hardwoods (*SPCD* ≥300; *D* ≥11.0 inches)) proceeds similarly, with calculation of the sawlog height (h_s) being obtained from minimization the following:

$$|9 - (0.00334258499 \times 11.3^{1.861924531448} \times 28^{1.015964521941}/0.005454154/28 \times 2.317280548447 \times 0.846218848701 \times (1 - h_s/28)^{(2.317280548447-1)} \times (1 - (1 - h_s/28)^{2.317280548447})^{(0.846218848701-1)})^{0.5}|$$

Iterative minimization results in $h_s = 8.10427459853$. To determine sawlog volume, use model 6 and the coefficients from the inside-bark volume ratio table (table S5) to find the proportion of total stem volume for both the 1-foot stump height and the 9 inch top diameter height (R_s):

$$R_1 = (1 - (1 - h_1/H)^{\alpha})^{\beta}$$

$$R_1 = (1 - (1 - 1/28)^{2.353772358051})^{0.831640004254} = 0.124985332188$$

$R_s = (1 - (1 - h_s/H)^{\alpha})^{\beta}$
$R_s = (1 - (1 - 8.10427459853/28)^{2.353772358051})^{0.831640004254} = 0.610622756652$

Then, multiply the ratios by the already estimated total inside-bark stem wood volume and subtract:

$Vsaw_{ib}Gross = (R_s \times Vtot_{ib}Gross) - (R_1 \times Vtot_{ib}Gross)$
$Vsaw_{ib}Gross = (0.610622756652 \times 7.283117547652) - (0.124985332188 \times 7.283117547652) = 3.536954447910$

The same procedure can be used to estimate the sawlog outside-bark volume:

$Vsaw_{ob}Gross = (R_s \times Vtot_{ob}Gross) - (R_1 \times Vtot_{ob}Gross)$
$Vsaw_{ob}Gross = (0.610622756652 \times 9.190253692783) - (0.124985332188 \times 9.190253692783) = 4.463131133534$

Sawlog stem bark volume is then calculated via subtraction:

$Vsaw_{bk}Gross = Vsaw_{ob}Gross - Vsaw_{ib}Gross$
$Vsaw_{bk}Gross = 4.463131133534 - 3.536954447910 = 0.926176685624$

Stump volumes are estimated using the same volume ratio approach as previously used:

$Vstump_{ob}Gross = (R_1 \times Vtot_{ob}Gross)$
$Vstump_{ob}Gross = (0.124985332188 \times 9.190253692783) = 1.148646910689$
$Vstump_{ib}Gross = (R_1 \times Vtot_{ib}Gross)$
$Vstump_{ib}Gross = (0.124985332188 \times 7.283117547652) = 0.910282866061$
$Vstump_{bk}Gross = V\,stump_{ob}Gross - V\,stump_{ib}Gross$
$Vstump_{bk}Gross = 1.148646910689 - 0.910282866061 = 0.238364044628$

At this point, calculations are needed to account for the broken top. The broken top at AH = 21 feet occurs at a height below the calculated 4.0-inch top diameter height (h_m = 21.790361419761); therefore, no stem top wood component is present and the volume of the merchantable stem needs to be reduced. Any cull that might be present is also considered (*CULL* = 10 percent in this example) to obtain sound wood volume. Initially, the volume of the merchantable stem is adjusted by recalculating R_m based on *AH*:

$R_m = (1 - (1 - 21/28)^{2.353772358051})^{0.831640004254} = 0.968066877159$

$Vmer_{ib}Sound = ((R_m \times Vtot_{ib}Gross) - (R_1 \times Vtot_{ib}Gross)) \times (1 - CULL/100)$

$Vmer_{ib}Sound = ((0.968066877159 \times 7.283117547652) - (0.124985332188 \times 7.283117547652)) \times (1 - 10/100) = 5.526235794852$

Similarly estimate the remaining merchantable component bark volume:

$Vmer_{bk}Sound = ((R_m \times Vtot_{bk}Gross) - (R_1 \times Vtot_{bk}Gross))$

$Vmer_{bk}Sound = (0.968066877159 \times 1.907136145131) - (0.124985332188 \times 1.907136145131) = 1.607871287707$

Merchantable stem sound volume outside bark arises via addition:

$Vmer_{ob}Sound = Vmer_{ib}Sound + Vmer_{bk}Sound$

$Vmer_{ob}Sound = 5.526235794852 + 1.607871287707 = 7.134107082559$

Calculations for stump wood volumes are unaffected by the broken top, but any cull present affects the amount of sound stump wood:

$Vstump_{ib}Sound = Vstump_{ib}Gross \times (1 - CULL/100)$

$Vstump_{ib}Sound = 0.910282866061 \times (1 - 10/100) = 0.819254579455$

Because bark is unaffected by wood cull, it is not included in the following calculation:

$Vstump_{ob}Sound = Vstump_{ib}Sound + Vstump_{bk}Gross$

$Vstump_{ob}Sound = 0.819254579455 + 0.238364044628 = 1.057618624083$

Now the total sound wood inside and outside bark volumes can be obtained, in this case, by summing the stem components present (no top wood):

$Vtot_{ob}Sound = Vmer_{ob}Sound + Vstump_{ob}Sound$

$Vtot_{ob}Sound = 7.134107082559 + 1.057618624083 = 8.191725706642$

$Vtot_{ib}Sound = Vmer_{ib}Sound + Vstump_{ib}Sound$
$Vtot_{ib}Sound = 5.526235794852 + 0.819254579455 = 6.345490374317$

$Vtot_{bk}Sound = Vtot_{ob}Sound - Vtot_{ib}Sound$
$Vtot_{bk}Sound = 8.191725706642 - 6.345490374317 = 1.846235332335$

Stem-top volumes are calculated by subtracting the other stem volume subcomponents. Due to the broken top height being below the height to a 4.0-inch top diameter, the stem-top wood and bark volumes are zero:

$Vtop_{ob}Sound = Vtot_{ob}Sound - Vmer_{ob}Sound - Vstump_{ob}Sound$

$Vtop_{ob}Sound = 8.191725706642 - 7.134107082559 - 1.057618624083 = 0.000000000000$

$Vtop_{ib}Sound = Vtot_{ib}Sound - Vmer_{ib}Sound - Vstump_{ib}Sound$

$Vtop_{ib}Sound = 6.345490374317 - 5.526235794852 - 0.819254579455 = 0.000000000000$

$Vtop_{bk} = Vtop_{ob}Sound - Vtop_{ib}Sound$

$Vtop_{bk} = 0.000000000000 - 0.000000000000 = 0.000000000000$

Total stem wood volume is next converted to total stem wood dry weight (lb) using the correct *WDSG* value from the FIA REF_SPECIES table and the water weight conversion factor (62.4 lb/ft^3):

$Wtot_{ib} = Vtot_{ib}Gross \times WDSG \times 62.4$
$Wtot_{ib} = 7.283117547652 \times 0.58 \times 62.4 = 263.590590284621$

A second calculation accounts for the broken top and the dead tree density reduction (table 1) associated with *DECAYCD* = 2 for this tree. While the inside-bark weight includes the weight loss for wood cull (*CULL*) in live trees, cull weight is not included for dead trees as it is considered to be already accounted for by the density reduction:

$Wtot_{ib}red = Vtot_{ib}Sound/(1 - CULL/100) \times WDSG * DensProp \times 62.4$
$Wtot_{ib}red = 6.345490374317/(1 - 10/100) \times 0.58 \times 0.8 \times 62.4 = 204.13865566837$

Total stem bark weight can be estimated by consulting the stem bark weight coefficient table (table S6), which indicates the use of model 1 with the appropriate coefficients. Also, calculate the value for the proportion of the stem remaining (via R_m

in this case) while incorporating a density reduction factor for dead trees and the remaining bark proportion (*BarkProp*) (table 1):

$$Wtot_{bk} = a \times D^{b} \times H^{c}$$

$$Wtot_{bk} = (0.06020544773 \times 11.3^{1.933727566198} \times 28^{0.590397069325}) = 46.816664266025$$

$$Wtot_{bk}red = (a \times D^{b} \times H^{c}) \times R_{m} \times DensProp \times BarkProp$$

$$Wtot_{bk}red = (0.06020544773 \times 11.3^{1.933727566198} \times 28^{0.590397069325}) \times 0.968066877159 \times 0.8 \times 0.8 = 29.005863664008$$

Consulting the branch weight coefficient table (table S7), use model 5 with the appropriate coefficients and *WDSG* value to estimate total branch weight. Subsequently, also use table 1 to account for the remaining dead tree branch proportion (*BranchProp*), dead tree wood density reduction (*DensProp*), and branches remaining due to the broken top (*BranchRem*). The latter adjustment requires consulting the crown ratio table (table S11) to assume the proportion of the stem having branch wood, which indicates the expected crown ratio calculated from live trees by hardwood/softwood species designation and *DIVISION*.

$$Wbranch = a \times D^{b} \times H^{c} \times WDSG$$

$$Wbranch = 0.798604849948 \times 11.3^{2.969162133333} \times 28^{-0.301902411279} \times 0.58 = 226.788002348975$$

$$BranchRem = (AH - H \times (1 - CR))/(H \times CR)$$

$$BranchRem = (21 - 28 \times (1 - 0.378))/(28 \times 0.378) = 0.338624338624$$

$$Wbranchred = a \times D^{b} \times H^{c} \times WDSG \times DensProp \times BranchProp \times BranchRem$$

$$Wbranchred = 0.798604849948 \times 11.3^{2.969162133333} \times 28^{-0.301902411279} \times 0.58 \times 0.8 \times 0.5 \times 0.338624338624 = 30.718374921312$$

Total aboveground biomass can be estimated by consulting the total biomass coefficient table (table S8), which specifies the use of model 5 with the appropriate coefficients. Again, as Jenkins group coefficients are being used, multiplication by specific gravity (*WDSG*) is required:

$$AGB_{Predicted} = a \times D^{b} \times H^{c} \times WDSG$$

$AGB_{Predicted} = 0.433906440864 \times 11.3^{2.115626101921} \times 28^{0.735074517922} \times 0.58 =$
492.621457718427

Next, the three independently estimated components (stem wood weight, stem bark weight, and branch weight) need to be harmonized with the predicted total aboveground biomass. First, estimate a reduced total aboveground biomass based on the reduced component weights:

$AGB_{Component}red = Wtot_{ib}red + Wtot_{bk}red + Wbranchred$
$AGB_{Component}red = 204.13865566837 + 29.005863664008 + 30.718374921312 =$
263.862894253690

Subsequently, $AGB_{Predicted}$ needs to be reduced to account for component rot and loss by calculating a reduction factor:

$AGB_{Reduce} = AGB_{Component}red / (Wtot_{ib} + Wtot_{bk} + Wbranch)$

$AGB_{Reduce} = 263.862894253690/(263.590590284621 + 46.816664266025 +$
$226.788002348975) = 0.491186195084$

$AGB_{Predicted}red = AGB_{Predicted} \times AGB_{Reduce}$

$AGB_{Predicted}red = 492.621457718427 \times 0.491186195084 = 241.968859433448$

$AGB_{Diff} = AGB_{Predicted}red - AGB_{Component}red$

$AGB_{Diff} = 241.968859433448 - 263.862894253690 = -21.894034820242$

Next, proportionally distribute AGB_{Diff} across the components:

$Wood_{Harmonized} = AGB_{Predicted}red \times (Wtot_{ib}red / AGB_{Component}red)$
$Wood_{Harmonized} = 241.968859433448 \times (204.13865566837/263.862894253690) =$
187.200242072923

$Bark_{Harmonized} = AGB_{Predicted}red \times (Wtot_{bk}red / AGB_{Component}red)$
$Bark_{Harmonized} = 241.968859433448 \times$
$(29.005863664008/263.862894253690) = 26.599100898644$

$Branch_{Harmonized} = AGB_{Predicted}red \times (Wbranchred / AGB_{Component}red)$

$Branch_{Harmonized} = 241.968859433448 \times (30.718374921312/263.862894253690) = 28.169516461881$

In the case of dead trees, foliage weight is assumed to be zero:

$Wfoliage = 0$

Finally, calculate a new adjusted wood density using the harmonized total stem wood weight and the total sound inside-bark stem wood volume. Although $Vtot_{ib}Gross$ and $Vtot_{bk}Gross$ provided the correct bases in previous examples, their use here is inappropriate as reductions incurred by the broken top are not accounted for. Also, any reductions due to *CULL* >0 need to be excluded. Thus, this example represents a special case of a broken top tree with *CULL* = 0, such that $Vtot_{ib}Sound$ and $Vtot_{bk}Sound$ are the appropriate volumes to use in the calculations:

$WDSG_{Adj} = Wood_{Harmonized}/Vtot_{ib}Sound/62.4$

$WDSG_{Adj} = 187.200242072923/7.050544860341/62.4 = 0.425499580359$

Similarly, calculate an adjusted bark density using the harmonized total stem bark weight and the predicted total stem bark volume:

$BKSG_{Adj} = Bark_{Harmonized}/Vtot_{bk}Sound/62.4$

$BKSG_{Adj} = 26.599100898644/(8.896780192676 - 7.050544860341)/62.4 = 0.230884782206$

Merchantable stem wood and bark weights can be determined as follows:

$Wmer_{ib} = (Vtot_{ib}Sound - Vstump_{ib}Sound - Vtop_{ib}Sound) \times WDSG_{Adj} \times 62.4$

$Wmer_{ib} = (7.050544860341 - 0.910282866061 - 0.000000000000) \times 0.425499580359 \times 62.4 = 163.031163476092$

$Wmer_{bk} = (Vtot_{bk}Sound - Vstump_{bk}Sound - Vtop_{bk}Sound) \times BKSG_{Adj} \times 62.4$

$Wmer_{bk} = (1.846235332335 - 0.238364044628 - 0.000000000000) \times 0.230884782206 \times 62.4 = 23.164939953637$

Merchantable stem outside-bark weight is then calculated via addition:

$Wmer_{ob} = Wmer_{ib} + Wmer_{bk}$

$Wmer_{ob} = 163.031163476092 + 23.164939953637 = 186.196103429729$

Similarly, stump weights are calculated:

$Wstump_{ib} = Vstump_{ib}Sound \times WDSG_{Adj} \times 62.4$

$Wstump_{ib} = 0.910282866061 \times 0.425499580359 \times 62.4 = 24.169078597057$

$Wstump_{bk} = Vstump_{bk}Sound \times BKSG_{Adj} \times 62.4$

$Wstump_{bk} = 0.238364044628 \times 0.230884782206 \times 62.4 = 3.434160945052$

$Wstump_{ob} = Wstump_{ib} + Wstump_{bk}$

$Wstump_{ob} = 24.169078597057 + 3.434160945052 = 27.603239542109$

The component DRYBIO_TOP (dry biomass in the top and limbs of the tree) is calculated as follows:

$DRYBIO\_TOP = AGB_{Predicted}red - Wmer_{ob} - Wstump_{ob}$

$DRYBIO\_TOP = 241.968859433448 - 186.196103429729 - 27.603239542109 = 28.169516461610$

The carbon content (*C*) of the dead tree is obtained via multiplication by the appropriate *C* fraction for a hardwood species (tanoak, *SPCD* = 631) with *DECAYCD* = 2 (table S10):

$C = AGB_{predicted}red \times CF$

$C = 241.968859433448 \times 0.473000000000 = 114.451270512021$

Example 4

Assume the following measurements were taken for a live white oak (*SPCD* = 802) tree having *D* = 18.1 inch, *H* = 65 feet, a broken top (actual height (*AH*) = 59 foot), *CULL* = 2 percent, and a crown ratio of 30 percent (*CR* = 30) growing in the Hot Continental Regime - Mountain (*DIVISION* = M220):

The first step is to predict total inside-bark stem wood volume by consulting the inside-bark wood volume coefficient table (table S1). There are coefficients given for the *SPCD/DIVISION* combination of 802/M220 along with the specification to use model 1:

$$Vtot_{ib}Gross = a \times D^{b} \times H^{c}$$

$$Vtot_{ib}Gross = 0.002062931814 \times 18.1^{1.852527628718} \times 65^{1.09312644716} = 42.277832913225$$

Total bark volume is accomplished by consulting the bark volume coefficient table (table S2), which indicates the use of model 2 with the appropriate coefficients:

$$Vtot_{bk}Gross = a_0 \times k^{(b0-b1)} \times D^{b_1} \times H^{c}$$

$$Vtot_{bk}Gross = 0.002020025979 \times 11^{(1.957775262905-1.618455676343)} \times 18.1^{1.618455676343} \times 65^{0.677400740385} = 8.361568823386$$

Total outside-bark volume is then calculated via addition:

$$Vtot_{ob}Gross = Vtot_{ib}Gross + Vtot_{bk}Gross$$

$$Vtot_{ob}Gross = 42.277832913225 + 8.361568823386 = 50.639401736611$$

Merchantable and sawlog stem volumes are calculated using equation 7 that can be minimized to estimate the height to any top diameter. For the height to a 4.0-inch top diameter (h_m), inserting the correct coefficients from tables S3 and S4 produces the following:

$$|4 - (0.003504073654 \times 18.1^{1.821357964958} \times 65^{1.031766698583} / 0.005454154 / 65 \times 2.413673220682 \times 0.851093936311 \times (1 - h_m/65)^{(2.413673220682-1)} \times (1 - (1 - h_m/65)^{2.413673220682})^{(0.851093936311-1)})^{0.5}|$$

Iterative minimization results in $h_m = 56.72042843$. The broken top actual height (*AH*) of 59 feet is greater than the predicted h_m for an intact top, so the merchantable top height is unaffected (see example 3 for $AH < h_m$). To determine merchantable volume, use model 6 and the coefficients from the inside-bark volume ratio table (table S5) to find the proportion of total stem volume for both the 1-foot stump height and the 4.0-inch top diameter height:

$$R_1 = (1 - (1 - h_1/H)^{\alpha})^{\beta}$$

$$R_1 = (1 - (1 - 1/65)^{2.466800456074})^{0.842271677308} = 0.062976290396$$

$$R_m = (1 - (1 - h_m/H)^{\alpha})^{\beta}$$

$$R_m = (1 - (1 - 56.72042843/65)^{2.466800456074})^{0.842271677308} = 0.994774693648$$

where h_1 is stump height (1 foot), h_m is the merchantable height, R_1 is the proportion of volume to 1 foot and R_m is the proportion of volume to the merchantable height.

Then, multiply the ratios by the already estimated total stem wood volume and subtract:

$$Vmer_{ib}Gross = (R_m \times Vtot_{ib}Gross) - (R_1 \times Vtot_{ib}Gross)$$

$$Vmer_{ib}Gross = (0.994774693648 \times 42.277832913225) - (0.062976290396 \times 42.277832913225) = 39.394417201498$$

The same procedure can be used to estimate the merchantable outside-bark volume:

$$Vmer_{ob}Gross = (R_m \times Vtot_{ob}Gross) - (R_1 \times Vtot_{ob}Gross)$$

$$Vmer_{ob}Gross = (0.994774693648 \times 50.639401736611) - (0.062976290396 \times 50.639401736611) = 47.185713679811$$

Merchantable stem bark volume is then calculated via subtraction:

$$Vmer_{bk}Gross = Vmer_{ob}Gross - Vmer_{ib}Gross$$

$$Vmer_{bk}Gross = 47.185713679811 - 39.394417201498 = 7.791296478313$$

Calculating cubic-foot volume in the sawlog portion of the stem (1-foot stump height to 7 inch top diameter for softwoods (*SPCD* <300) and 9 inch top diameter for hardwoods (*SPCD* ≥300)) proceeds similarly, with the sawlog height (h_s) being obtained from the following:

$$|9 - (0.003504073654 \times 18.1^{1.821357964958} \times 65^{1.031766698583}/0.005454154/65 \times 2.413673220682 \times 0.851093936311 \times (1 - h_s/65)^{(2.413673220682 - 1)} \times (1 - (1 - h_s/65)^{2.413673220682})^{(0.851093936311 - 1)})^{0.5}|$$

Iterative minimization results in $h_s = 39.214128405$. The broken top actual height of 59 feet is greater than the predicted h_s for an intact top, so the sawlog top height is unaffected. To determine merchantable volume, use model 6 and the coefficients from the inside-bark volume ratio table (table S5) to find the proportion of total stem volume for both the 1-foot stump height and the 9.0-inch top diameter height (R_s):

$$R_1 = (1 - (1 - h_1/H)^{\alpha})^{\beta}$$

$R_1 = (1 - (1 - 1/65)^{2.466800456074})^{0.842271677308} = 0.062976290396$

$R_s = (1 - (1 - h_s/H)^{\alpha})^{\beta}$
$R_s = (1 - (1 - 39.214128405/65)^{2.466800456074})^{0.842271677308} = 0.913186793241$

where h_1 is stump height (1 foot), h_s is the merchantable height, R_1 is the proportion of volume to 1 foot, and R_s is the proportion of volume to the sawlog height.

Then, multiply the ratios by the already estimated total stem wood volume and subtract:

$Vsaw_{ib}Gross = (R_s \times Vtot_{ib}Gross) - (R_1 \times Vtot_{ib}Gross)$

$Vsaw_{ib}Gross = (0.913186793241 \times 42.277832913225) - (0.062976290396 \times 42.277832913225) = 35.945057580350$

The same procedure can be used to estimate the sawlog outside-bark volume:

$Vsaw_{ob}Gross = (R_s \times Vtot_{ob}Gross) - (R_1 \times Vtot_{ob}Gross)$

$Vsaw_{ob}Gross = (0.913186793241 \times 50.639401736611) - (0.062976290396 \times 50.639401736611) = 43.054151214254$

Sawlog stem bark volume is then calculated via subtraction:

$Vsaw_{bk}Gross = Vsaw_{ob}Gross - Vsaw_{ib}Gross$

$Vsaw_{bk}Gross = 43.054151214254 - 35.945057580350 = 7.109093633904$

Stump volumes are estimated using the same volume ratio approach as used previously:

$Vstump_{ob}Gross = (R_1 \times Vtot_{ob}Gross)$

$Vstump_{ob}Gross = (0.062976290396 \times 50.639401736611) = 3.189081669245$

$Vstump_{ib}Gross = (R_1 \times Vtot_{ib}Gross)$

$Vstump_{ib}Gross = (0.062976290396 \times 42.277832913225) = 2.662501082857$

$Vstump_{bk}Gross = Vstump_{ob}Gross - Vstump_{ib}Gross$

$Vstump_{bk}Gross = 3.189081669245 - 2.662501082857 = 0.526580586388$

Typically, stem-top volumes are calculated by subtracting the other stem volume subcomponents from the total stem volume:

$Vtop_{ob}Gross = Vtot_{ob}Gross - Vmer_{ob}Gross - Vstump_{ob}Gross$

$Vtop_{ob}Gross$ = 50.639401736611 - 47.185713679811 - 3.189081669245 = 0.264606387555

$Vtop_{ib}Gross = Vtot_{ib}Gross - Vmer_{ib}Gross - Vstump_{ib}Gross$

$Vtop_{ib}Gross$ = 42.277832913225 - 39.394417201498 - 2.662501082857 = 0.220914628870

$Vtop_{bk}Gross = Vtop_{ob}Gross - Vtop_{ib}Gross$

$Vtop_{bk}Gross$ = 0.264606387555 - 0.220914628870 = 0.043691758685

In this case, the stem-top volume must account for the broken top height (AH = 59). Thus, determination of the missing top volume requires a ratio calculation to obtain the proportion of remaining stem volume R_b:

$R_b = (1 - (1 - AH/H)^{\alpha})^{\beta}$

$R_b = (1 - (1 - 59/65)^{2.466800456074})^{0.842271677308} = 0.997639540140$

Thus, the missing volume amount is calculated as follows:

$Vmiss_{ob}Gross = Vtot_{ob}Gross \times (1 – R_b)$

$Vmiss_{ob}Gross$ = 50.639401736611 × (1 - 0.997639540140) = 0.119532275134

$Vmiss_{ib}Gross = Vtot_{ib}Gross \times (1 – R_b)$

$Vmiss_{ib}Gross$ = 42.277832913225× (1- 0.997639540140) = 0.099795127559

$Vmiss_{bk}Gross = Vmiss_{ob}Gross - Vmiss_{ib}Gross$

$Vmiss_{bk}Gross$ = 0.119532275134 - 0.099795127559 = 0.019737147575

Volumes of the remaining top wood (including the cull deduction) and bark are now defined as follows:

$Vtop_{ib}Sound = (Vtot_{ib}Gross - Vmer_{ib}Gross - Vstump_{ib}Gross – Vmiss_{ib}Gross) \times (1 – CULL/100)$

$Vtop_{ib}Sound = (42.277832913225 - 39.394415319923 - 2.662501082857 - 0.099795127559) \times (1 - 2/100) = 0.118698955228$

$Vtop_{ob}Sound = Vtop_{ib}Sound + Vtot_{bk}Gross \times (1 - R_m) - Vmiss_{bk}Gross$

$Vtop_{ob}Sound = 0.118698955228 + 8.361568823386 \times (1 - 0.994774693648) - 0.019737147575 = 0.142653566339$

$Vtop_{bk}Sound = Vtop_{ob}Sound - Vtop_{ib}Sound$

$Vtop_{bk}Sound = 0.142653566339 - 0.118698955228 = 0.023954611111$

As shown above, AH = 59 occurs at a height above the 4.0-inch top diameter; therefore, sound volumes for the stump and merchantable stem only require deduction of cull:

$Vmer_{ib}Sound = Vmer_{ib}Gross \times (1 - CULL/100)$

$Vmer_{ib}Sound = 39.394417201498 \times (1 - 2/100) = 38.606528857468$

$Vstump_{ib}Sound = Vstump_{ib}Gross \times (1 - CULL/100)$

$Vstump_{ib}Sound = 2.662501082857 \times (1 - 2/100) = 2.609251061200$

Sound stem wood volume needed to account for the broken top and cull can be calculated as follows:

$Vtot_{ib}Sound = (Vmer_{ib}Sound + Vstump_{ib}Sound + Vtop_{ib}Sound)$

$Vtot_{ib}Sound = (38.606528857468 + 2.609251061200 + 0.118698955228) = 41.334478873896$

Other sound stem components are also calculated:

$Vtot_{ob}Sound = Vtot_{ib}Sound + Vtot_{bk}Gross - Vmiss_{bk}Gross$

$Vtot_{ob}Sound = 41.334478873896 + 8.361568823386 - 0.019737147575 = 49.676310549707$

$Vtot_{bk}Sound = Vtot_{ob}Sound - Vtot_{ib}Sound$

$Vtot_{bk}Sound = 49.676310549707 - 41.334478873896 = 8.341831675811$

Total stem wood volume is next converted to total stem wood dry weight using the wood density value from the REF_SPECIES table. It is considered that some cull will be rotten wood, which would still contribute to the stem weight. As such, it is assumed the density of cull wood is reduced by the proportion for *DECAYCD* = 3 (table 1; *DensProp* = 0.54 for hardwood species, 0.92 for softwood species) as reported by Harmon et al. (2011) to obtain the reduced weight due to cull. The weight is also reduced to account for missing top wood:

$$Wtot_{ib} = Vtot_{ib}Gross \times WDSG \times 62.4$$

$$Wtot_{ib} = 42.277832913225 \times 0.60 \times 62.4 = 1582.882064271140$$

$$Wtot_{ib}red = (Vtot_{ib}Gross - Vmiss_{ib}Gross) \times (1 - CULL/100 \times (1 - DensProp)) \times WDSG \times 62.4$$

$$Wtot_{ib}red = (42.277832913225 - 0.099795127559) \times (1 - 2/100 \times (1 - 0.54)) \times 0.60 \times 62.4 = 1564.617593936140$$

Next, total stem bark weight can be estimated by consulting the stem bark weight coefficient table (table S6), which specifies to use model 2 with the appropriate coefficients. Also, calculate the value for the proportion of the stem remaining (via R_b in this case):

$$Wtot_{bk} = a_0 \times k^{(b0-b1)} \times D^{b1} \times H^{c}$$

$$Wtot_{bk} = 0.013653815808 \times 11^{(2.255437355705 - 1.777569692133)} \times 18.1^{1.777569692133} \times 65^{0.830992810735} = 237.154413924445$$

$$Wtot_{bk}red = (a_0 \times k^{(b0-b1)} \times D^{b1} \times H^{c}) \times R_b$$

$$Wtot_{bk}red = (0.013653815808 \times 11^{(2.255437355705 - 1.777569692133)} \times 18.1^{1.777569692133} \times 65^{0.830992810735}) \times 0.997639540140 = 236.594620449755$$

Consulting the branch weight coefficient table (table S7), use model 1 with the appropriate coefficients to estimate total branch weight. Additionally, account for the branches remaining due to the broken top (*BranchRem*). The latter adjustment requires use of the observed crown ratio (*CR* = 30 percent) based on *AH* to standardize the *CR* value to *H* (CR_H) and then assess the proportion of the branch wood still intact:

$$Wbranch = a \times D^{b} \times H^{c}$$

$$Wbranch = 0.003795934624 \times 18.1^{2.337549205679} \times 65^{1.30586951288} = 770.251512414918$$

$$CR_H = (H - AH \times (1 - CR))/H$$

$CR_H = (65 - 59\times (1 - .30))/65 = 0.364615384615$

$BranchRem = (\mathrm{AH} - \mathrm{H}\times (1 - CR_H))/(\mathrm{H} \times CR_H)$
$BranchRem = (59 - 65\times (1 - 0.364615384615))/(65 \times 0.364615384615) = 0.746835443038$

$Wbranchred = a \times D^b \times H^c \times BranchRem$
$Wbranchred = 0.003795934624 \times 18.1^{2.337549205679}\times 65^{1.30586951288}\times 0.746835443038 = 575.250923828242$

Now, total aboveground biomass can be estimated by consulting the total biomass coefficient table (table S8), which indicates the use of model 2 with the appropriate coefficients:

$AGB_{Predicted} = a_0 \times k^{(b0-b1)} \times D^{b1} \times H^c$

$AGB_{Predicted} = 0.024470323124 \times 11^{(1.93799905037- 1.886819489967)} \times 18.1^{1.886819489967}\times 65^{1.403264431619} = 2285.319903933610$

Next, the three independently estimated components (stem wood weight, stem bark weight, and branch weight) need to be harmonized with the predicted total aboveground biomass. First, estimate a second total aboveground biomass by summing the three components:

$AGB_{Component}red = Wtot_{ib}red + Wtot_{bk}red + Wbranchred$
$AGB_{Component}red = 1564.617593936140 + 236.594620449755 + 575.250923828242 = 2376.463138214140$

Subsequently, $AGB_{Predicted}$ needs to be reduced to account for component rot and loss by calculating a reduction factor:

$AGB_{Reduce} = AGB_{Component}red/ (Wtot_{ib} + Wtot_{bk} +Wbranch)$

$AGB_{Reduce} = 2376.463138214140/(1582.882064271140 + 237.154413924445 + 770.251512414918) = 0.917451320791$

$AGB_{Predicted}red = AGB_{Predicted} \times AGB_{Reduce}$

$AGB_{Predicted}red = 2285.319903933610\times 0.917451320791 = 2096.669764293850$

$AGB_{Diff} = AGB_{Predicted}red - AGB_{Component}red$

$AGB_{Diff} = 2096.669764293850 - 2376.463138214140 = -279.793373920290$

Next, proportionally distribute AGB_{Diff} across the components:

$Wood_{Harmonized} = AGB_{Predicted}red \times (Wtot_{ib}red/AGB_{Component}red)$
$Wood_{Harmonized} = 2096.669764293850 \times (1564.617593936140/2376.463138214140) = 1380.407021315430$

$Bark_{Harmonized} = AGB_{Predicted}red \times (Wtot_{bk}red/AGB_{Component}red)$
$Bark_{Harmonized} = 2096.669764293850 \times (236.594620449755/2376.463138214140) = 208.739104392067$

$Branch_{Harmonized} = AGB_{Predicted}red \times (Wbranchred/AGB_{Component}red)$
$Branch_{Harmonized} = 2096.669764293850 \times (575.250923828242/2376.463138214140) = 507.523638586351$

At this point, all the individual tree components have been harmonized and are additive with the predicted total aboveground biomass estimate. The final biomass component that may be predicted is foliage weight. Foliage weight can be estimated by consulting the foliage weight coefficient table (table S9), which stipulates the use of model 1 with the appropriate coefficients:

$Wfoliage = a \times D^b \times H^c$
$Wfoliage = 0.03832401169 \times 18.1^{1.740655717258} \times 65^{0.500290321354} = 47.823281355886$

As with branches, the weight of foliage needs to be reduced to account for remaining portion after the broken top loss:

$FoliageRem = (AH - H \times (1 - CR_H))/(H \times CR_H)$
$FoliageRem = (59 - 65 \times (1 - 0.364615384615))/(65 \times 0.364615384615) = 0.746835443038$

$Wfoliagered = a \times D^b \times H^c \times FoliageRem$

$Wfoliagered = 0.03832401169 \times 18.1^{1.740655717258} \times 65^{0.500290321354} \times 0.746835443038 = 35.716121518954$

New adjusted wood and bark densities are calculated using the harmonized total stem weights and the appropriate volume bases. As in previous examples, the wood and bark volume bases need to account for missing material due to a broken top but exclude any deductions for *CULL* >0. Therefore, the correct values are obtained by subtraction as $VtotibGross - VmissibGross$ and $VtotobGross – VtotibGross – Vmiss_{bk}$ for wood and bark volume bases, respectively:

$WDSG_{Adj} = Wood_{Harmonized}/(Vtot_{ib}Gross - Vmiss_{ib}Gross)/62.4$
$WDSG_{Adj} = 1380.407021315430/(42.277832913225 - 0.099795127559)/62.4 = 0.524488775540$

Similarly, calculate an adjusted bark density using the harmonized total stem bark weight and the predicted total stem bark volume:

$BKSG_{Adj} = Bark_{Harmonized}/(Vtot_{ob}Gross – Vtot_{ib}Gross – Vmiss_{bk})/62.4$
$BKSG_{Adj} = 208.739104392067/(50.639401736611 - 42.277832913225 - 0.019737147575) /62.4 = 0.401012401713$

Because the broken top does not affect the merchantable volume and cull is excluded, merchantable stem wood and bark weights can be determined as follows:

$Wmer_{ib} = Vmer_{ib}Gross \times WDSG_{Adj} \times 62.4$

$Wmer_{ib} = 39.394417201498 \times 0.524488775540 \times 62.4 = 1289.304409606240$

$Wmer_{bk} = Vmer_{bk}Gross \times BKSG_{Adj} \times 62.4$

$Wmer_{bk} = 7.791296478313 \times 0.401012401713 \times 62.4 = 194.962966425323$

Merchantable stem outside bark weight is then calculated via addition:

$Wmer_{ob} = Wmer_{ib} + Wmer_{bk}$

$Wmer_{ob} = 1289.304409606240 + 194.962966425323= 1484.267376031560$

Similarly, stump weights are calculated as follows:

$Wstump_{ib} = Vstump_{ib}Gross \times WDSG_{Adj} \times 62.4$
$Wstump_{ib} = 2.662501082857 \times 0.524488775540 \times 62.4 = 87.138600608067$

$Wstump_{bk} = Vstump_{bk}Gross \times BKSG_{Adj} \times 62.4$
$Wstump_{bk} = 0.526580586388 \times 0.401012401713 \times 62.4 = 13.176717568116$

$Wstump_{ob} = Wstump_{ib} + Wstump_{bk}$
$Wstump_{ob}$ = 87.138600608067 + 13.176717568116 = 100.315318176183

The component DRYBIO_TOP (dry biomass in the top and branches of the tree) is calculated using the following equation:

$DRYBIO\_TOP = AGB_{Predicted}red - Wmer_{ob} - Wstump_{ob}$
$DRYBIO\_TOP$ = 2096.669764293850 - 1484.267376031560 - 100.315318176183 = 512.087070086107

The carbon content (*C*) of the tree is obtained via multiplication by the appropriate C fraction for *SPCD* = 802 (table 10):

$C = AGB_{predicted}red \times CF$
C = 2096.669764293850 × 0.495700000000 = 1039.319202160460

The above examples use trees with $D \geq 5.0$ inches, which implies a merchantable portion of the stem exists. It is assumed no merchantable volume is present for sapling-sized trees ($1.0 \leq D < 5.0$); however, total stem wood and bark volume components are present. Prediction of biomass (and subsequently carbon) for saplings proceeds in the same manner as for larger trees, with stem and branch components being harmonized with $AGB_{Predicted}$ and foliage biomass being obtained directly from the model. Readers desiring to implement the NSVB modeling system for their own applications can find resources via the Forest Service National Volume Estimator Library (NVEL): https://www.fs.usda.gov/forestmanagement/products/measurement/volume/nvel/index.php.

Comparisons with Current Methods

It is also useful to examine the results in the context of current FIA tree volume models, the component ratio method (CRM) for biomass (Woodall et al. 2011), and the subsequent carbon values. Due to the nearly limitless number of potential comparisons, only broad-scale differences are illustrated within this publication; however, readers interested in making more customized evaluations are invited to access data tables where the previous and current values of volume and biomass components for individual trees are stored (https://usfs-public.box.com/s/8xzlkg8epthml2l5idkd5laxs0uy5tbz).

At the national scale, there were only minor differences in merchantable wood cubic-foot volume (1.6 percent), merchantable wood and bark weight (4.0 percent), and stump wood and bark weight (-1.6 percent). A large difference was seen for weights of top/limbs (70.1 percent), which translates into increased tree aboveground biomass of 14.6 percent nationally. The change in biomass basis and implementation of new carbon fractions resulted in a national-scale change for carbon content of 11.6 percent (fig. 2).

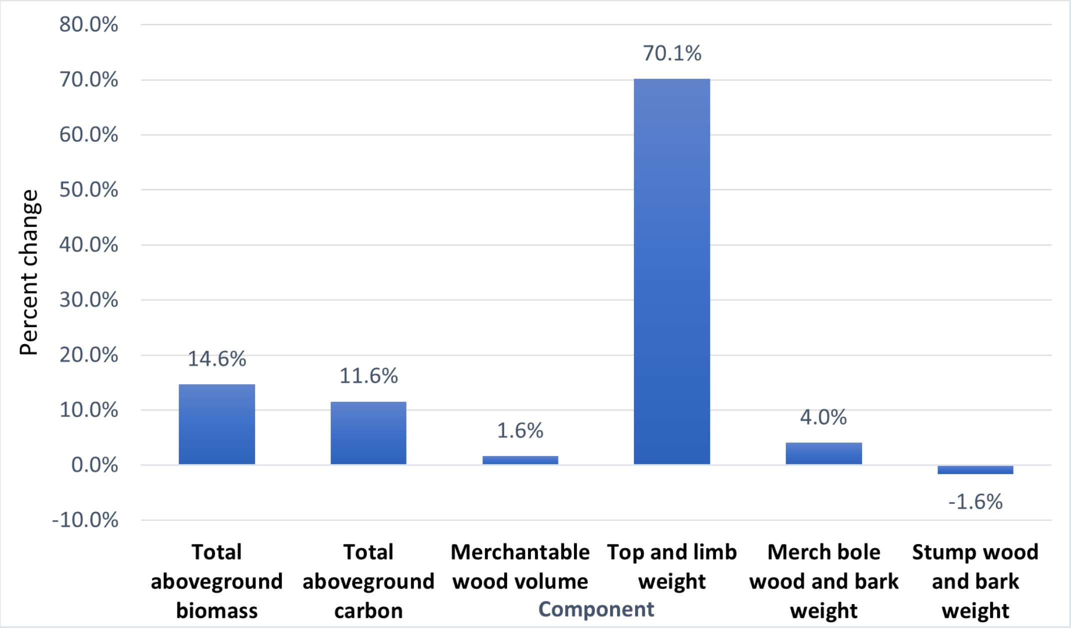


Figure 2.—National-scale differences in volume, biomass, and carbon by component between national-scale volume and biomass (NSVB) and regionally implemented volume models/component ratio method (CRM).

Because the CRM is based on volume models implemented within FIA regions, another point of reference is made at the regional level where increases in tree aboveground biomass ranged from 528 to 1,676 million tons across all four regions (fig. 3a). Corresponding percentage increases were 15.7 percent, 7.2 percent, 20.0 percent, and 17.4 percent for Southern, Pacific Northwest, Rocky Mountain, and Northern regions, respectively. Increases in merchantable wood volume were found in the Northern (19,380 million cubic feet; 5.1 percent) and Southern (13,708 million cubic feet; 3.2 percent) regions. In contrast, decreases in volume were realized for the Rocky Mountain (-4,918 million cubic feet; -2.4 percent) and Pacific Northwest (-5,679 cubic feet; -1.4 percent) regions (fig. 3b). At this broad spatial scale, these outcomes arise from many sources such as model prediction differences and relative tree species frequency that influence the effects of those differences.

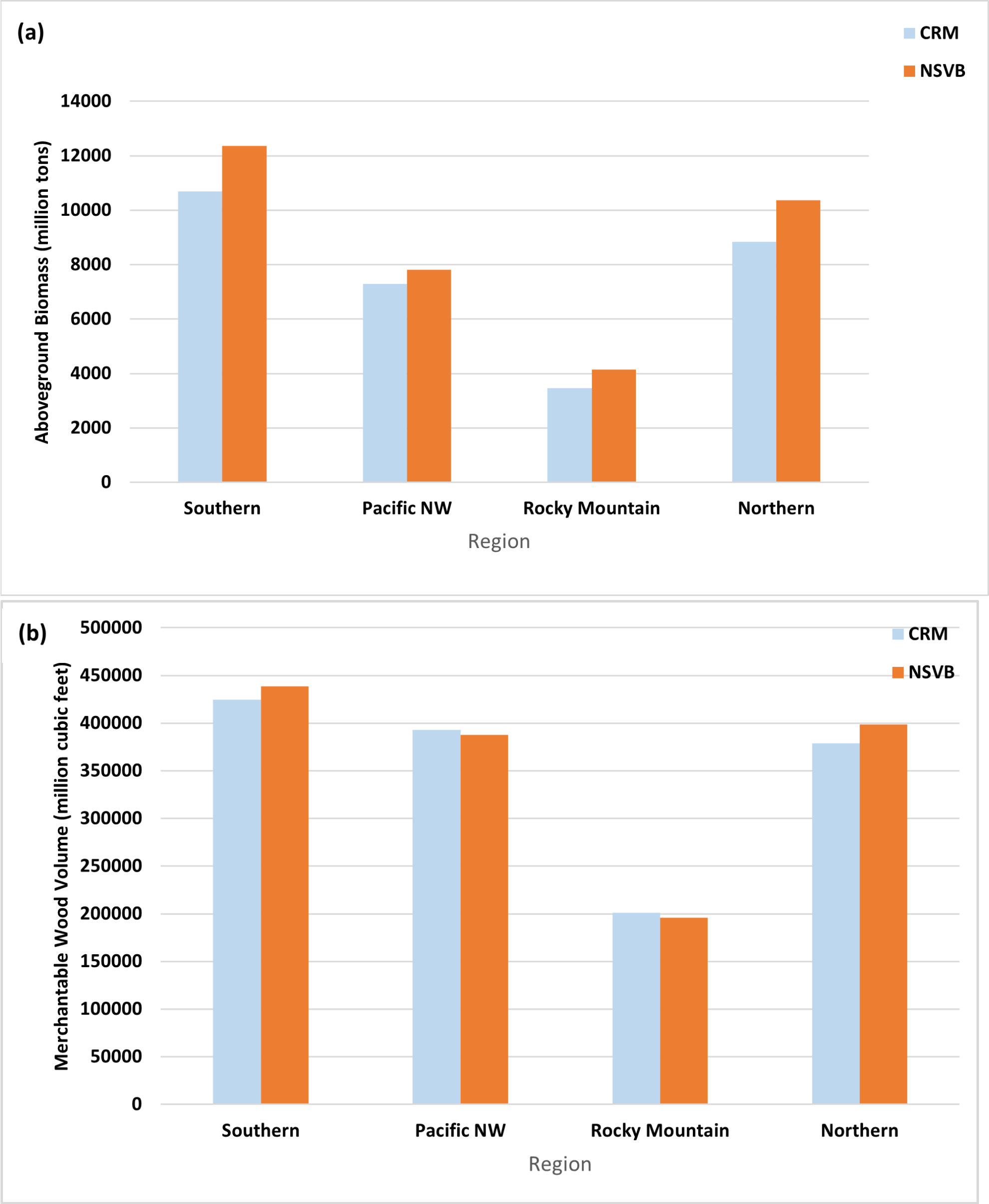


Figure 3.—Differences in (a) aboveground biomass and (b) merchantable wood volume between national-scale volume and biomass (NSVB) and regionally implemented volume models/component ratio method (CRM) by Forest Inventory and Analysis (FIA) region.

A more detailed examination of biomass component contributions to the overall increases revealed that, in most cases, increases in biomass for the top/limbs component were a large driver of change in aboveground tree biomass for both hardwood and softwood species (fig. 4). It is particularly apparent when both stump and merchantable bole biomass changes are negative or only slightly positive, such that little overall change would be observed unless the top/limbs were a primary contributor to the increase. The primary exceptions to this paradigm were for hardwood species in the Southern region and softwood species in the Northern region, where nontrivial increases in both stump and merchantable bole biomass reduced the proportional contribution of the top/limbs to total aboveground biomass. Although various factors may have influenced the systematic underprediction of top/limbs biomass using CRM, one likely cause is that top/limbs biomass is not directly modeled but instead is determined from the difference between total aboveground biomass and the sum of the other tree biomass components (see equation 9 in Woodall et al. 2011).

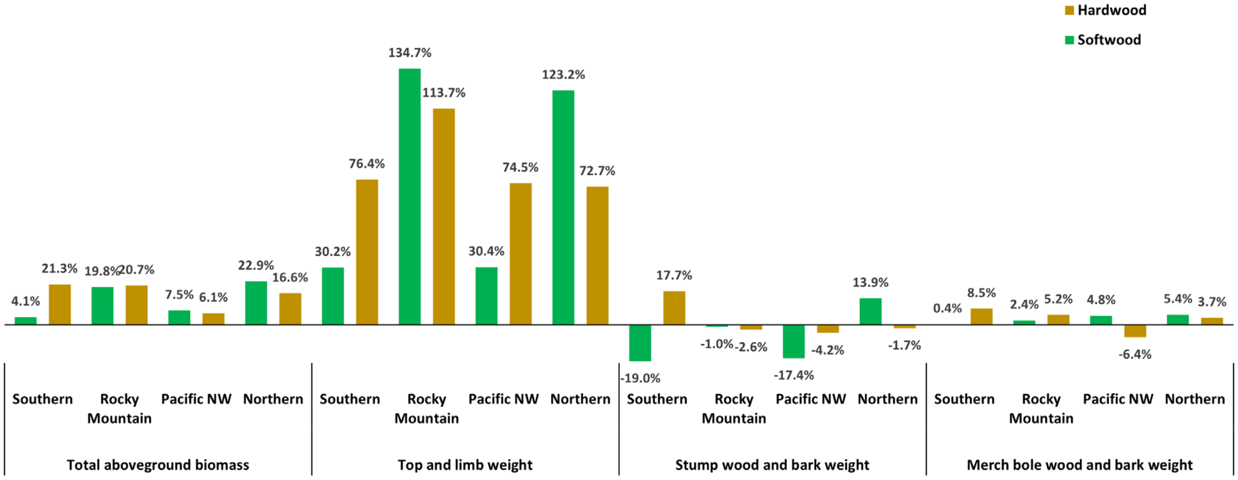


Figure 4.—Percent change in biomass between national-scale volume and biomass (NSVB) and regionally implemented volume models/component ratio method (CRM) by component, Forest Inventory and Analysis (FIA) region, and hardwood or softwood species designation.

Within regions, State-level biomass and volume changes depend on various factors, including species composition, tree size class distributions, and differences in the volume and biomass model predictions. For biomass differences, the largest increases (>25 percent) were found in Oklahoma, Indiana, Illinois, Missouri, and Michigan (fig. 5a). The CRM-based biomass estimates in these States were found to substantially underpredict values compared to the data used in the NSVB study. Changes in other States were generally positive, except for North Dakota and Washington, where slight decreases were realized. The largest volume increases mimicked the biomass increases, i.e., most notably in Indiana, Illinois, Missouri, and Michigan (fig. 5b), due to the regional volume models tending to underpredict volume relative to NSVB models. Generally, 23 of the 48 conterminous U.S. States exhibited slight to moderate reductions in volume. Figure 6 depicts (a) biomass differences and (b) volume differences for portions of the State of Alaska, where results indicated increases in biomass of about 10 percent for coastal areas and 40 percent for interior areas. A slight increase in volume was noted in the coastal region, whereas interior volume increases were >5 percent.

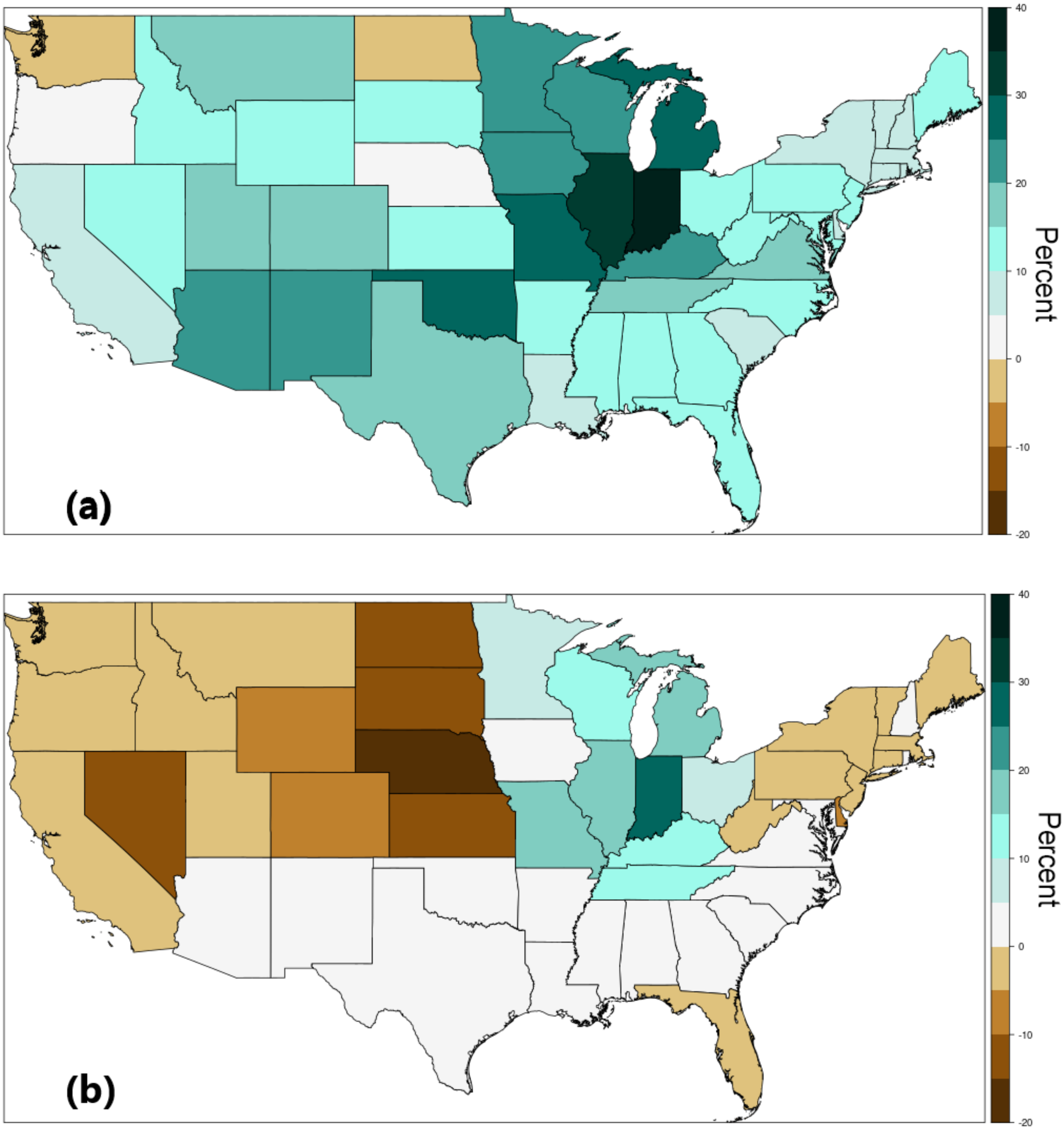


Figure 5.—Percent difference in (a) aboveground biomass and (b) merchantable volume between national-scale volume and biomass (NSVB) and regionally implemented volume models/component ratio method (CRM) for the 48 conterminous U.S. States.

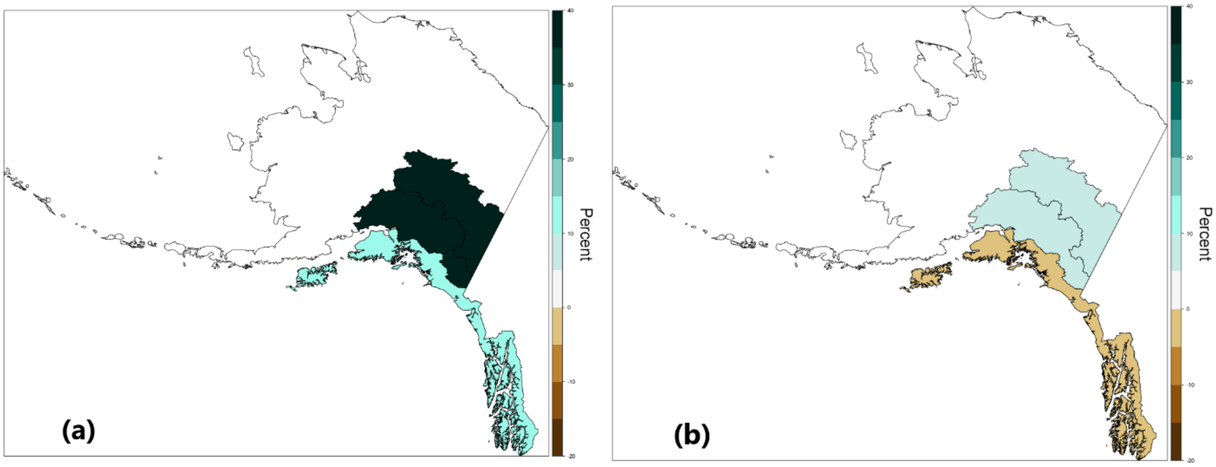


Figure 6.—Percent difference in (a) aboveground biomass and (b) merchantable volume between national-scale volume and biomass (NSVB) and regionally implemented volume models/component ratio method (CRM) for coastal Alaska and portions of interior Alaska completed to date.

Comparisons with CRM aboveground biomass (AGB) predictions showed increases in AGB from NSVB models for most species, primarily due to the underestimation of the top/limbs component by CRM (table 2). The top 10 eastern species (Southern and Northern regions) all exhibited positive increases ranging from approximately 0.6 percent for loblolly pine to 27.9 percent for quaking aspen. Results for the top 10 western species (Rocky Mountain and Pacific Northwest regions) were more variable, ranging from about -6.5 percent for western hemlock to greater than 25 percent for both subalpine fir (*Abies lasiocarpa*) and white fir (*Abies concolor*). Differences between NSVB and regionally implemented volume models/CRM predictions exhibited increases due to NSVB of nearly 0.5 percent (sweetgum) to 10.5 percent (shortleaf pine) for the 10 most common eastern species. In contrast, changes in volume of the 10 primary western species were more mixed with differences ranging from -8.2 percent (Engelmann spruce) to 6.5 percent (white fir). The differences in volume and biomass shown in table 2 underscore the premise that changes between current FIA methods and the NSVB framework depend upon various factors, including species or species assemblages.

Table 2.—Percent change in aboveground biomass and merchantable volume for the 10 most common species in the Eastern (Southern and Northern Forest Inventory and Analysis (FIA) regions) and Western (Pacific Northwest and Rocky Mountain FIA regions) United States.

Eastern species	**Aboveground biomass (percent change)**	**Merchantable volume (percent change)**	**Western species**	**Aboveground biomass (percent change)**	**Merchantable volume (percent change)**
loblolly pine (*Pinus taeda*)	0.59	4.51	Douglas-fir (*Pseudotsuga menziesii*)	0.74	-0.95
red maple (*Acer rubrum*)	20.11	1.30	lodgepole pine (*Pinus contorta*)	18.90	-4.67
white oak (*Quercus alba*)	24.07	10.27	ponderosa pine (*Pinus ponderosa*)	18.63	2.70
sugar maple (*Acer saccharum*)	16.22	8.89	subalpine fir (*Abies lasiocarpa*)	27.72	-7.68
sweetgum (*Liquidambar styraciflua*)	5.83	0.45	western hemlock (*Tsuga heterophylla*)	-6.47	-1.60
northern red oak (*Quercus rubra*)	16.04	4.79	Engelmann spruce (*Picea engelmannii*)	12.83	-8.20
yellow-poplar (*Liriodendron tulipifera*)	10.81	3.80	white fir (*Abies concolor*)	29.06	6.45
quaking aspen (*Populus tremuloides*)	27.89	5.69	grand fir (*Abies grandis*)	19.15	-0.20
shortleaf pine (*Pinus echinata*)	14.27	10.50	red alder (*Alnus rubra*)	8.12	-3.54
eastern white pine (*Pinus strobus*)	17.47	7.52	western redcedar (*Thuja plicata*)	12.98	0.74

DISCUSSION

The NSVB modeling framework presents several potential advantages for the FIA Program and data users. First, tree volume predictions are greatly simplified because only five model specifications are used nationally and the appropriate form and coefficients can be found easily for any species and ecodivision (*SPCD/DIVISION*) combination. Currently, FIA uses numerous model forms from a wide range of studies, largely depending on broad generalizations of species and location parameters. Second, NSVB eliminates administrative boundaries in favor of more sensible ecological definitions of spatial differences (fig. 1). With some exceptions, current FIA volume model applications are based on State or regional boundaries (Woodall et al. 2011) that often have no relevance to environmental gradients that may influence tree size, form, and growth. Third, the models are based on actual tree measurements instead of pseudo-data that underlies the biomass calculations in the current CRM implementation. Using raw empirical data also allows for accurate quantification of model uncertainty (as indicated in tables S12–S20) so that users can assess the reliability of the predictions. Fourth, the new models provide consistent behavior for all trees measured by FIA (D ≥1.0 inch). In contrast, the CRM uses an ad hoc adjustment factor for saplings to help smooth predictions for trees crossing the D = 5.0-inch threshold. Fifth, conversions from biomass to carbon content use species-specific carbon fractions, compared to a rudimentary 0.5 multiplier used for all trees in the CRM. In summary, taking a holistic national-scale approach resulted in substantial improvements to the tree volume, biomass, and carbon models compared to those currently used by the FIA Program.

While considerable effort was expended to develop a robust prediction framework, several challenges still remain to be addressed. Perhaps the most obvious is the inability to provide adequate coverage of all species occurring on FIA plots nationally. The two main contributing factors are land/tree accessibility and the time/cost necessary to locate specific trees that fill information gaps in spatial distribution, species, and size (Frank et al. 2019). Regarding the former, a considerable amount of forest land is simply inaccessible due to private ownership or other constraints such as remote location or challenging topographical gradient. Even in accessible areas, it is often difficult to obtain permission to destructively sample large-sized trees that tend to have substantial economic or intrinsic value. More generally, locating uncommon trees often requires a substantial time and cost commitment due to rarity on the landscape. This requires tradeoffs in project execution to balance efficiency against the perceived knowledge gain of rare tree inclusion.

Other potential near-term refinements to the NSVB framework could include: (1) expansion to a broader range of species, e.g., woodland species (see FIADB

REF_SPECIES); (2) incorporation of nonlinear reductions in branches and foliage for broken top trees; (3) more advanced methods of weight deductions for rotten cull wood; and (4) improvements in wood density decay reductions and bark/branch weight loss reductions for dead trees (table 1). This research also serves as a foundation for prospective long-term advances in tree volume, biomass, and carbon prediction where enhancements that further explore ecological differences, provide alternative model formulations, and account for changing environmental conditions may be possible. Realization of these types of improvements depends on numerous factors, particularly the availability of requisite data at appropriate spatial and temporal scales.

CONCLUSIONS

The work presented herein provides transparent and fully documented methods for national-scale prediction of tree volume, biomass, and carbon attributes. Highlights of the new model framework include (1) consistent modeling results for all trees having a diameter at breast height ≥1.0 inch; (2) considerable increases in analytical flexibility attained by using the entire tree stem as the basis and the ability to determine attribute values for any desired portion of the stem; (3) explicit separation of stem bark and wood attributes; and (4) abandonment of the 0.5 carbon fraction for all species through formulation of more appropriate species-level carbon values. The models were developed using the most comprehensive database ever assembled for the United States across a wide range of species, tree characteristics, and spatial domains. In this sense, the study results are the best available science to date.

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APPENDIX: Supplemental Data Files

The following tables (in CSV format) with statistics and data values used in the national-scale volume and biomass (NSVB) modeling framework for predicting tree volume, biomass, and carbon content across the United States are available at https://doi.org/10.2737/WO-GTR-104-Supp1.

Table S1a.—Coefficients for predicting total stem inside-bark wood cubic-foot volume based on FIA species code (SPCD).

Table S1b.—Coefficients for predicting total stem inside-bark wood cubic-foot volume based on Jenkins species group (JENKINS_SPGRPCD).

Table S2a.—Coefficients for predicting total stem bark cubic-foot volume based on FIA species code (SPCD).

Table S2b.—Coefficients for predicting total stem bark cubic-foot volume based on Jenkins species group (JENKINS_SPGRPCD).

Table S3a.—Coefficients for predicting total stem outside-bark cubic-foot volume based on FIA species code (SPCD).

Table S3b.—Coefficients for predicting total stem outside-bark cubic-foot volume based on Jenkins species group (JENKINS_SPGRPCD).

Table S4a.—Coefficients for predicting outside-bark volume ratio based on FIA species code (SPCD).

Table S4b.—Coefficients for predicting outside-bark volume ratio based on Jenkins species group (JENKINS_SPGRPCD).

Table S5a.—Coefficients for predicting inside-bark volume ratio based on FIA species code (SPCD).

Table S5b.—Coefficients for predicting inside-bark volume ratio based on Jenkins species group (JENKINS_SPGRPCD).

Table S6a. Coefficients for predicting total stem bark biomass based on FIA species code (SPCD).

Table S6b.—Coefficients for predicting total stem bark biomass based on Jenkins species group (JENKINS_SPGRPCD).

Table S7a.—Coefficients for predicting total branch biomass based on FIA species code (SPCD).

Table S7b.—Coefficients for predicting total branch biomass based on Jenkins species group (JENKINS_SPGRPCD).

Table S8a.—Coefficients for predicting total tree biomass based on FIA species code (SPCD).

Table S8b.—Coefficients for predicting total tree biomass based on Jenkins species group (JENKINS_SPGRPCD).

Table S9a.—Coefficients for predicting total foliage biomass based on FIA species code (SPCD).

Table S9b.—Coefficients for predicting total foliage biomass based on Jenkins species group (JENKINS_SPGRPCD).

Table S10a.—Biomass percent carbon fraction for live trees based on FIA species code (SPCD).

Table S10b.—Biomass percent carbon fraction for dead trees based on hardwood/softwood classification and FIA decay code (*DECAYCD*).

Table S11.—Mean crown ratio (CR) percentage by ecodivision and hardwood/softwood species classification.

Table S12.—Model fit statistics for volume and biomass components.

Table S13.—Model fit statistics for volume and biomass components by FIA species code (SPCD).

Table S14.—Model fit statistics for volume and biomass components by current FIA volume model region.

Table S15.—Model fit statistics for volume and biomass components by FIA species code (SPCD) and current FIA volume model region.

Table S16.—Model fit statistics for volume and biomass components by State.

Table S17.—Model fit statistics for volume and biomass components by FIA species code (SPCD) and State.

Table S18.—Model fit statistics for volume and biomass components by ecodivision.

Table S19.—Model fit statistics for volume and biomass components by FIA species code (SPCD) and ecodivision.

Table S20.—Model fit statistics for volume and biomass components by tree diameter class.

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Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022

Updates on Proposed Methodology for Petrochemicals Production

1. Background

EPA has researched and is proposing a methodological refinement to estimate process CO_2 emissions from methanol production as part of the petrochemicals production source category included in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (GHGI), based on data from the Greenhouse Gas Reporting Program (GHGRP) for methanol production, consistent with the 2006 IPCC Guidelines (IPCC 2006).[1] This memorandum outlines a proposed methodological improvement to integrate these data for 2015 through 2022 and also includes preliminary national estimates reflecting improvements. The proposed approach is considered an improvement in the accuracy of the estimate, since it utilizes facility reported data as opposed to using global default emission factors. The process CO_2 emissions from methanol production will be updated in section 4.13 of the GHGI for 2010 through 2014 to be consistent with other petrochemical types, and the full time series data will be reported under Category 2.B.8.a in the Common Reporting Tables (CRT). Emissions from fuel used for energy at methanol production facilities are already included in the overall industrial sector energy use (as obtained from the Energy Information Administration (EIA)) and accounted for as part of energy sector emissions in Chapter 3 of the GHGI. This memo focuses on methods to account for process CO_2 emissions from methanol production; no changes are proposed to the approach used for estimating the process CH_4 emissions associated with methanol production. Section 6 includes questions where EPA is requesting feedback from technical experts on the updates under consideration.

2. Current National GHGI Methodology (1990-2021 GHGI)

Process CO_2 emissions for each year in the time series under the current methodology are calculated based on the 2006 IPCC Guidelines Tier 1 method by multiplying the national quantity of methanol produced per year by the IPCC default emission factor for conventional steam reforming, without primary reformer in metric tons CO_2/metric ton methanol produced (0.67) as shown in Appendix 1. The annual methanol production quantities are based on data published in the American Chemistry Council's Business of Chemistry[2].

3. Proposed National GHGI Methodological Refinements

3.1. Incorporating GHGRP Data for 2015 and Onward

The proposed refinement for estimating process CO_2 emissions from methanol production for years 2015 through 2022 is to use the aggregated emissions reported to the GHGRP subpart X[3] petrochemical production because it represents actual mass balance emissions calculated according to IPCC Tier 3

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[1] *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 3 Industrial Processes and Product Use, Chapter 3 Chemical Industry Emissions, Section 3.9 Petrochemical and Carbon Black Production.

[2] More information is available online at https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/resources/2022-guide-to-the-business-of-chemistry.

[3] Methanol is also produced as a coproduct from hydrogen production (GHGRP subpart P) and ammonia production (GHGRP subpart G), but that production is excluded here as emissions from coproduct methanol production from those sources are covered elsewhere in the GHGI.

methodology for all facilities nationwide that produce methanol as a primary product. EPA has not used GHGRP data collected in Reporting Years 2010 through 2014 in order to shield confidential business information in the data from public disclosure. EPA determines which data will be protected as confidential business information (CBI) through rulemakings and other actions. Any data submitted under the GHGRP that is classified as CBI is protected under the provisions of 40 CFR part 2, subpart B.

3.2. Time Series Considerations and Back-Casting for 1990 through 2014

As indicated in Section 2, the current methodology uses an IPCC default emission factor (in mt CO_2/mt methanol produced) to calculate emissions for every year in the time series. Appendix 1 presents all of the factors that are listed in the 2006 IPCC Guidelines. The factor that has been used to calculate emissions from methanol production in previous versions of the Inventory is 0.67 mt CO_2/mt methanol produced, which is applicable for conventional steam reforming of natural gas using a single reformer (i.e., a process without a primary reformer). As shown in Appendix 1, the 2006 IPCC Guidelines list other emission factors for conventional stream reforming with two reformer units, for conventional steam reforming combined with several different types of Lurgi process units, for partial oxidation processes, and for conventional steam reforming combined with integrated ammonia production. The 2006 IPCC Guidelines indicate that the factors for the Lurgi process units should be used only if information is available confirming that such units are in use; these factors have not been used to estimate emissions for the GHGI because EPA does not have information indicating that methanol production facilities in the U.S. prior to 2010 were using such process units. EPA also does not have information indicating that any of the methanol processes operating in 1990 through 2009 were integrated with ammonia units or that they used two steam reformers instead of only one. We know that one facility was using partial oxidation of coal to produce the syngas feedstock, but we do not have publicly available information on the methanol production rate for this unit. Thus, the factor for conventional steam reforming without a primary reformer was considered the most representative for methanol process units in the absence of GHGRP data.

The average annual emission factor developed from the GHGRP data for Reporting Year 2015 through Reporting Year 2022 is 0.261; excluding the slightly higher value in 2015, the average is 0.247 with very little variation from year-to-year. In response to correspondence in e-GGRT asking about apparent emissions factors being much lower than the default, some reporters have indicated that new methanol processes are much more efficient than older processes. Thus, EPA does not believe it would be appropriate to apply the emission factor developed based on aggregated GHGRP data for 2015 through 2022 to emissions calculations for 1990 through 2014. Considering the significant difference between the IPCC default factor and the factor based on GHGRP data, we also do not believe there should be an abrupt transition from calculating emissions using the IPCC default factor for 1990 through 2014 to using the aggregated GHGRP emissions in 2015 through 2022. Thus, this proposed methodology would continue to use the IPCC default emission factor to estimate emissions only for 1990 through 2009. For 2010 through 2014, the proposed methodology would calculate emissions using emission factors based on linear interpolation between the IPCC factor used for 2009 (0.67) and the factor based on GHGRP data for 2015 (0.355). The 2010 timeframe was chosen for the switch to linear interpolation as that was a low year for methanol production, signifying when newer plants would presumably start coming online after as production increased.

Another issue is that the annual aggregated methanol production data reported to the GHGRP is significantly higher than the production levels obtained from ACC (see Table 1). The difference between the annual GHGRP production values relative to the ACC production values ranges from about 8 percent to 35 percent, with an average difference of 19 percent. Thus, it appears the production values used to calculate emissions for 1990 to 2014 may be too low, but it is not clear how the production values could be adjusted.

Table 1: Methanol production using the current and proposed methodologies (kt)

Methodologies	2015	2016	2017	2018	2019	2020	2021	2022
Current Methodology	3,065	4,250	4,295	5,200	5,730	4,940	6,000	7,430
Proposed refinement	3,320	5,730	5,460	5,830	6,460	6,580	7,110	8,030
Difference (%)	8.3	34.8	27.1	12.1	12.7	33.2	18.5	8.1

4. Preliminary Emissions Estimates

Overall, the proposed methodological refinements led to significant changes in emissions for 2015 through 2021 and lesser changes for 2010 through 2014 (see Table 2 for the emissions[4]). The significant changes for 2015 through 2021 were due to the average emission factor for facilities reporting under subpart X of the GHGRP being about 63 percent lower than the IPCC default emission factor, which was partially offset by the greater production levels reported under subpart X compared to the production levels provided by ACC. The lesser changes for 2010 through 2014 were due to using an emission factor that was linearly interpolated from the IPCC and GHGRP values with the originally used ACC provided production values. There are no changes to emissions for 1990 through 2009 because the proposed methodology for those years is to continue using the default IPCC emission factor (with the production values obtained from ACC) because the emission factor based on the GHGRP data likely is not representative of emissions for older process units.

Table 2: Emissions estimates using the current and proposed methodologies (kt CO2e)

Methodologies	1990	2005	2010	2015	2016	2017	2018	2019	2020	2021	2022
Current Methodology	2,513	821	489	2,054	2,848	2,878	3,484	3,839	3,310	4,020	4,978
Proposed refinement	2,513	821	451	1,180	1,520	1,320	1,370	1,620	1,630	1,700	2,000
Difference (kt)	0	0	-38	-874	-1,328	-1,558	-2,114	-2,219	-1,680	-2,320	-2,978
Implied EF (mt CO_2/mt methanol)	0.67	0.67	0.618	0.355	0.265	0.242	0.235	0.251	0.248	0.239	0.249

5. Uncertainty

In the current methodology, the emission factor values for methanol are obtained from the default Tier 1 CO_2 emission factors in the 2006 IPCC Guidelines. The 2006 IPCC Guidelines have uncertainty ranges

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[4] The full time series of results are shown in Appendix 2.

for the default Tier 1 emission factors used, so those ranges were used directly. For methanol, EPA assigned an uncertainty range of ±30 percent for the CO_2 emission factor.

The 2006 IPCC Guidelines also indicate for Tier 3 methods that the uncertainty associated with direct measurement of fuel consumption together with gas composition samples for all substances is ±5 percent. The proposed approach for estimating near term CO_2 emissions associated with methanol production utilizing GHGRP data is equivalent to direct measurement of fuel data and composition sampling, so the ±5 percent is considered representative of the uncertainty of the GHGRP data variables.

Therefore, the proposed new approach for calculating uncertainty for methanol CO_2 emission estimates is to assume an uncertainty range ±30 percent for CO_2 emission factor the years 1990-2014 and a ±5 percent uncertainty range around CO_2 emission estimates for 2015 through 2022.

6. Request for Feedback

EPA seeks technical expert feedback on the updates under consideration discussed in this memo and the questions below.

1. For 1990 through 2009, EPA is proposing to continue using the IPCC default emission factor of 0.67 mt CO_2/mt of methanol production based on the assumption that conventional steam reforming of natural gas with a single reformer was the most prevalent type of methanol process in operation during those years. Please provide information that either supports this assumption or supports use of any of the other default IPCC emission factors presented in Appendix 1 for all or a portion of the methanol production in these years. Since the number of methanol-producing facilities and the total amount of methanol produced increased modestly in the mid and late 1990s and then steadily and significantly declined through 2011, is it reasonable to use the same emission factor over this entire time period? If not, what would be more appropriate and why?
2. For 2010 through 2014, EPA is proposing to calculate emissions based on emission factors developed based on linear interpolation between the IPCC factor used in 2009 and the aggregated GHGRP emission factor of 0.355 for 2015. If applicable, please provide alternative methods that would more accurately estimate emissions for these years.
3. The proposed new approach for calculating uncertainty for methanol CO_2 emission estimates is to assume an uncertainty range ±30 percent for CO_2 emission factor the years 1990-2014 and a ±5 percent uncertainty range around CO_2 emission estimates for 2015 through 2022. Does this seem like a reasonable approach? Should different uncertainty ranges be use for the linear interpolation years of 2010-2014?
4. Please provide recommendations for reconciling the ACC and GHGRP production data. For example, should the production data for 1990 to 2014 from ACC be adjusted in some manner, and how would any adjustment be justified? Are there any other available sources of production data?
5. Please provide recommendations for any information that could be added to the discussion to provide additional transparency and clarity.

7. References

ACC (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

EPA (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart X for Calendar Years 2015 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Appendix 1

IPCC CO_2 Emission Factors for Methanol Production[5]

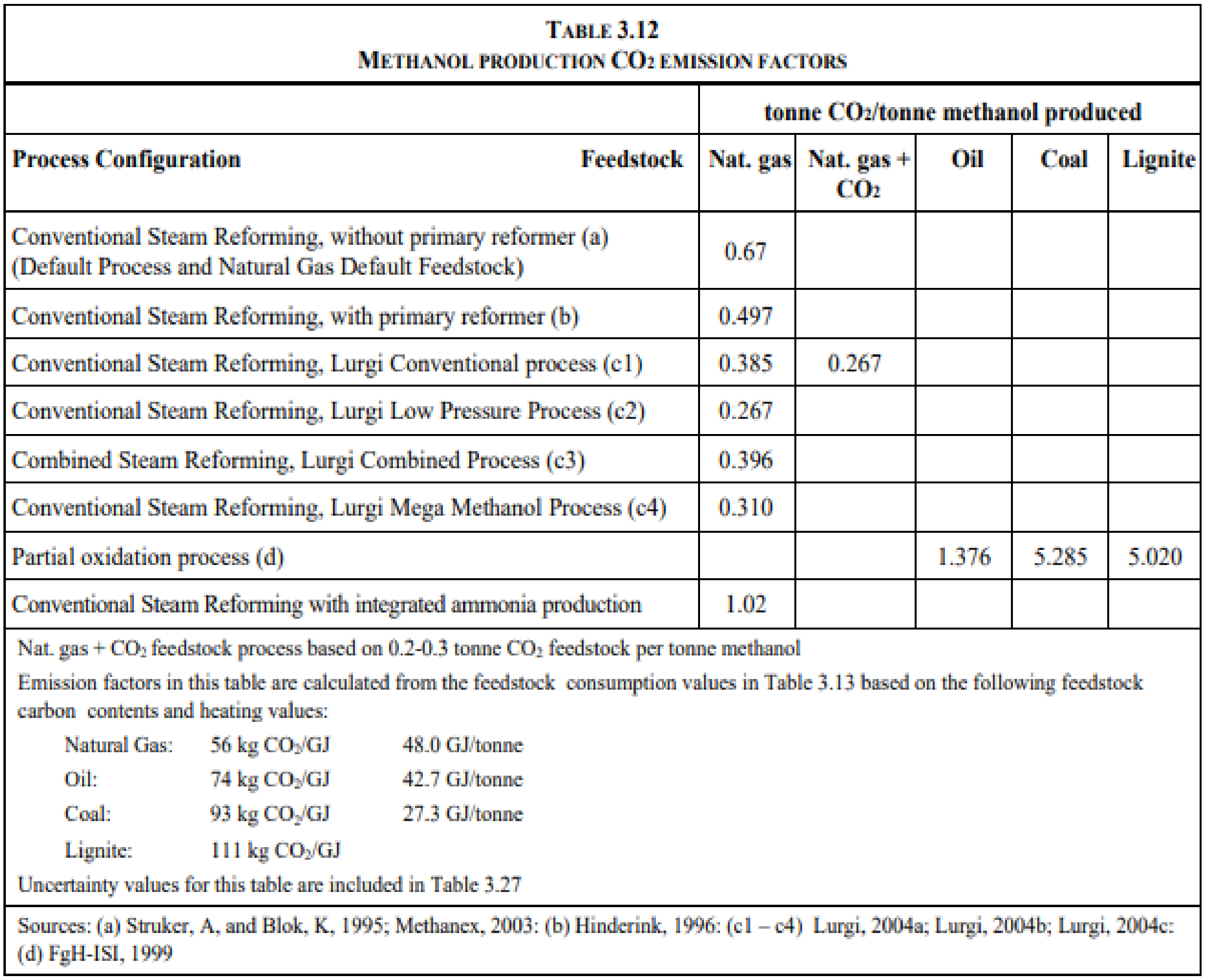

TABLE 3.12
METHANOL PRODUCTION CO_2 EMISSION FACTORS

	tonne CO_2/tonne methanol produced				
Process Configuration **Feedstock**	**Nat. gas**	**Nat. gas + CO_2**	**Oil**	**Coal**	**Lignite**
Conventional Steam Reforming, without primary reformer (a) (Default Process and Natural Gas Default Feedstock)	0.67				
Conventional Steam Reforming, with primary reformer (b)	0.497				
Conventional Steam Reforming, Lurgi Conventional process (c1)	0.385	0.267			
Conventional Steam Reforming, Lurgi Low Pressure Process (c2)	0.267				
Combined Steam Reforming, Lurgi Combined Process (c3)	0.396				
Conventional Steam Reforming, Lurgi Mega Methanol Process (c4)	0.310				
Partial oxidation process (d)			1.376	5.285	5.020
Conventional Steam Reforming with integrated ammonia production	1.02				

Nat. gas + CO_2 feedstock process based on 0.2-0.3 tonne CO_2 feedstock per tonne methanol

Emission factors in this table are calculated from the feedstock consumption values in Table 3.13 based on the following feedstock carbon contents and heating values:

Natural Gas:	56 kg CO_2/GJ	48.0 GJ/tonne
Oil:	74 kg CO_2/GJ	42.7 GJ/tonne
Coal:	93 kg CO_2/GJ	27.3 GJ/tonne
Lignite:	111 kg CO_2/GJ	

Uncertainty values for this table are included in Table 3.27

Sources: (a) Struker, A, and Blok, K, 1995; Methanex, 2003: (b) Hinderink, 1996: (c1 – c4) Lurgi, 2004a; Lurgi, 2004b; Lurgi, 2004c: (d) FgH-ISI, 1999

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[5] *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 3 Industrial Processes and Product Use, Chapter 3 Chemical Industry Emissions, Section 3.9.2.2 Choice of emission Factors, Table 3.12.

Appendix 2

Time Series of Methanol Production and Emissions Data

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
ACC Methanol Production (kt)	3,750	3,950	3,670	4,765	4,905	5,210	5,610	5,980	5,900	5,690	4,970	3,370	3,515	3,410	2,830	1,225	745	800	745	775	730	700	995	1,235	2,105	3,065	4,250	4,295	5,200	5,730	4,940	6,000	7,430
GHGRP Methanol Production (kt)																										3,320	5,730	5,460	5,830	6,460	6,580	7,110	8,030
Emissions using existing approach (kt CO_2)	2,513	2,647	2,459	3,193	3,286	3,491	3,759	4,007	3,953	3,812	3,330	2,258	2,355	2,285	1,896	821	499	536	499	519	489	469	667	827	1,410	2,054	2,848	2,878	3,484	3,839	3,310	4,020	4,978
Emissions using proposed approach (kt CO_2)	2,513	2,647	2,459	3,193	3,286	3,491	3,759	4,007	3,953	3,812	3,330	2,258	2,355	2,285	1,896	821	499	536	499	519	451	396	510	568	859	1,180	1,520	1,320	1,370	1,620	1,630	1,700	2,000
Estimated EF (kt CO_2/kt methanol)	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.670	0.618	0.565	0.513	0.460	0.408	0.385	0.358	0.307	0.263	0.283	0.330	0.283	0.269

November 2023

Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022

Updates on Methodological Refinements for Iron and Steel and Metallurgical Coke Production

1. Background

EPA is initiating consideration of proposed methodological refinements in estimating process CO_2 emissions from the iron and steel production source category included in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (GHGI) due to changes in the availability of relevant data. The memo outlines proposed updates being considered, highlights challenges associated with data sources and includes specific questions where EPA is requesting technical expert feedback. Based on feedback received and ongoing analysis, EPA plans to provide further information on a proposed approach as part of the next inventory cycle to be potentially included in the 2025 release of the GHGI.

1.1. Data Availability and Planned Improvements for the GHGI

The existing methodology included in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (GHGI) for estimating carbon dioxide (CO_2) and methane (CH_4) emissions from processes in iron and steel production and metallurgical coke production relies on activity data obtained from several sources, including the American Iron and Steel Institute (AISI), the Energy Information Administration (EIA), and the United States Geological Survey (USGS). As a result of industry consolidation, publication of significant portions of this activity data ceased beginning in 2020 due to the potential for disclosure of confidential business information (CBI). Specifically, certain data elements from the AISI *Annual Statistical Report* (ASR) including fuel consumption (natural gas, coke oven gas, blast furnace gas, and fuel oil) disaggregated by process type (blast furnaces, coke oven underfiring, steel making furnaces, heating and annealing furnaces, and other uses including boilers and heating) were no longer available for use in GHGI development. To account for this data limitation, activity data for subsequent inventory years was estimated by adjusting the 2019 activity data value (i.e., the last year available) based upon emissions data reported to the Greenhouse Gas Reporting Program (GHGRP) for subpart Q – Iron and Steel Production. This adjustment factor was calculated as the ratio of total process emissions reported to subpart Q in the relevant year divided by the total process emissions reported for 2019.

EPA has continued to evaluate and analyze data reported under the GHGRP to improve the emission estimates for Iron and Steel Production process categories. This memorandum continues the EPA's work by comparing methodology used in the GHGRP to that currently in the GHGI. The intent of this memorandum is to identify opportunities to integrate additional data from the GHGRP into GHGI estimates for the Iron and Steel Production category, identify any challenges with use of GHGRP data, and ensure that any improvements are consistent with the latest guidance on the use of facility-level data in national inventories from the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC).[1]

As part of the analysis of the potential integration of GHGRP data into the national inventory, EPA is also evaluating a number of other improvements. Additional improvements include accounting for emission estimates for the production of metallurgical coke in the Energy chapter as well as better identifying the coke production inputs and outputs including at merchant coke plants. This includes identifying the amount of coke breeze, coal tar, and light oil produced during coke production. Efforts will also be made to identify information to better characterize emissions from the use of process gases and fuels within the Energy and IPPU chapters and additional efforts will be made to improve the reporting and

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[1] *See* http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

transparency in accounting for fuel use between the IPPU and Energy chapters. To the extent that these improvements can be informed by GHGRP data, EPA will seek to include these improvements as part of this effort but notes that these planned improvements are part of a long-term effort and are still in development.

1.2. Background on the GHGRP

Subpart Q of the GHGRP is a direct emitter[2] subpart that contains stationary source emissions from iron and steel production facilities. Generally, the emissions in subpart Q are a combination of melting iron ore and combustion of a carbon-containing fuel, resulting in the release of CO_2. Reporting to the GHGRP subpart Q began in 2010. Subpart Q is a threshold subpart, meaning that it is required to be reported if the facility meets the definition of the source category[3] and if the facility (i.e., combined emissions of all subparts) emits 25,000 metric tons (mt) of carbon dioxide equivalent (CO_2e) or more per year.

Process emissions within subpart Q are calculated using the following methods:

- The carbon mass balance method, using equations Q-1 through Q-7 to calculate emissions from each type of process equipment located at the facility.
- The site-specific emission factor method, where facilities conduct a performance test to determine the CO_2 emissions from all exhaust stacks, measure either the feed rate or the production rate of the materials during this test, and then calculate the hourly CO_2 emission rate using equation Q-8. This hourly rate is multiplied by the measured feed or production to calculate CO_2 emissions.
- For coke-pushing processes, CO_2 emissions are calculated by multiplying the mt of coal charged to the by-product recovery and non-recovery coke ovens during the reporting period by 0.008.
- If the facility uses a continuous emissions monitoring system (CEMS) that complies with the Tier 4 methodology in subpart C, then the facility must report under subpart Q the combined stack emissions according to the Tier 4 Calculation Methodology described in subpart C and comply with all associated requirements for Tier 4 in subpart C.

Stationary combustion emissions from subpart Q facilities are reported as follows:

- All stationary combustion emissions of CO_2, CH_4, and N_2O at a subpart Q facility must be reported under subpart C except for flares.
- For flares, CO_2 emissions from the burning of blast furnace gas or coke oven gas must be reported to subpart Y, and CH_4 and N_2O emissions must be reported to subpart C.

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[2] "Direct emitters" are facilities that combust fuels or otherwise put GHGs into the atmosphere directly from their facility. In the context of the GHGRP, this term is used to distinguish from "suppliers" which are entities that supply products into the economy which if combusted, released or oxidized emit greenhouse gases into the atmosphere.

[3] The definition of the source category for the subpart is provided at 40 CFR 98.170 as follows: The iron and steel production source category includes facilities with any of the following processes: taconite iron ore processing, integrated iron and steel manufacturing, cokemaking not collocated with an integrated iron and steel manufacturing process, direct reduction furnaces not collocated with an integrated iron and steel manufacturing process, and electric arc furnace (EAF) steelmaking not collocated with an integrated iron and steel manufacturing process. Integrated iron and steel manufacturing means the production of steel from iron ore or iron ore pellets. At a minimum, an integrated iron and steel manufacturing process has a basic oxygen furnace for refining molten iron into steel. Each cokemaking process and EAF process located at a facility with an integrated iron and steel manufacturing process is part of the integrated iron and steel manufacturing facility.

For data elements identified as CBI, data is not available at the facility-level. However, subject to meeting aggregation criteria, this data may be published at the subpart level. Data reported to the GHGRP using the inputs verification tool (IVT) is used in the calculation of GHG emissions as well as for verification but is not electronically accessible by EPA or retained as part of the GHGRP. Appendix A: Summary of CBI and Equation Data Elements in the IVT lists the subpart Q data elements, their classification as CBI or IVT elements, and the associated emissions calculations equations in subpart Q. Section 4.1 further discusses the background of the IVT and the implications for integration of GHGRP data into the GHGI.

The GHGRP data could be used directly to provide emissions associated with I&S production however it would be difficult to track carbon flows between the different processes with this approach as is done now in the GHGI accounting. The GHGRP data provides emissions from the different processes but not necessarily the carbon inputs and outputs associated with the process. Those data elements are often considered to have the potential to cause competitive harm if disclosed publicly or to be CBI in the GHGRP reporting as discussed in the following section. Therefore, if the emissions from GHGRP were used directly without knowing the inputs and outputs there could be double counting in other portions of the inventory including fossil fuel combustion in the industrial sector, process uses of carbonates and non-energy use emissions.

1.3. GHGRP Coverage Analysis

As part of the 2009 GHGRP rulemaking, EPA conducted an analysis of the impact of different reporting thresholds. At the time, EPA estimated that there were 130 operational facilities meeting the I&S source category definition. The total emissions estimated from these facilities were 85.2 million mt CO_2e per year. For the reporting threshold of 25,000 mt CO_2e per year that was proposed, it was estimated that 121 facilities (93% coverage by facility count) associated with 85.0 million mt CO_2e per year (99.8% coverage by emissions) would be reported to the GHGRP. It was estimated that the facilities not captured by this threshold would be small EAF facilities (EPA 2009).

In the first year of reporting in 2010, there were 125 reporters. The number of reporters increased in 2011 to 129, and has declined slightly in subsequent reporting years. In 2022 there were 121 reporters to subpart Q of the GHGRP. Note that facilities are eligible to off-ramp (i.e., stop reporting) if they emit less than 25,000 mtCO_2e per year for 5 consecutive years or less than 15,000 mtCO_2e per year for 3 consecutive years. One facility has off-ramped since RY2010, and review of public reporting has identified several other facilities that have ceased reporting to subpart Q were idled or shut down.

Based upon the coverage analysis conducted to support the 2009 GHGRP rulemaking and subsequent reporting to the GHGRP, it is believed that subpart Q achieves a high degree of coverage of GHG emissions from the iron and steel production industry.

2. Current National GHGI Methodology and Comparison with GHGRP Methodology

Both the existing GHGI approach and GHGRP include eight processes for Iron and Steel and Metallurgic Coke production. The processes are similar between the two programs but do not align exactly. The processes can be matched as shown in Table 1:

Table 1. Processes for Which Emissions Are Reported by GHGI and GHGRP

GHGI	**GHGRP**
Metallurgical Coke Production	Non-recovery coke oven battery combustion stack Coke pushing process
Sinter Production	Sinter process, including continuous emission measurement systems (CEMS)
Pellet Production	Taconite indurating furnace
Direct Reduced Iron (DRI)	Direct reduction furnace, including CEMS
Blast Furnace, including Pig Iron Production	Emissions are covered under 40 CFR part 60 subpart C data
Electric arc furnace (EAF)	EAF, decarburization vessel, combined EAF/decarburization vessel, and CEMS
Basic oxygen furnace (BOF)	BOF, decarburization vessel
Other Steel Mill Activities	Emissions are covered under 40 CFR part 60 subpart C data
[Included with other process emissions]	Flares

For the GHGI, emission estimates for metallurgical coke production, electric arc furnace (EAF) steel production, and basic oxygen furnace production steel production utilize a country-specific approach based on Tier 2 methodologies provided by the 2006 IPCC Guidelines.[4] These Tier 2 methodologies call for a mass balance accounting of the carbonaceous inputs and outputs during the iron and steel production process and the metallurgical coke production process. Estimates for pig iron production also apply Tier 2 methods consistent with the 2006 IPCC Guidelines. Tier 1 methods are used for certain iron and steel production processes (i.e., sinter production, pellet production and direct reduced iron (DRI) production) for which available data are insufficient to apply a Tier 2 method (e.g., country-specific carbon contents of inputs and outputs are not known). The majority of emissions are captured with higher tier methods, as sinter production, pellet production, and DRI production only account for roughly 8 percent of total iron and steel production emissions.[5]

The remainder of this section compares the GHGI and the GHGRP methodologies for estimating emissions from processes in iron and steel production and metallurgic coke production. Emission data comparing GHGI and GHGRP methodologies are reported below for 2015 through 2019. Emissions from 2020 and subsequent years are not included in this comparison as emissions for these years are estimated by adjusting the 2019 activity data (i.e., last year available) based upon total process emissions data from the GHGRP.

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[4] *2006 IPCC Guidelines*, Volume 3 Industrial Processes and Product Use, Chapter 4 Metal Industry Emissions, Section 4.2 Iron & steel and Metallurgical Coke Production.

[5] EPA (2023), Chapter 4 Industrial Processes and Product Uses, Section 4.17 Iron and Steel Production (CRF Source Category 2C1) and Metallurgical Coke Production.

2.1. Coke Production

2.1.1 GHGRP Approach

Emissions from metallurgic coke production as specified in the GHGRP include emissions from non-recovery coke ovens as well as from coke pushing.

Emissions from non-recovery coke oven batteries are calculated as:

$$CO_2 = \frac{44}{12} * \left[(Coal) * (C_{Coal}) - (Coke) * (C_{Coke}) - (R) * (C_R) \right] \qquad \text{(Eq. Q-3)}$$

Where:

CO_2 = Annual CO_2 mass emissions from the non-recovery coke oven battery (metric tons).
44/12 = Ratio of molecular weights, CO_2 to carbon.
(Coal) = Annual mass of coal charged to the battery (metric tons).
(C_{Coal}) = Carbon content of the coal, from the carbon analysis results (expressed as a decimal fraction).
(Coke) = Annual mass of coke produced by the battery (metric tons).
(C_{Coke}) = Carbon content of the coke, from the carbon analysis results (expressed as a decimal fraction).
(R) = Annual mass of air pollution control residue collected (metric tons).
(C_R) = Carbon content of the air pollution control residue, from the carbon analysis results (expressed as a decimal fraction).

Emissions of CO_2 from the coke pushing process (in mt CO2e) are determined by multiplying the metric tons of coal charged to by-product recovery and non-recovery coke ovens during the reporting period by 0.008.

2.1.2 GHGI Approach

A mass balance accounting of the carbonaceous inputs and outputs during metallurgical coke production process is used to estimate emissions. Carbon inputs and outputs are determined, and the difference is assumed to be emissions. Inputs and outputs for the mass and carbon balance are provided in Table 2:

Table 2. GHGI Coke Production Approach

Inputs		
Input Variable	Data Source	Relevant Conversions
Coking Coal Consumption	EIA Quarterly Coal Report	0.754 kg C/kg coking coal
Natural Gas (NG) Consumption	AISI report	1,037 Btu/ft^3 14.45 kg C / MMBtu
Blast Furnace Gas (BFG) Consumption	AISI report	95 Btu/ft^3 74.7 kg C / MMBtu
Outputs		
Output Variable	Data Source	Relevant Conversions
Coke Production at Coke Plants	EIA Quarterly Coal Report	0.83 kg C / kg coke
Coke Oven Gas (COG) Production[1]	AISI report[2]	500 Btu/ft^3 12.8 kg C / MMBtu
Coal Tar Production	Based on coking coal consumption (input)	Assumes coal tar production is 3% of coking coal consumption

Coke Breeze Production	Based on coking coal consumption (input)	Assumes 150 lbs/ton coking coal consumption 0.83 kg C / kg

[1] COG used for coke oven underfiring is assumed to be emitted, so these emissions are not an output.

[2] Data is only for integrated plants, so this approach may not include merchant coke plant COG use.

2.1.3 Comparison of Approaches for Coke Production

Figure 1 provides a graphic depiction of these approaches and resulting emissions. A comparison between emissions calculated based upon GHGRP data and the associated emissions from the GHGI are presented in Table 3.

Figure 1. Comparison of GHGRP and GHGI Approaches for Coke Production

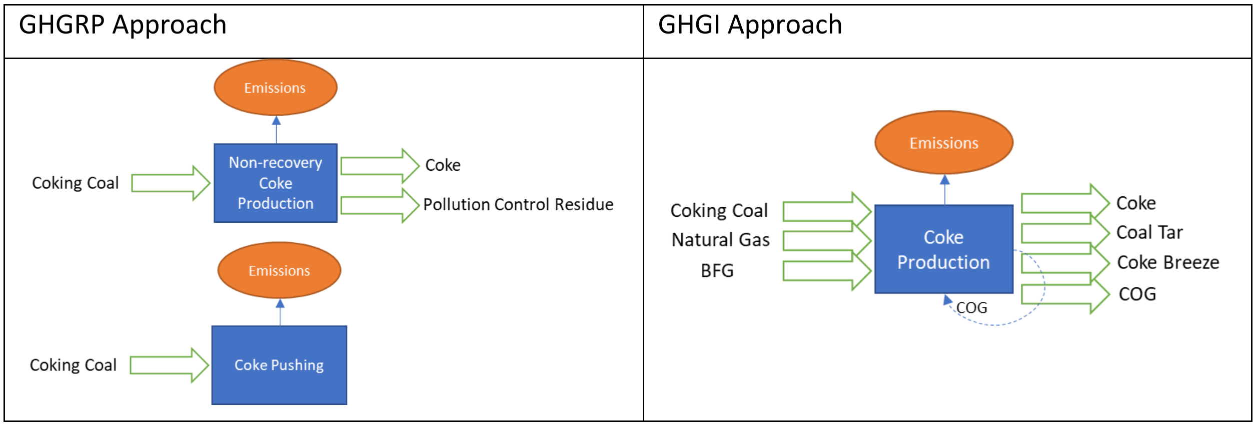


Table 3. Estimated Emissions for Coke Production Between GHGRP and GHGI

	2015	2016	2017	2018	2019
GHGRP Emissions (Tonnes CO_2)	3,448,158	3,370,020	3,233,015	3,213,732	3,337,838
Coke Pushing	135,058	116,179	123,277	128,778	120,319
Non-Recovery Coke Oven	3,313,100	3,253,840	3,109,737	3,084,953	3,217,519
Inventory Emissions (Tonnes CO_2)	4,416,595	2,642,630	1,978,267	1,282,119	3,005,595

2.2. Sinter Production

2.2.1 GHGRP Approach

Emissions from sinter production are calculated as follows, or from CEMS reporting, if applicable:

$$CO_2 = \frac{44}{12} * \left[(F_g) * (C_{gf}) * \frac{MW}{MVC} * 0.001 + (Feed) * (C_{Feed}) - (\text{Sinter}) * (C_{Sinter}) - (R) * (C_R) \right] \qquad \text{(Eq. Q-4)}$$

Where:

CO_2 = Annual CO_2 mass emissions from the sinter process (metric tons).
44/12 = Ratio of molecular weights, CO_2 to carbon.
(F_g) = Annual volume of the gaseous fuel used (scf).
(C_{gf}) = Carbon content of the gaseous fuel, from the fuel analysis results (kg C per kg of fuel).

MW = Molecular weight of the gaseous fuel (kg/kg-mole).
MVC = Molar volume conversion factor (849.5 scf per kg-mole at standard conditions).
0.001 = Conversion factor from kg to metric tons.
(Feed) = Annual mass of sinter feed material (metric tons).
(C_{Feed}) = Carbon content of the mixed sinter feed materials that form the bed entering the sintering machine, from the carbon analysis results (expressed as a decimal fraction).
(Sinter) = Annual mass of sinter produced (metric tons).
(C_{Sinter}) = Carbon content of the sinter pellets, from the carbon analysis results (expressed as a decimal fraction).
(R) = Annual mass of air pollution control residue collected (metric tons).
(C_R) = Carbon content of the air pollution control residue, from the carbon analysis results (expressed as a decimal fraction).

2.2.2 GHGI Approach

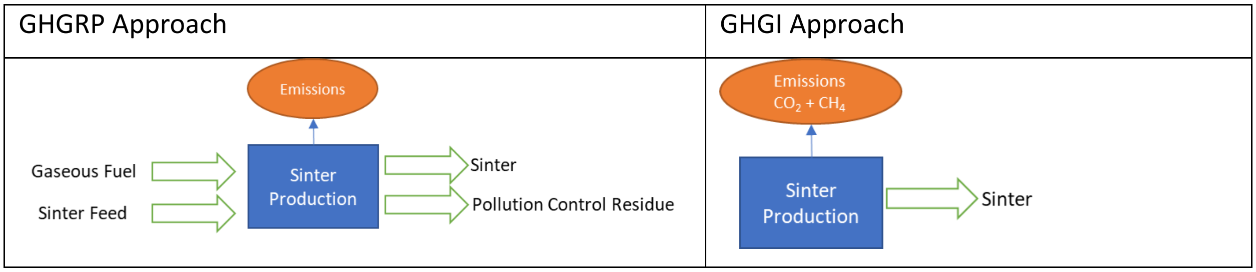
Emissions CO_2 and CH_4 from sinter production are calculated by multiplying production by an emission factor. Production is assumed to equal consumption of sinter, briquettes, nodules and others as previously provided in the AISI ASR[6] for both blast and steel making furnaces. These data are no longer available due to industry consolidation. Default emission factors from the 2006 IPCC Guidelines are as follows:

- CO_2 EF for Sinter Production = 0.2 tonnes CO_2/tonne sinter produced[7]
- CH_4 EF for Sinter Production = 0.07 kg CH_4/tonne sinter produced[8]

2.2.3 Comparison of Approaches for Sinter Production

Figure 2 provides a graphic depiction of these approaches and resulting emissions. A comparison between emissions calculated based upon GHGRP data and the associated emissions from the GHGI are presented in Table 4.

Figure 2. Comparison of GHGRP and GHGI Approaches for Sinter Production



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[6] AISI (2019) Annual Statistical Report, Table 37.

[7] *2006 IPCC Guidelines*, Volume 3 Industrial Processes and Product Use, Chapter 4 Metal Industry Emissions, Table 4.1, Tier 1 Default CO_2 Emission Factors for Coke Production and Iron & Steel Production.

[8] *2006 IPCC Guidelines*, Volume 3 Industrial Processes and Product Use, Chapter 4 Metal Industry Emissions, Table 4.2, Tier 1 Default CH_4 Emission Factors for Coke Production and Iron & Steel Production.

Table 4. Estimated Emissions for Sinter Production Between GHGRP and GHGI

	2015	2016	2017	2018	2019
GHGRP Emissions (Tonnes CO_2)	754,684	771,252	671,392	595,617	878,499
Sinter	209,048	219,807	87,248	33,973	297,033
CEMS*	545,636	551,445	584,144	561,644	581,466
Inventory Emissions (Tonnes)	1,024,311	884,478	876,790	945,243	883,291
CO_2	1,015,701	877,081	869,460	937,319	875,629
CH_4	8,610	7,397	7,330	7,924	7,662
Sinter Consumed (tonnes) - Inventory	5,078,506	4,385,405	4,347,302	4,686,595	4,378,147
GHGRP IEF (tonnes CO_2/tonne sinter)	0.15	0.18	0.15	0.13	0.20
Inventory EF (tonnes CO_2/tonne sinter)	0.20	0.20	0.20	0.20	0.20

* Note: GHGRP CEMS has data on CH_4 and N_2O emissions. They were not compiled as part of this analysis but could be included if GHGRP data was used in calculations.

2.3. Pellet Production

2.3.1 GHGRP Approach

Emissions from pellet production, or taconite production as referred to in the GHGRP, are calculated as:

$$CO_2 = \frac{44}{12} * \left[(F_s) * (C_{sf}) + (F_g) * (C_{gf}) * \frac{MW}{MVC} * 0.001 + (F_l) * (C_{lf}) * 0.001 + (O) * (C_o) - (P) * (C_p) - (R) * (C_R) \right] \qquad \text{(Eq. Q-1)}$$

Where:

CO_2 = Annual CO_2 mass emissions from the taconite indurating furnace (metric tons).
44/12 = Ratio of molecular weights, CO_2 to carbon.
(F_s) = Annual mass of the solid fuel used (metric tons).
(C_{sf}) = Carbon content of the solid fuel, from the fuel analysis (expressed as a decimal fraction).
(F_g) = Annual volume of the gaseous fuel used (scf).
(C_{gf}) = Average carbon content of the gaseous fuel, from the fuel analysis results (kg C per kg of fuel).
MW = Molecular weight of the gaseous fuel (kg/kg-mole).
MVC = Molar volume conversion factor (849.5 scf per kg-mole at standard conditions).
0.001 = Conversion factor from kg to metric tons.
(F_l) = Annual volume of the liquid fuel used (gallons).
(C_{lf}) = Carbon content of the liquid fuel, from the fuel analysis results (kg C per gallon of fuel).
(O) = Annual mass of greenball (taconite) pellets fed to the furnace (metric tons).
(C_O) = Carbon content of the greenball (taconite) pellets, from the carbon analysis results (expressed as a decimal fraction).
(P) = Annual mass of fired pellets produced by the furnace (metric tons).
(C_p) = Carbon content of the fired pellets, from the carbon analysis results (expressed as a decimal fraction).
(R) = Annual mass of air pollution control residue collected (metric tons).
(C_R) = Carbon content of the air pollution control residue, from the carbon analysis results (expressed as a decimal fraction).

2.3.2. GHGI Approach

Emissions of CO_2 from pellet production are calculated from the production times an emission factor. Production is assumed to equal consumption, which was previously provided in the AISI ASR[9] for both blast and steel making furnaces. both blast and steel making furnaces. These data are no longer available due to industry consolidation. The default emission factor for CO_2 as reported in the 2006 IPCC Guidelines[10] is 0.03 tonnes CO_2/tonne pellets produced.

2.3.3. Comparison of Approaches for Pellet Production

Figure 3 provides a graphic depiction of these approaches and resulting emissions. A comparison between emissions calculated based upon GHGRP data and the associated emissions from the GHGI are presented in Table 5.

Figure 3. Comparison of GHGRP and GHGI Approaches for Pellet Production

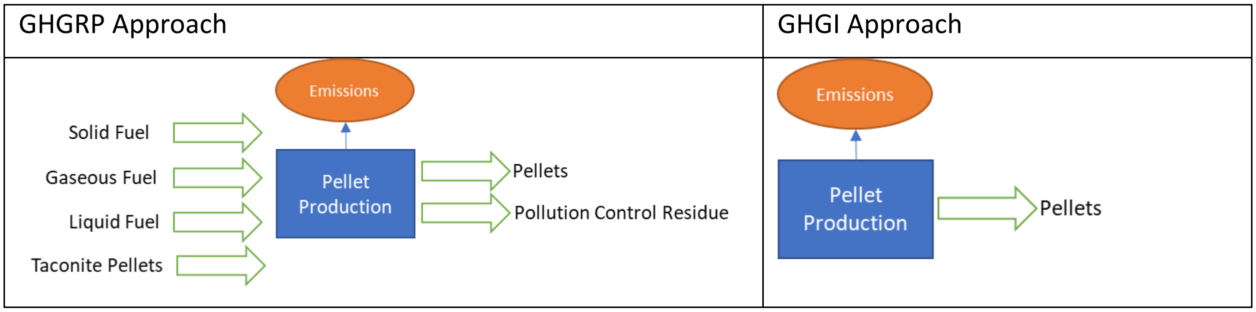

Table 5. Estimated Emissions for Pellet Production Between GHGRP and GHGI

	2015	2016	2017	2018	2019
GHGRP Emissions (Tonnes CO_2)	3,088,752	2,935,605	3,433,910	3,505,575	3,336,148
Inventory Emissions (Tonnes CO_2)	964,372	869,019	867,468	923,777	877,860
Pellet Consumed (tonnes) – Inventory	32,145,725	28,967,316	28,915,610	30,792,570	29,262,000
GHGRP IEF (tonnes CO_2 / tonne pellets)	0.10	0.10	0.12	0.11	0.11
Inventory EF (tonnes CO_2 / tonne pellets)	0.30	0.03	0.03	0.03	0.03

2.4. DRI Production

2.4.1 GHGRP Approach:

Emissions from DRI production are calculated as follows, or from CEMS reporting, if applicable:

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[9] AISI (2019) Annual Statistical Report, Table 37.

[10] *2006 IPCC Guidelines*, Volume 3 Industrial Processes and Product Use, Chapter 4 Metal Industry Emissions, Table 4.1, Tier 1 Default CO2 Emission Factors for Coke Production and Iron & Steel Production.

$$CO_2 = \frac{44}{12} * \Big[(F_g) * (C_{gf}) * \frac{MW}{MVC} * 0.001 + (Ore) * (C_{Ore}) \qquad \text{(Eq. Q-7)}$$

$$+ (Carbon) * (C_{Carbon}) + (Other) * (C_{Other})$$

$$- (Iron)\ (C_{Iron}) - (NM) * (C_{NM}) - (R) * (C_R) \Big]$$

Where:

CO_2 = Annual CO_2 mass emissions from the direct reduction furnace (metric tons).
44/12 = Ratio of molecular weights, CO_2 to carbon.
(F_g) = Annual volume of the gaseous fuel used (scf).
(C_{gf}) = Carbon content of the gaseous fuel, from the fuel analysis results (kg C per kg of fuel).
MW = Molecular weight of the gaseous fuel (kg/kg-mole).
MVC = Molar volume conversion factor (849.5 scf per kg-mole at standard conditions).
0.001 = Conversion factor from kg to metric tons.
(Ore) = Annual mass of iron ore or iron ore pellets fed to the furnace (metric tons).
(C_{Ore}) = Carbon content of the iron ore or iron ore pellets, from the carbon analysis results (expressed as a decimal fraction).
(Carbon) = Annual mass of carbonaceous materials (e.g., coal, coke) charged to the furnace (metric tons).
(C_{Carbon}) = Carbon content of the carbonaceous materials, from the carbon analysis results (expressed as a decimal fraction).
(Other) = Annual mass of other materials charged to the furnace (metric tons).
(C_{Other}) = Average carbon content of the other materials charged to the furnace, from the carbon analysis results (expressed as a decimal fraction).
(Iron) = Annual mass of iron produced (metric tons).
(C_{Iron}) = Carbon content of the iron, from the carbon analysis results (expressed as a decimal fraction).
(NM) = Annual mass of non-metallic materials produced by the furnace (metric tons).
(C_{NM}) = Carbon content of the non-metallic materials, from the carbon analysis results (expressed as a decimal fraction).
(R) = Annual mass of air pollution control residue collected (metric tons).
(C_R) = Carbon content of the air pollution control residue, from the carbon analysis results (expressed as a decimal fraction).

2.4.2 GHGI Approach

Emissions of CO_2 from DRI production are calculated from the production times an emission factor. Production is assumed to equal consumption as provided in the USGS Iron & Steel Scrap Minerals Yearbook, Table 4 for use in EAF and BOF.[11] The default emission factor for CO_2 as reported in the 2006 IPCC Guidelines[12] is 0.7 tonnes CO_2/tonne DRI produced.

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[11] USGS Iron & Steel Scrap Minerals Yearbook, Table 4.

[12] *2006 IPCC Guidelines*, Volume 3 Industrial Processes and Product Use, Chapter 4 Metal Industry Emissions, Table 4.1, Tier 1 Default CO2 Emission Factors for Coke Production and Iron & Steel Production.

2.4.3 Comparison of Approaches for DRI Production

Figure 4 provides a graphic depiction of these approaches and resulting emissions. A comparison between emissions calculated based upon GHGRP data and the associated emissions from the GHGI are presented in Table 6.

Figure 4. Comparison of GHGRP and GHGI Approaches for DRI Production

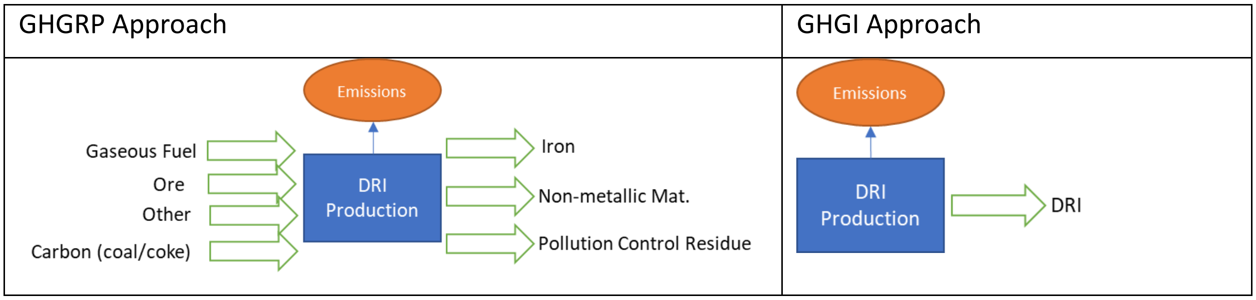


Table 6. Estimated Emissions for DRI Production Between GHGRP and GHGI

	2015	2016	2017	2018	2019
GHGRP Emissions (Tonnes CO_2)	948,447	1,350,890	1,771,024	2,160,661	2,150,645
DRI	373,496	540,031	1,109,162	1,144,394	1,212,855
CEMS	574,951	810,859	661,862	1,016,268	937,791
Inventory Emissions (Tonnes CO_2)	1,905,400	3,346,000	1,283,800	1,656,200	1,743,000
DRI Consumed (tonnes) – Inventory	2,722,000	4,780,000	1,834,000	2,366,000	2,490,000
GHGRP IEF (tonnes CO_2/tonne DRI)	0.35	0.28	0.97	0.91	0.86
Inv EF (tonnes CO_2/tonne DRI)	0.70	0.70	0.70	0.70	0.70

2.5. Electric Arc Furnace (EAF)

2.5.1 GHGRP Approach

Emissions include emissions from EAF, decarburization vessel, combined EAF/ decarburization vessel, as well as from CEMS reporting, if applicable:

EAF calculation:

$$CO_2 = \frac{44}{12} * \left[\frac{(Iron) * (C_{Iron}) + (Scrap) * (C_{Scrap}) + (Flux) * (C_{Flux}) + (Electrode) * (C_{Electrode}) + (Carbon)}{* (C_{Carbon}) - (Steel) * (C_{Steel}) + (F_g) * (C_{gf}) * \frac{MW}{MVC} * 0.001 - (Slag) * (C_{Slag}) - (R) * (C_R)} \right] \quad \text{(Eq. Q-5)}$$

Where:

CO_2 = Annual CO_2 mass emissions from the EAF (metric tons).
44/12 = Ratio of molecular weights, CO_2 to carbon.
(Iron) = Annual mass of direct reduced iron (if any) charged to the furnace (metric tons).
(C_{Iron}) = Carbon content of the direct reduced iron, from the carbon analysis results (expressed as a decimal fraction).
(Scrap) = Annual mass of ferrous scrap charged to the furnace (metric tons).
(C_{Scrap}) = Carbon content of the ferrous scrap, from the carbon analysis results (expressed as a decimal fraction).
(Flux) = Annual mass of flux materials (e.g., limestone, dolomite) charged to the furnace (metric tons).

(C_{Flux}) = Carbon content of the flux materials, from the carbon analysis results (expressed as a decimal fraction).
(Electrode) = Annual mass of carbon electrode consumed (metric tons).
($C_{Electrode}$) = Carbon content of the carbon electrode, from the carbon analysis results (expressed as a decimal fraction).
(Carbon) = Annual mass of carbonaceous materials (e.g., coal, coke) charged to the furnace (metric tons).
(C_{Carbon}) = Carbon content of the carbonaceous materials, from the carbon analysis results (expressed as a decimal fraction).
(Steel) = Annual mass of molten raw steel produced by the furnace (metric tons).
(C_{Steel}) = Carbon content of the steel, from the carbon analysis results (expressed as a decimal fraction).
(F_g) = Annual volume of the gaseous fuel used (scf at 60 degrees F and one atmosphere).
(C_{gf}) = Average carbon content of the gaseous fuel, from the fuel analysis results (kg C per kg of fuel).
(MW) = Molecular weight of the gaseous fuel (kg/kg-mole).
(MVC) = Molar volume conversion factor (836.6 scf per kg-mole at standard conditions of 60 degrees F and one atmosphere).
(0.001) = Conversion factor from kg to metric tons.
(Slag) = Annual mass of slag produced by the furnace (metric tons).
(C_{Slag}) = Carbon content of the slag, from the carbon analysis results (expressed as a decimal fraction).
(R) = Annual mass of air pollution control residue collected (metric tons).
(C_R) = Carbon content of the air pollution control residue, from the carbon analysis results (expressed as a decimal fraction).

Emissions from decarburization vessel are calculated as follows:

$$CO_2 = \frac{44}{12} * \{(Steel) * [(C_{Steelin}) - (C_{Steelout})] - (R) * (C_R)\} \qquad \text{(Eq. Q-6)}$$

Where:

CO_2 = Annual CO_2 mass emissions from the decarburization vessel (metric tons).
44/12 = Ratio of molecular weights, CO_2 to carbon.
(Steel) = Annual mass of molten steel charged to the vessel (metric tons).
($C_{Steelin}$) = Carbon content of the molten steel before decarburization, from the carbon analysis results (expressed as a decimal fraction).
($C_{Steelout}$) = Carbon content of the molten steel after decarburization, from the carbon analysis results (expressed as a decimal fraction).
(R) = Annual mass of air pollution control residue collected (metric tons).
(C_R) = Carbon content of the air pollution control residue, from the carbon analysis results (expressed as a decimal fraction).

2.5.2 GHGI Approach

A mass balance accounting of the carbonaceous inputs and outputs to the EAF is used to estimate emissions. Carbon inputs and outputs are determined, and the difference is assumed to be emissions. Inputs and outputs for the mass and carbon balance are provided in Table 7:

Table 7. GHGI Inputs and Conversions for Estimating EAF Emissions

Inputs		
Input Variable	Data Source	Relevant Conversions
Natural Gas Consumption	AISI report	1,037 Btu/cuft 14.45 kg C / MMBtu
EAF Anode Consumption	Assumes 0.002 tonnes anode/ton steel produced	0.82 kg C / kg electrode
EAF Charge Carbon Consumption	Based on data from AISI	0.83 kg C / kg charge carbon
Direct Reduced Iron Consumption	USGS Iron & Steel Scrap Minerals Yearbook	0.02 kg C/ kg
Limestone Consumption	AISI report	0.12 kg C / kg limestone
Dolomite Consumption	Starting in 2015, this value is set to be equal to limestone use in EAF	0.13 kg C / kg dolomite
Scrap Steel Consumption	USGS Iron & Steel Scrap Minerals Yearbook	0.01 kg C / kg steel
Pig Iron Consumption	USGS Iron & Steel Scrap Minerals Yearbook	0.04 kg C/ kg pig iron
Output		
Output Variable	Data Source	Relevant Conversions
EAF Steel Production	AISI report	0.01 kg C / kg steel

2.5.3 Comparison of Approaches for EAF Production

Figure 5 provides a graphic depiction of these approaches and resulting emissions. A comparison between emissions calculated based upon GHGRP data and the associated emissions from the GHGI are presented in Table 8.

Figure 5. Comparison of GHGRP and GHGI Approaches for EAFs

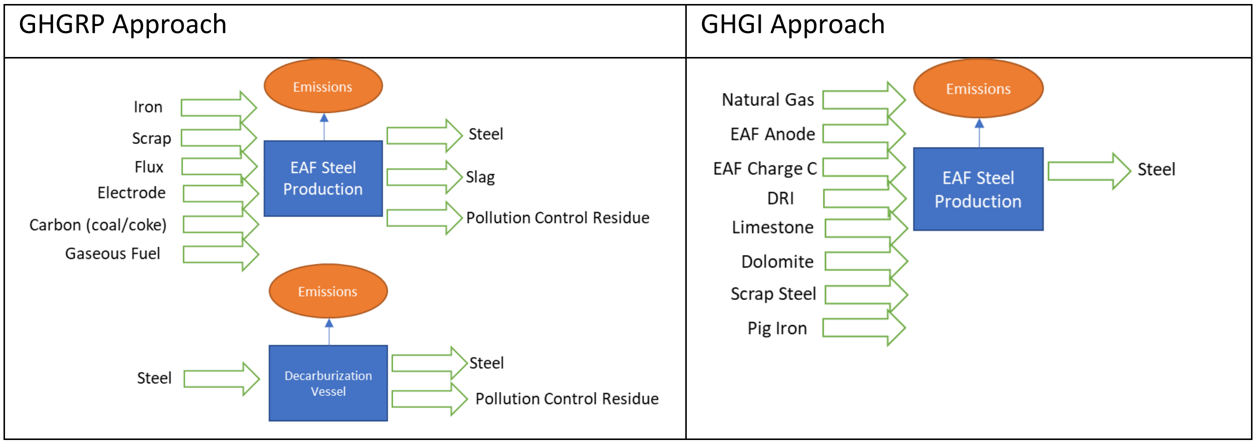


Table 8. Estimated Emissions from EAFs Between GHGRP and GHGI

	2015	2016	2017	2018	2019
GHGRP Emissions (Tonnes CO_2)	5,784,062	5,947,913	6,258,492	7,066,010	6,683,361
CEMS	1,454,980	2,092,657	2,001,402	2,298,081	2,178,809
Decarburization Vessel	70,957	96,349	92,413	88,111	69,926
Electric Arc Furnace (EAF)	4,226,478	3,750,507	4,161,129	4,672,690	4,421,436
EAF/Decarburization Vessel Common Stack	31,647	8,399	3,548	7,128	13,189
Inventory Emissions (Tonnes CO_2)	4,471,267	4,390,109	4,224,318	4,208,974	4,312,890

2.6. Basic Oxygen Furnace (BOF)

2.6.1 GHGRP Approach

Emissions include emissions from emissions from BOF calculations as well as from decarburization vessels that are located with BOFs. The BOF calculations are as follows:

$$CO_2 = \frac{44}{12} * \Big[(Iron) * (C_{Iron}) + (Scrap) * (C_{Scrap}) + (Flux) * (C_{Flux}) + (Carbon) * (C_{Carbon}) - (Steel) * (C_{Steel}) - (Slag) * (C_{Slag}) - (R) * (C_R) \Big] \qquad \text{(Eq. Q-2)}$$

Where:

CO_2 = Annual CO_2 mass emissions from the basic oxygen furnace (metric tons).
44/12 = Ratio of molecular weights, CO_2 to carbon.
(Iron) = Annual mass of molten iron charged to the furnace (metric tons).
(C_{Iron}) = Carbon content of the molten iron, from the carbon analysis results (expressed as a decimal fraction).
(Scrap) = Annual mass of ferrous scrap charged to the furnace (metric tons).
(C_{Scrap}) = Carbon content of the ferrous scrap, from the carbon analysis results (expressed as a decimal fraction).
(Flux) = Annual mass of flux materials (e.g., limestone, dolomite) charged to the furnace (metric tons).
(C_{Flux}) = Carbon content of the flux materials, from the carbon analysis results (expressed as a decimal fraction).
(Carbon) = Annual mass of carbonaceous materials (e.g., coal, coke) charged to the furnace (metric tons).
(C_{Carbon}) = Carbon content of the carbonaceous materials, from the carbon analysis results (expressed as a decimal fraction).
(Steel) = Annual mass of molten raw steel produced by the furnace (metric tons).
(C_{Steel}) = Carbon content of the steel, from the carbon analysis results (expressed as a decimal fraction).
(Slag) = Annual mass of slag produced by the furnace (metric tons).
(C_{Slag}) = Carbon content of the slag, from the carbon analysis (expressed as a decimal fraction).
(R) = Annual mass of air pollution control residue collected (metric tons).

(C_R) = Carbon content of the air pollution control residue, from the carbon analysis results (expressed as a decimal fraction).

Emissions from the decarburization vessel associated with the BOF are provided above in Eq. Q-6.

2.6.2 GHGI Approach

A mass balance accounting of the carbonaceous inputs and outputs to the BOF is used to estimate emissions. Carbon inputs and outputs are determined, and the difference is assumed to be emissions. Inputs and outputs for the mass and carbon balance are provided in Table 9.

Table 9. GHGI Inputs and Conversion Factors for Estimating BOF Emissions

Inputs		
Input Variable	Data Source	Relevant Conversions
Coke Oven Gas Consumption	AISI report	500 Btu/cuft 12.8 kg C / MMBtu
Pig Iron Consumption	USGS Iron & Steel Scrap Minerals Yearbook	0.04 kg C/ kg pig iron
Scrap Steel Consumption	USGS Iron & Steel Scrap Minerals Yearbook	0.01 kg C / kg steel
Limestone Consumption	AISI report	0.12 kg C / kg limestone
Dolomite Consumption	Starting in 2015, this value is set to be equal to limestone use in BOF	0.13 kg C / kg dolomite
Direct Reduced Iron Consumption	USGS Iron & Steel Scrap Minerals Yearbook	0.02 kg C/ kg
Natural Ore Consumption	AISI report	0.02 kg C/ kg
Pellets Consumption	AISI report	0.02 kg C/ kg
Sinter, Briquettes, etc. Consumption	AISI report	0.02 kg C/ kg
Outputs		
Output Variable	Data Source	Relevant Conversions
BOF Steel Production	AISI report	0.01 kg C / kg steel

2.6.3 Comparison of Approaches for BOF Production

Figure 6 provides a graphic depiction of these approaches and resulting emissions. A comparison between emissions calculated based upon GHGRP data and the associated emissions from the GHGI are presented in Table 10.

Figure 6. Comparison of GHGRP and GHGI Approaches for BOFs

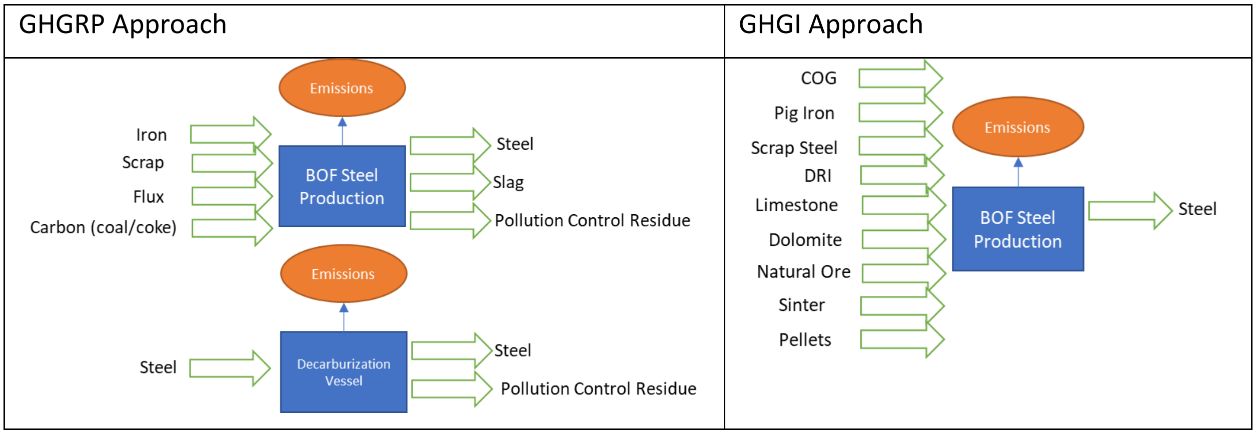


Table 10. Estimated Emissions from BOFs Between GHGRP and GHGI

	2015	2016	2017	2018	2019
GHGRP Emissions (Tonnes CO_2)	4,161,799	3,990,539	4,016,946	3,873,021	3,772,060
BOF	4,153,792	3,982,455	3,997,644	3,862,874	3,749,588
Decarburization Vessel	8,006	8,083	19,301	10,147	22,472
Inventory Emissions (Tonnes CO_2)	2,463,369	2,463,644	1,993,440	1,545,438	1,499,547

2.7. Other Sources

2.7.1 GHGRP Approach

Emissions from flares and fuel combustion are reported in other subparts in the GHGRP. Emissions from flares that burn blast furnace gas or coke oven gas under subpart Y. Emissions are reported under subpart C for fuels combusted in I&S facilities. Data are reported for a number of fuel types that can be combined into the following categories:

- Industrial Coal
- BFG
- Coke
- COG
- Natural Gas
- Petro Other

2.7.2 GHGI Approach

Other sources of emissions in GHGI include emissions from pig iron production (blast furnace). A mass balance accounting of the carbonaceous inputs and outputs to the blast furnace is used to estimate emissions. Carbon inputs and outputs are determined, and the difference is assumed to be emissions. Inputs and outputs for the mass and carbon balance are provided in Table 11:

Table 11. GHGI Inputs and Conversion Factors for Other Sources

Inputs		
Input Variable	Data Source	Relevant Conversions
Natural Gas Consumption	AISI report	1,037 Btu/cuft 14.45 kg C / MMBtu
Fuel Oil Consumption	AISI report	5.83 MMBtu/bbl 20.17 kg C / MMBtu
Coke Oven Gas Consumption	AISI report	500 Btu/cuft 12.8 kg C / MMBtu
Coal used for Direct Injection	AISI report	23.9 MMBtu/ton 25.8 kg C / MMBtu
Coke Consumption	AISI report	0.83 kg C / kg coke
Sinter, Briquettes, etc. Consumption	AISI report	0.02 kg C/ kg
Natural Ore Consumption	AISI report	0.02 kg C/ kg
Pellets Consumption	AISI report	0.02 kg C/ kg
Outputs		
Output Variable	Data Source	Relevant Conversions
Pig Iron Production	AISI report	0.04 kg C/ kg pig iron
Blast Furnace Gas Production[1]	AISI report	95 Btu/cuft 74.7 kg C / MMBtu

[1] BFG used for Blast Furnace is assumed to be emitted, so it is not an output.

Emissions from other sources besides pig iron production include coke over gas consumption and blast furnace gas consumption. Emissions are estimated by multiplying fuel usage by the appropriate conversion factor as noted in Table 12:

Table 12. Gas Consumption Conversion Factors

Variable	**Data Source**	**Relevant Conversions**
Coke Oven Gas Consumption[1]	AISI report	500 Btu/cuft 12.8 kg C / MMBtu
Blast Furnace Gas Consumption[2]	AISI report	95 Btu/cuft 74.7 kg C / MMBtu

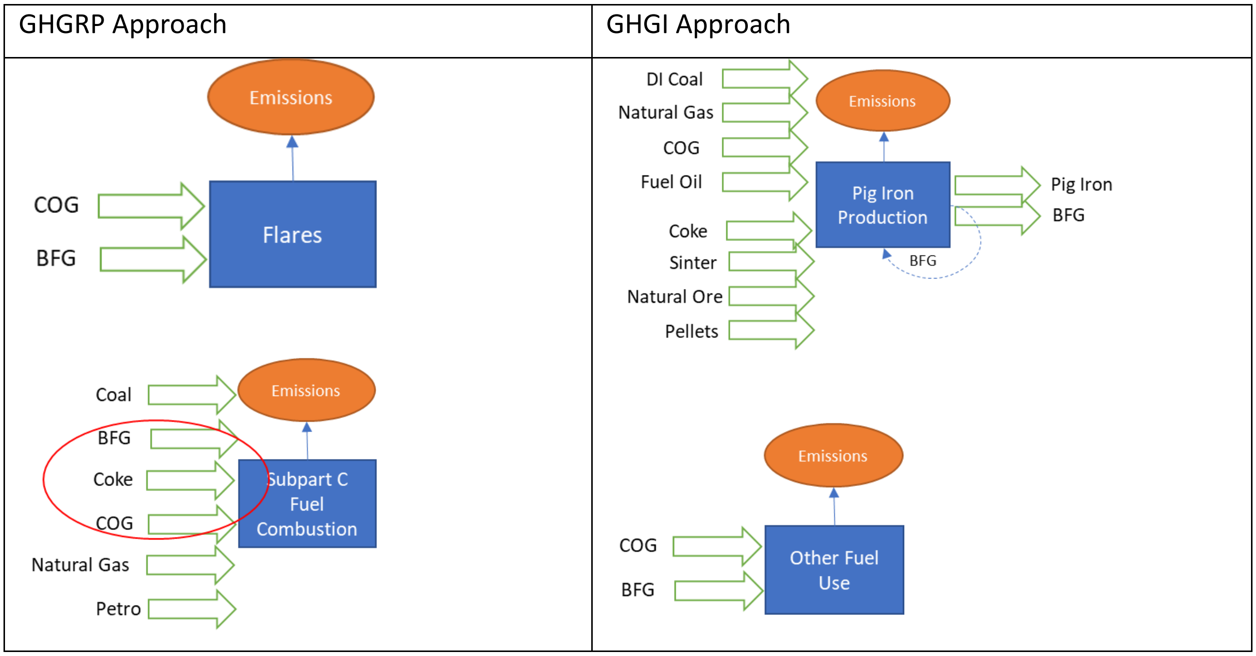
[1] This approach excludes COG sent offsite and used as Synthetic Natural Gas (SNG) based on data from EIA, which is assumed to be counted for in energy sector emissions.

[2] This approach excludes BFG sent offsite and used as SNG based on data from EIA, which is assumed to be counted for in energy sector emissions.

2.7.3 Comparison of Approaches for Other Sources

Figure 7 provides a graphic depiction of these approaches and resulting emissions. A comparison between emissions calculated based upon GHGRP data and the associated emissions from the GHGI are presented in Table 13.

Figure 7. Comparison of GHGRP and GHGI Approaches for Other Sources



BFG = blast furnace gas; COG = coke oven gas

Table 13. Estimated Emissions from Other Sources Between GHGRP and GHGI

	2015	**2016**	**2017**	**2018**	**2019**
GHGRP Emissions (Tonnes CO_2)	33,412,383	33,569,645	33,264,628	33,646,059	34,232,645
Flare	6,478,784	6,971,004	8,506,226	9,113,868	8,432,332
BFG combustion	24,407,996	24,187,200	22,501,192	22,192,381	23,676,619
Coke combustion	894	979	1,225	1,212	978
COG combustion	2,524,709	2,410,463	2,255,985	2,338,599	2,122,717
Inventory Emissions (Tonnes CO_2)	32,704,847	29,032,986	29,348,887	32,073,564	30,775,016
Other Steel Mill Activities	24,279,544	22,450,767	22,396,071	24,149,263	23,158,284
Blast Furnace	8,425,303	6,582,219	6,952,816	7,924,301	7,616,732

2.8. Overall Comparison

Overall, the GHGRP emission estimates for iron and steel production and metallurgic production, including all sources, is generally higher than the estimates from the GHGI as shown in Table 14. Total Estimated Emissions for GHGRP and GHGI. The differences are spread out across the different process types as shown in Table 15. Contribution by Process to Differences Between GHGRP and GHGI Estimates (mt CO_2e) and Figure 8. Contribution by Process to Differences Between GHGRP and GHGI Estimates (mt CO_2e).

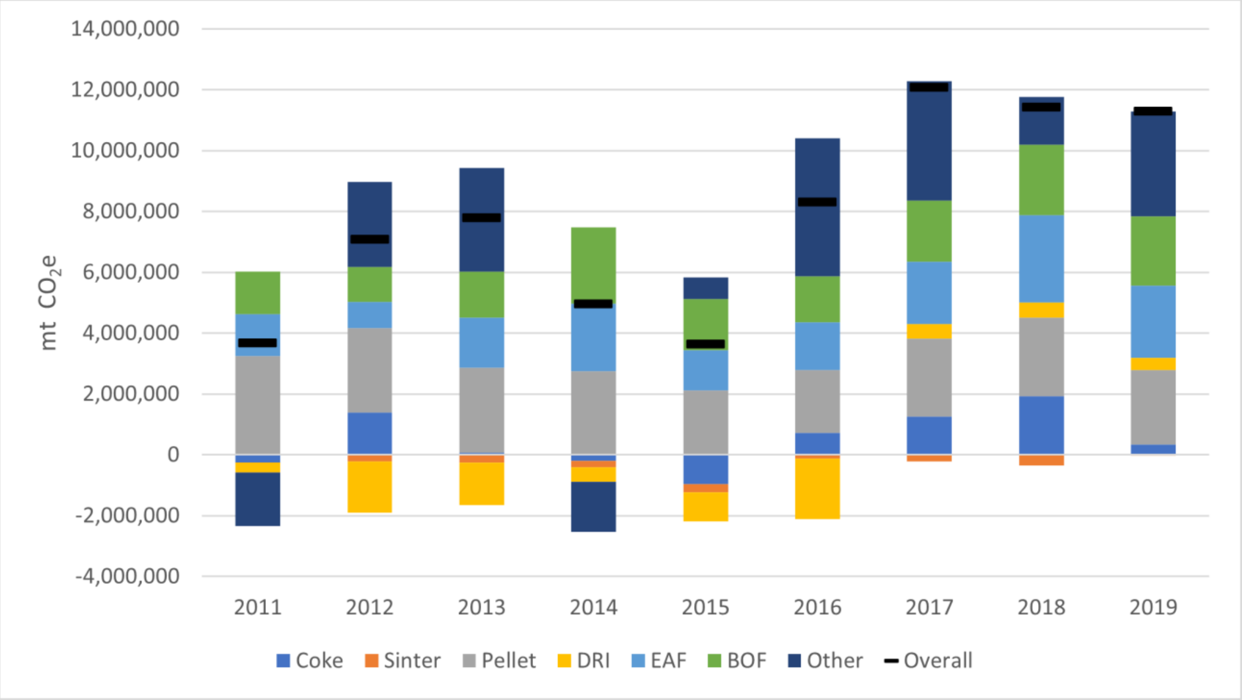
Table 14. Total Estimated Emissions for GHGRP and GHGI (mt CO_2e)

	2015	2016	2017	2018	2019
GHGRP	51,598,284	51,935,863	52,649,406	54,060,674	54,391,196
Inventory	47,950,161	43,628,866	40,572,971	42,635,315	43,097,198
GHGRP % Diff	8%	19%	30%	27%	26%

Table 15. Contribution by Process to Differences Between GHGRP and GHGI Estimates (mt CO_2e)

	2015	2016	2017	2018	2019
Coke	-968,437	727,389	1,254,747	1,931,612	332,242
Sinter	-269,627	-113,225	-205,399	-349,626	-4,792
Pellet	2,124,380	2,066,585	2,566,442	2,581,798	2,458,288
DRI	-956,953	-1,995,110	487,224	504,461	407,645
EAF	1,312,795	1,557,804	2,034,174	2,857,037	2,370,471
BOF	1,698,430	1,526,895	2,023,506	2,327,582	2,272,513
Other	707,535	4,536,660	3,915,741	1,572,495	3,457,629
Overall	3,648,123	8,306,998	12,076,435	11,425,359	11,293,997

Figure 8. Contribution by Process to Differences Between GHGRP and GHGI Estimates (mt CO_2e)

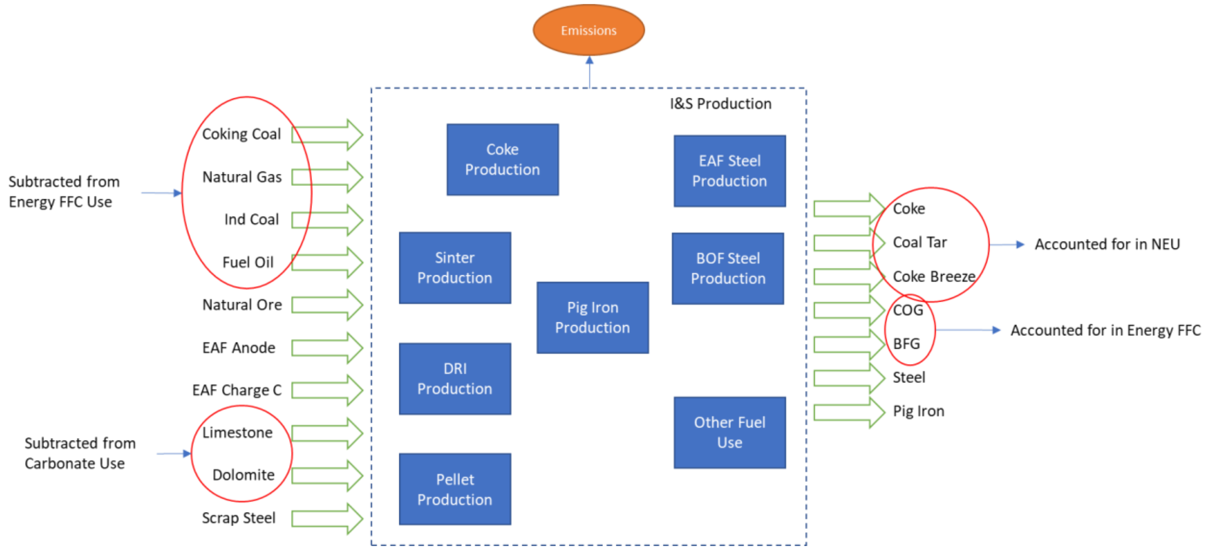


One potential reason for the higher emission associated with the GHGRP approach is that the GHGRP approach could be considering more fuel use as process emissions than does the GHGI approach. The GHGI allocates some fuel use to the iron and steel process emissions and subtracts them from fossil fuel combustion (FFC) energy use but it is unclear how that lines up with the GHGRP approach, see for example section 4. The following figures show the overall inputs and outputs for both approaches across all the different process categories.

2.8.1 GHGI Approach

Figure 9 provides an overview of the inputs and outputs of the current GHGI emissions estimation methodology. Specific inputs and outputs that are used within other chapters of the GHGI are highlighted.

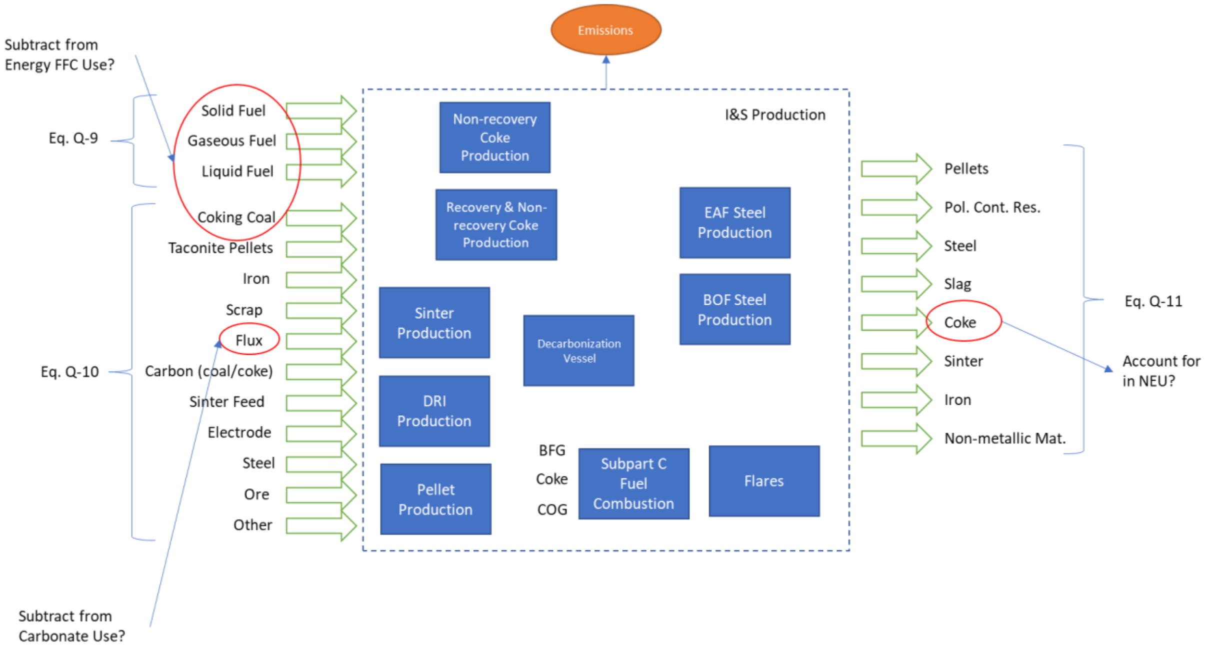
Figure 9. GHGI Methodology Inputs and Outputs



2.8.2 GHGRP Approach

Figure 10 provides an overview of the inputs and outputs for a potential GHGRP emissions estimation methodology. Specific inputs and outputs that could be used within other chapters of the GHGI are highlighted. However, due to data limitation and aggregation challenges that are further discussed in section 4 these inputs and outputs cannot be directly obtained from the GHGRP.

Figure 10. GHGRP Inputs and Outputs Methodology



3. Methodology in the Context of IPCC Guidelines

Emissions from iron and steel (I&S) production in the GHG Inventory are organized into:

(1) process emissions, included under the Industrial Processes and Product Use (IPPU) sector in the GHGI and
(2) energy or combustion emissions, included under the Energy sector in the GHGI.

In developing the GHGI, the EPA uses the tiered IPCC methodological framework and supplements them with available national methodologies and data where possible if more appropriate to national technologies and operating practices. Figure 11 is from the 2019 Refinements to the 2006 IPCC Guidelines.[13] It shows the allocation and reporting of emissions from iron and steel production related emissions across the IPPU and Energy sector.

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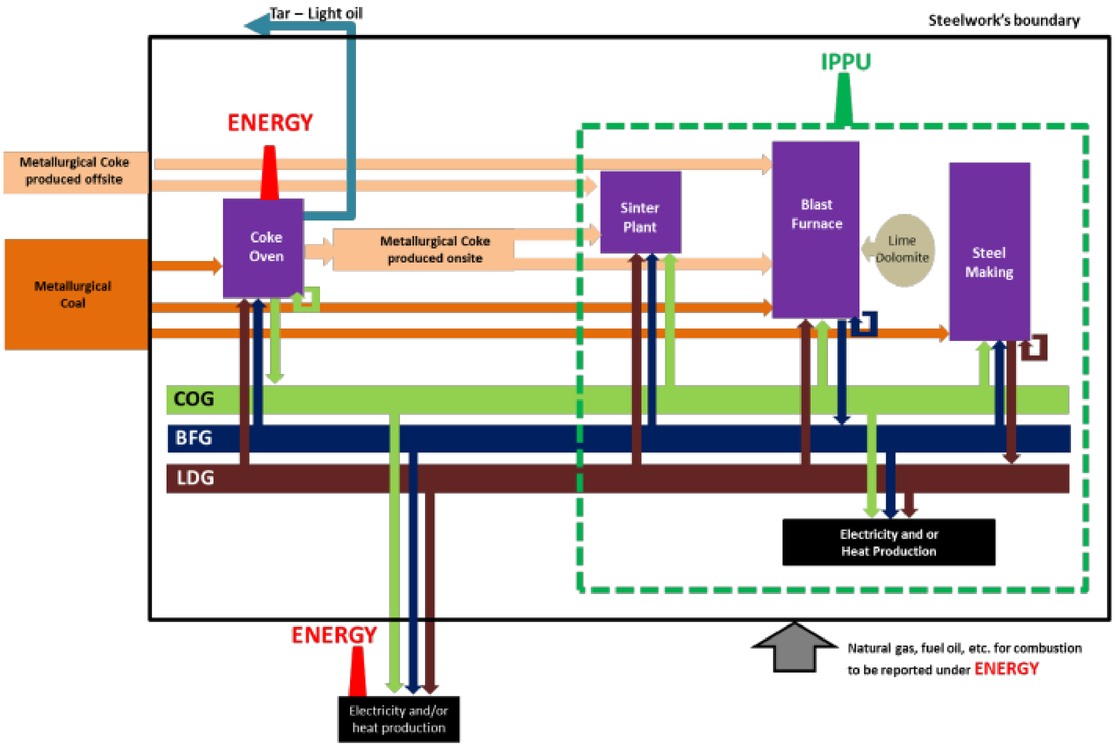
[13] *2019 Refinement to the 2006 IPCC Guidelines*, Volume 3 Industrial Processes and Product Use, Chapter 4 Metal Industry Emissions, Figure 4.8d.

Figure 11. Allocation of I&S Emissions to IPPU or Energy Sector

Figure 4.8d (New) **Energy or IPPU CO_2 emissions allocation in an integrated iron and steel facility**



As can be seen above, there is a connection between emission reporting of iron and steel related emissions under Energy and IPPU. The GHGI follows the 2006 IPCC Guidelines but has a country specific approach to splitting emissions reporting that is based on available data and data resolution. Key aspects of the U.S. country specific approach for reporting I&S emissions are listed below:

- The GHGI counts emissions from metallurgical coke production as part of IPPU with I&S. The main reason for this is the strong link to iron and steel production (e.g., integrated facilities) and the difficulty in splitting them.
- The GHGI includes some emissions from coal, natural gas, and fuel oil use as part of IPPU since it is unclear if they are combusted for energy or used as process inputs (e.g., direct injection coal).
- Emissions from processes like pellet and direct reduced iron production are included under IPPU but may involve energy use that is already captured under the energy sector.
- Other emissions splits generally follow the approach in the 2006 IPCC guidelines.

Energy or combustion related emissions from iron and steel production are not specifically estimated in the GHGI but are included within industrial combustion estimates reported in the Energy Chapter of the GHGI and. The GHGI estimates CO_2 emissions from fossil fuel combustion applying a Tier 2 method described by the 2006 IPCC Guidelines.

1. Determine total fuel consumption aggregated by end-use sector (i.e., residential, commercial, industrial, transportation, and electric power) and fuel category (e.g., motor gasoline, distillate

fuel oil). Fuel consumption data for the United States is obtained directly from the EIA of the U.S. Department of Energy (DOE), primarily from the Monthly Energy Review.[14]

2. Subtract the amount of energy that is accounted for under the IPPU sector, for example, as described above for I&S.

Table 16 shows total industrial sector energy use in 2019 and the amount subtracted that is assumed to be used by I&S, as an example.

Table 16. Total Industrial Sector Energy Use and Quantities Assumed to be I&S Usage

Industrial Sector	**2019 Total (Trillion Btu)**	**Subtracted (based on use in the IPPU Sector)**	
Coking Coal	514.4	Used in I&S (also Lead & Zinc)	382.3
Other Coal	602.9	Used in I&S (direct injection)	58.9
Natural Gas	10,659.6	Used in I&S	51.1
Asphalt & Road Oil	843.9		
Distillate Fuel	1,263.4	Used in I&S	0.3
Kerosene	2.0		
HGL / LPG	2,887.4		
Lubricants	117.6		
Motor Gasoline	268.8		
Residual Fuel	37.4		
Other Petroleum	3,522.1		

Combustion emissions are then calculated based on multiplying the adjusted energy use activity data by carbon factors. Because totals are available for the industrial sector as a whole and not by specific industrial sub sectors like I&S, emissions in the GHGI are reported by fuel type and by end use sector.

4. Challenges with the Use of GHGRP Data

The GHGRP data could be used directly to provide emissions associated with I&S production however it would be difficult to track carbon flows between the different processes with this approach as is done now in the GHGI accounting. The GHGRP data provides emissions from the different processes but not necessarily the carbon inputs and outputs associated with the process. Those data elements are often considered to have the potential to cause competitive harm if disclosed publicly and are classified as CBI in the GHGRP reporting as discussed in the following section. Therefore, if the emissions from GHGRP were used directly without knowing the inputs and outputs there could be double counting in other portions of the inventory including fossil fuel combustion in the industrial sector, process uses of carbonates and non-energy use emissions.

4.1. The Inputs Verification Tool (IVT)

Under the GHGRP, facilities determine emissions using a variety of methods, including direct measurement, mass balance, and the use of emission factors. This means that many facilities use equations to calculate emissions. The data used in these equations often include process or production

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[14] US EIA, *Monthly Energy Review,* 2015 through 2019

data specific to each facility's operations. EPA assessed that these inputs to emission equations meet the definition of "emission data" under 40 CFR 2.301(a)(2)(i), and the Clean Air Act precludes "emission data" from being treated as confidential. EPA received comments indicating significant stakeholder concerns regarding potential release of these data. EPA subsequently evaluated each data element used as an input to an emission equation to determine whether the data would cause competitive harm if released to the public. Where the Agency identified disclosure concerns, the implemented an alternative electronic verification approach, specifically the Inputs Verifier Tool (79 FR 63750, October 24, 2014). This tool allows EPA to verify equation inputs without requiring the data to be reported to the program.

Where iron and steel production facilities use mass balance methods, Subpart Q requires the usage of the IVT. Specifically, each of the material inputs to equations Q-1 through Q-7 are handled through the IVT and therefore are unavailable for use in estimating activity data or emissions for the GHGI, either on a facility-specific basis or aggregated at the industry level.

Where iron and steel production facilities use direct measurement methods (i.e., CEMS), the following data elements are reported to subpart Q and are protected as CBI. As noted in section 1.2, data elements identified as CBI are not available at the facility-level but subject to meeting aggregation criteria may be published at the subpart level:

- The annual production quantity of taconite pellets, coke, sinter, iron, and raw steel for coke pushing operations [40 CFR 98.176(b)]; and
- The total coal charged to coke ovens for each process, in metric tons per year [40 CFR 98.177(f)(9)].

Appendix A: Summary of CBI and Equation Data Elements in the IVT to this memorandum presents the CBI and IVT data elements under subpart Q of the GHGRP.

4.2. Data Aggregation

As noted in section 1.1, EPA is evaluating additional improvements including:

- accounting for emissions from metallurgical coke production in the Energy chapter;
- identifying the amount of coke breeze, coal tar, and light oil produced during coke production; and
- methodologies to better characterize emissions from the use of process gases and fuels within the Energy and IPPU chapters.

Although many of the data elements needed to inform these improvements are inputs to the emissions equations in subpart Q, due to the IVT process discussed in section The Inputs Verification Tool (IVT), this data is not available to inform the GHGI. The specific data inputs from the GHGRP and their associated potential use as part of the GHGI are presented in Table 17.

Table 17. Subpart Q Data Inputs and Associated GHGI Use

GHGRP Equation	Data Input	Potential Use
Eq. Q-9	Mass of solid fuel combusted (mt)	Energy Fossil Fuel Combustion
Eq. Q-9	Volume of liquid fuel combusted (gallons)	
Eq. Q-9	Volume of gaseous fuel combusted (scf)	
Eq. Q-10	Mass of coal charged to coke oven battery (mt)	
Eq. Q-10	Mass of flux materials charged to BOF (mt)	Carbonate Use

GHGRP Equation	Data Input	Potential Use
Eq. Q-11	Mass of coke produced by non-recovery coke batteries (mt)	Non-Energy Use

Given this limitation, approaches would need to be developed to determine these quantities based upon available data from the GHGRP directly and/or other data sources. One potential approach would be to use historic activity data available from the AISI ASR (available for the time series from 1990 to 2019, inclusive) to align with trends in reported GHGRP emissions for the period of overlap from 2010 to 2019. The correlation between these values could then be used to back-calculate sector level estimates of these data inputs that are otherwise unavailable for 2020 and following years of the GHGI. This is a proxy approach and introduces additional uncertainty, as it assumes relationships across time.

5. Time Series Considerations

Integration of GHGRP data into the GHGI would require that particular attention be made to ensure time-series consistency. This is required as the facility-level reporting data from EPA's GHGRP are not available for all inventory years (i.e., 1990 through 2009) required to be reported in the GHGI.

Further, visual evaluation of subpart Q emissions data for reporting year 2010 is suggestive of the potential for significant underestimation of emission. For this reason, it is proposed that any methodology relying principally on GHGRP data would be applied beginning in reporting year 2011 and onward and that time series consistency adjustments would be applied for reporting years 1990 through 2010, inclusive.

Chapter 5 of the *2006 IPCC Guidelines* provides recommendations of methodologies to address time series consistency. These methodologies include the overlap, surrogate data, interpolation, and extrapolation methods.

6. Uncertainty

The current estimation approach for iron and steel and coke emissions relies on a number of inputs and emission factors. There is uncertainty associated with each of those which is used in the current approach to determining uncertainty with the emission estimates.

For example, for subcategories using a Tier 1 method (i.e., sinter production, pellet production, and DRI production), emission factors are obtained from the default Tier 1 emission factors for CO_2 and CH_4 in the 2006 IPCC Guidelines. According to the 2006 IPCC Guidelines, where Tier 1 default emission factors are used the uncertainty range is ±25 percent. Therefore, an uncertainty range of ±25 percent was assumed for those subcategories using the Tier 1 approach.

For other subcategories a Tier 2 mass balance approach was used, the 2006 IPCC Guidelines indicate, "Tier 2 material-specific carbon contents would be expected to have an uncertainty of 10 percent… For Tier 2, the total amount of reducing agents and process materials used for iron and steel production would likely be within 10 percent." Therefore, an uncertainty range of ±10 percent was assumed for carbon contents, reducing agents, and process materials.

For the use of GHGRP data, the 2006 IPCC Guidelines indicate, "actual emissions data for Tier 3 would be expected to have a ±5 percent uncertainty." As the GHGRP activity data are obtained at the plant level, the uncertainty would be assumed to be low, and the ±5 percent described in the 2006 IPCC Guidelines may be an appropriate uncertainty range to apply if GHGRP data is used. The uncertainty analysis associated with iron and steel and coke production emission estimates would need to be updated with and changes in the methodology, as it depends on data used. This will be something considered along with any new methodological approach.

7. Request for Feedback

EPA seeks technical expert feedback on the methodology and issues discussed in this memo and the questions below.

1. For certain activity data that are no longer available due to CBI concerns, EPA makes estimates by adjusting the 2019 activity data (i.e., last year available) based upon total process emissions data from the GHGRP (*i.e.*, 2019 activity data is scaled based upon the change in 2019 GHGRP reported emissions and emissions for the year being estimated). Please provide any recommendations to improve the transparency, accuracy, consistency, and/or completeness of the estimation methods.
2. EPA continues to consider moving metallurgical coke production as a separate process to be reported under energy use in the GHGI. Please provide any recommendations on this approach.
3. Please provide recommendations for any information that could be added to the discussion to provide additional transparency and clarity.
4. Please provide any suggestions of potential sources of activity data for the iron and steel production source category. Examples of activity data include the quantity and carbon content of the following:
   Molten iron charged to BOFs;
   Direct reduced iron charged to EAFs;
   Ferrous scrap charged to BOFs and EAFs;
   Flux materials charged to BOFs and EAFs;
   Carbonaceous materials (e.g., coal, coke) charged to the BOFs, EAFs, and direct reduction furnaces;
   Sinter feed material charged to the sinter processes;
   Carbon electrode consumed in EAFs;
   Molten steel charged to decarburization vessels;
   Iron ore or iron ore pellets fed to direct reduction furnaces;
   Fired pellets produced by taconite furnaces;
   Slag produced by BOFs and EAFs;
   Sinter produced;
   Non-metallic materials produced by direct reduction furnaces;
   Gaseous fuel combusted for sinter production and pellet production and in direct reduction furnaces;
   Liquid fuel combusted for taconite production; and
   Solid fuel combusted for taconite production.
5. Please provide any suggestions of potential sources of activity data for the metallurgical coke production source category. Examples of activity data include the quantity and carbon content of gaseous fuel (i.e., NG and BFG) consumed for coke production and the quantity of coke oven gases produced.
6. Please provide any information on how GHGRP emissions data could be used and avoid double counting in other sectors of the GHGI including fossil fuel combustion, process uses of carbonates and non-energy use emissions.
7. Please provide any data concerning uncertainty assumptions and how they might be updated based on use of GHGRP data if applicable.

8. Are there other sources of information that could be used in conjunction with the GHGRP data to provide insight into adjustments needed in other sectors of the GHGI.
9. Are there other ways to aggregate the data and provide emissions information without the need for detailed tracking of carbon flows between processes?
10. Is the conclusion reached in the 1.3 coverage analysis reasonable that subpart Q captures the majority of GHG emissions from the sector? Are there adjustments that should be made to ensure full coverage or alternative data sources to supplement GHGRP data?

8. References

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9. Appendix A: Summary of CBI and Equation Data Elements in the IVT

Rule Citation (40 CFR part 98)	Data Element Description	CBI or IVT	Q-1	Q-2	Q-3	Q-4	Q-5	Q-6	Q-7	98.173(b)	98.173(c)
98.176(b)	Annual quantity taconite pellets, coke, sinter, iron, and raw steel (CEMS) (for all units except decarborization vessels that are not argon-oxygen decarbonization vessels)	CBI									
98.176(b)	Annual quantity taconite pellets, coke, sinter, iron, and raw steel (CEMS) (for decarborization vessels that are not argon-oxygen decarbonization vessels) (reported beginning in RY2011)	CBI									
98.177(f)(1)(i)	Annual mass of each solid fuel (mt)	IVT	x								
98.177(f)(1)(ii)	Carbon content of each solid fuel, from the fuel analysis (expressed as a decimal fraction)	IVT	x								
98.177(f)(1)(iii)	Annual volume of each gaseous fuel (scf)	IVT	x								
98.177(f)(1)(iv)	Average carbon content of each gaseous fuel, from the fuel analysis results (kg C per kg of fuel)	IVT	x								
98.177(f)(1)(v)	Molecular weight of each gaseous fuel (kg/kg-mole)	IVT	x								
98.177(f)(1)(vi)	Annual volume of each liquid fuel (gallons)	IVT	x								
98.177(f)(1)(vii)	Carbon content of each liquid fuel, from the fuel analysis results (kg C per gallon of fuel)	IVT	x								
98.177(f)(1)(viii)	Annual mass of the greenball (taconite) pellets fed to the furnace (mt)	IVT	x								
98.177(f)(1)(ix)	Carbon content of the greenball (taconite) pellets, from the carbon analysis results (expressed as a decimal fraction)	IVT	x								
98.177(f)(1)(x)	Annual mass of fired pellets produced by the furnace (mt)	IVT	x								
98.177(f)(1)(xi)	Carbon content of the fired pellets, from the carbon analysis results (expressed as a decimal fraction)	IVT	x								
98.177(f)(1)(xii)	Annual mass of air pollution control residue collected (mt)	IVT	x								
98.177(f)(1)(xiii)	Carbon content of the air pollution control residue, from the carbon analysis results (expressed as a decimal fraction)	IVT	x								
98.177(f)(1)(xiv)	Annual mass of each other solid input containing carbon fed to each furnace (mt)	IVT	x								
98.177(f)(1)(xv)	Carbon content of each other solid input containing carbon fed to each furnace (expressed as a decimal fraction)	IVT	x								
98.177(f)(1)(xvi)	Annual mass of each other solid output containing carbon produced by each furnace (mt)	IVT	x								
98.177(f)(1)(xvii)	Carbon content of each other solid output containing carbon (expressed as a decimal fraction)	IVT	x								
98.177(f)(1)(xviii)	Annual mass of each other gaseous input containing carbon fed to each furnace (mt)	IVT	x								
98.177(f)(1)(xix)	Carbon content of each other gaseous input containing carbon fed to each furnace (expressed as a decimal fraction)	IVT	x								
98.177(f)(1)(xx))	Annual mass of each other gaseous output containing carbon produced by each furnace (mt)	IVT	x								

Rule Citation (40 CFR part 98)	Data Element Description	CBI or IVT	Q-1	Q-2	Q-3	Q-4	Q-5	Q-6	Q-7	98.173(b)	98.173(c)
98.177(f)(1)(xxi)	Carbon content of each other gaseous output containing carbon produced by each furnace (expressed as a decimal fraction)	IVT	x								
98.177(f)(1)(xxii)	Annual mass of each other liquid input containing carbon fed to each furnace (mt)	IVT	x								
98.177(f)(1)(xxiii)	Carbon content of each other liquid input containing carbon fed to each furnace (expressed as a decimal fraction)	IVT	x								
98.177(f)(1)(xxiv)	Annual mass of each other liquid output containing carbon produced by each furnace (mt)	IVT	x								
98.177(f)(1)(xxv)	Carbon content of each other liquid output containing carbon produced by each furnace (expressed as a decimal fraction)	IVT	x								
98.177(f)(2)(i)	Annual mass of molten iron charged to the furnace (mt)	IVT		x							
98.177(f)(2)(ii)	Carbon content of the molten iron charged to the furnace, from the carbon analysis results (expressed as a decimal fraction)	IVT		x							
98.177(f)(2)(iii)	Annual mass of ferrous scrap charged to the furnace (mt)	IVT		x							
98.177(f)(2)(iv)	Carbon content of the ferrous scrap charged to the furnace, from the carbon analysis results (expressed as a decimal fraction)	IVT		x							
98.177(f)(2)(v)	Annual mass of the flux materials (e.g., limestone, dolomite) charged to the furnace (mt)	IVT		x							
98.177(f)(2)(vi)	Carbon content of the flux materials charged to the furnace, from the carbon analysis results (expressed as a decimal fraction)	IVT		x							
98.177(f)(2)(vii)	Annual mass of the carbonaceous materials (e.g., coal, coke) charged to the furnace (mt)	IVT		x							
98.177(f)(2)(viii)	Carbon content of the carbonaceous materials charged to the furnace, from the carbon analysis results (expressed as a decimal fraction)	IVT		x							
98.177(f)(2)(ix)	Annual mass of molten raw steel produced by the furnace (mt)	IVT		x							
98.177(f)(2)(x)	Carbon content of the steel produced by the furnace, from the carbon analysis results (expressed as a decimal fraction)	IVT		x							
98.177(f)(2)(xi)	Annual mass of slag produced by the furnace (mt)	IVT		x							
98.177(f)(2)(xii)	Carbon content of the slag produced by the furnace, from the carbon analysis (expressed as a decimal fraction)	IVT		x							
98.177(f)(2)(xiii)	Annual mass of air pollution control residue collected for the furnace (mt)	IVT		x							
98.177(f)(2)(xiv)	Carbon content of the air pollution control residue collected for the furnace, from the carbon analysis results (expressed as a decimal fraction)	IVT		x							
98.177(f)(2)(xv)	Annual mass of each other solid input containing carbon fed to each furnace (mt)	IVT		x							
98.177(f)(2)(xvi)	Carbon content of each other solid input containing carbon fed to each furnace (expressed as a decimal fraction)	IVT		x							
98.177(f)(2)(xvii)	Annual mass of each other solid output containing carbon produced by each furnace (mt)	IVT		x							

Rule Citation (40 CFR part 98)	Data Element Description	CBI or IVT	Q-1	Q-2	Q-3	Q-4	Q-5	Q-6	Q-7	98.173(b)	98.173(c)
98.177(f)(2)(xviii)	Carbon content of each other solid output containing carbon (expressed as a decimal fraction)	IVT		x							
98.177(f)(2)(xix)	Annual mass of each other gaseous input containing carbon fed to each furnace (mt)	IVT		x							
98.177(f)(2)(xx))	Carbon content of each other gaseous input containing carbon fed to each furnace (expressed as a decimal fraction)	IVT		x							
98.177(f)(2)(xxi)	Annual mass of each other gaseous output containing carbon produced by each furnace (mt)	IVT		x							
98.177(f)(2)(xxii)	Carbon content of each other gaseous output containing carbon produced by each furnace (expressed as a decimal fraction)	IVT		x							
98.177(f)(2)(xxiii)	Annual mass of each other liquid input containing carbon fed to each furnace (mt)	IVT		x							
98.177(f)(2)(xxiv)	Carbon content of each other liquid input containing carbon fed to each furnace (expressed as a decimal fraction)	IVT		x							
98.177(f)(2)(xxv)	Annual mass of each other liquid output containing carbon produced by each furnace (mt)	IVT		x							
98.177(f)(2)(xxvi)	Carbon content of each other liquid output containing carbon produced by each furnace (expressed as a decimal fraction)	IVT		x							
98.177(f)(3)(i)	Annual mass of coal charged to the battery (mt)	IVT			x						
98.177(f)(3)(ii)	Carbon content of the coal, from the carbon analysis results (expressed as a decimal fraction)	IVT			x						
98.177(f)(3)(iii)	Annual mass of coke produced by the battery (mt)	IVT			x						
98.177(f)(3)(iv)	Carbon content of the coke, from the carbon analysis results (expressed as a decimal fraction)	IVT			x						
98.177(f)(3)(v)	Annual mass of air pollution control residue collected (mt)	IVT			x						
98.177(f)(3)(vi)	Carbon content of the air pollution control residue, from the carbon analysis results (expressed as a decimal fraction)	IVT			x						
98.177(f)(3)(vii)	Annual mass of each other solid input containing carbon fed to each battery (mt)	IVT			x						
98.177(f)(3)(viii)	Carbon content of each other solid input containing carbon fed to each battery (expressed as a decimal fraction)	IVT			x						
98.177(f)(3)(ix)	Annual mass of each other solid output containing carbon produced by each battery (mt)	IVT			x						
98.177(f)(3)(x)	Carbon content of each other solid output containing carbon (expressed as a decimal fraction)	IVT			x						
98.177(f)(3)(xi)	Annual mass of each other gaseous input containing carbon fed to each battery (mt)	IVT			x						
98.177(f)(3)(xii)	Carbon content of each other gaseous input containing carbon fed to each battery (expressed as a decimal fraction)	IVT			x						
98.177(f)(3)(xiii)	Annual mass of each other gaseous output containing carbon produced by each battery (mt)	IVT			x						
98.177(f)(3)(xiv)	Carbon content of each other gaseous output containing carbon produced by each battery (expressed as a decimal fraction)	IVT			x						

Rule Citation (40 CFR part 98)	Data Element Description	CBI or IVT	Q-1	Q-2	Q-3	Q-4	Q-5	Q-6	Q-7	98.173(b)	98.173(c)
98.177(f)(3)(xv)	Annual mass of each other liquid input containing carbon fed to each battery (mt)	IVT			x						
98.177(f)(3)(xvi)	Carbon content of each other liquid input containing carbon fed to each battery (expressed as a decimal fraction)	IVT			x						
98.177(f)(3)(xvii)	Annual mass of each other liquid output containing carbon produced by each battery (mt)	IVT			x						
98.177(f)(3)(xviii)	Carbon content of each other liquid output containing carbon produced by each battery (expressed as a decimal fraction)	IVT			x						
98.177(f)(4)(i)	Annual volume of the gaseous fuel (scf)	IVT				x					
98.177(f)(4)(ii)	Carbon content of the gaseous fuel, from the fuel analysis results (kg C per kg of fuel)	IVT				x					
98.177(f)(4)(iii)	Molecular weight of the gaseous fuel (kg/kg-mole)	IVT				x					
98.177(f)(4)(iv)	Annual mass of sinter feed material (mt)	IVT				x					
98.177(f)(4)(v)	Carbon content of the mixed sinter feed materials that form the bed entering the sintering machine, from the carbon analysis results (expressed as a decimal fraction)	IVT				x					
98.177(f)(4)(vi)	Annual mass of sinter produced (mt)	IVT				x					
98.177(f)(4)(vii)	Carbon content of the sinter pellets, from the carbon analysis results (expressed as a decimal fraction)	IVT				x					
98.177(f)(4)(viii)	Annual mass of air pollution control residue collected (mt)	IVT				x					
98.177(f)(4)(ix)	Carbon content of the air pollution control residue, from the carbon analysis results (expressed as a decimal fraction)	IVT				x					
98.177(f)(4)(x)	Annual mass of each other solid input containing carbon fed to each sinter process (mt)	IVT				x					
98.177(f)(4)(xi)	Carbon content of each other solid input containing carbon fed to each sinter process (expressed as a decimal fraction)	IVT				x					
98.177(f)(4)(xii)	Annual mass of each other solid output containing carbon produced by each sinter process (mt)	IVT				x					
98.177(f)(4)(xiii)	Carbon content of each other solid output containing carbon (expressed as a decimal fraction)	IVT				x					
98.177(f)(4)(xiv)	Annual mass of each other gaseous input containing carbon fed to each sinter process (mt)	IVT				x					
98.177(f)(4)(xv)	Carbon content of each other gaseous input containing carbon fed to each sinter process (expressed as a decimal fraction)	IVT				x					
98.177(f)(4)(xvi)	Annual mass of each other gaseous output containing carbon produced by each sinter process (mt)	IVT				x					
98.177(f)(4)(xvii)	Carbon content of each other gaseous output containing carbon produced by each sinter process (expressed as a decimal fraction)	IVT				x					
98.177(f)(4)(xviii)	Annual mass of each other liquid input containing carbon fed to each sinter process (mt)	IVT				x					
98.177(f)(4)(xix)	Carbon content of each other liquid input containing carbon fed to each sinter process (expressed as a decimal fraction)	IVT				x					

Rule Citation (40 CFR part 98)	Data Element Description	CBI or IVT	Q-1	Q-2	Q-3	Q-4	Q-5	Q-6	Q-7	98.173(b)	98.173(c)
98.177(f)(4)(xx))	Annual mass of each other liquid output containing carbon produced by each sinter process (mt)	IVT				x					
98.177(f)(4)(xxi)	Carbon content of each other liquid output containing carbon produced by each sinter process (expressed as a decimal fraction)	IVT				x					
98.177(f)(5)(i)	Annual mass of direct reduced iron (if any) charged to the furnace (mt)	IVT					x				
98.177(f)(5)(ii)	Carbon content of the direct reduced iron, from the carbon analysis results (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(iii)	Annual mass of ferrous scrap charged to the furnace (mt)	IVT					x				
98.177(f)(5)(iv)	Carbon content of the ferrous scrap, from the carbon analysis results (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(v)	Annual mass of flux materials (e.g., limestone, dolomite) charged to the furnace (mt)	IVT					x				
98.177(f)(5)(vi)	Carbon content of the flux materials, from the carbon analysis results (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(vii)	Annual mass of carbon electrode consumed (mt)	IVT					x				
98.177(f)(5)(viii)	Carbon content of the carbon electrode, from the carbon analysis results (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(ix)	Annual mass of carbonaceous materials (e.g., coal, coke) charged to the furnace (mt)	IVT					x				
98.177(f)(5)(x)	Carbon content of the carbonaceous materials, from the carbon analysis results (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(xi)	Annual mass of molten raw steel produced by the furnace (mt)	IVT					x				
98.177(f)(5)(xii)	Carbon content of the steel, from the carbon analysis results (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(xiii)	Annual volume of the gaseous fuel (scf at 60°F and 1 atm)	IVT					x				
98.177(f)(5)(xiv)	Average carbon content of the gaseous fuel, from the fuel analysis results (kg C per kg of fuel)	IVT					x				
98.177(f)(5)(xv)	Molecular weight of the gaseous fuel (kg/kg-mole)	IVT					x				
98.177(f)(5)(xvi)	Annual mass of slag produced by the furnace (mt)	IVT					x				
98.177(f)(5)(xvii)	Carbon content of the slag, from the carbon analysis (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(xviii)	Annual mass of air pollution control residue collected (mt)	IVT					x				
98.177(f)(5)(xix)	Carbon content of the air pollution control residue, from the carbon analysis results (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(xx))	Annual mass of each other solid input containing carbon fed to each furnace (mt)	IVT					x				
98.177(f)(5)(xxi)	Carbon content of each other solid input containing carbon fed to each furnace (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(xxii)	Annual mass of each other solid output containing carbon produced by each furnace (mt)	IVT					x				

Rule Citation (40 CFR part 98)	Data Element Description	CBI or IVT	Q-1	Q-2	Q-3	Q-4	Q-5	Q-6	Q-7	98.173(b)	98.173(c)
98.177(f)(5)(xxiii)	Carbon content of each other solid output containing carbon (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(xxiv)	Annual mass of each other gaseous input containing carbon fed to each furnace (mt)	IVT					x				
98.177(f)(5)(xxv)	Carbon content of each other gaseous input containing carbon fed to each furnace (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(xxvi)	Annual mass of each other gaseous output containing carbon produced by each furnace (mt)	IVT					x				
98.177(f)(5)(xxvii)	Carbon content of each other gaseous output containing carbon produced by each furnace (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(xxviii)	Annual mass of each other liquid input containing carbon fed to each furnace (mt)	IVT					x				
98.177(f)(5)(xxix)	Carbon content of each other liquid input containing carbon fed to each furnace (expressed as a decimal fraction)	IVT					x				
98.177(f)(5)(xxx)	Annual mass of each other liquid output containing carbon produced by each furnace (mt)	IVT					x				
98.177(f)(5)(xxxi))	Carbon content of each other liquid output containing carbon produced by each furnace (expressed as a decimal fraction)	IVT					x				
98.177(f)(6)(i)	Annual mass of molten steel charged to the vessel (mt)	IVT						x			
98.177(f)(6)(ii)	Carbon content of the molten steel before decarburization, from the carbon analysis results (expressed as a decimal fraction)	IVT						x			
98.177(f)(6)(iii)	Carbon content of the molten steel after decarburization, from the carbon analysis results (expressed as a decimal fraction)	IVT						x			
98.177(f)(6)(iv)	Annual mass of air pollution control residue collected (mt)	IVT						x			
98.177(f)(6)(v)	Carbon content of the air pollution control residue, from the carbon analysis results (expressed as a decimal fraction)	IVT						x			
98.177(f)(6)(vi)	Annual mass of each other solid input containing carbon fed to each decarburization vessel (mt)	IVT						x			
98.177(f)(6)(vii)	Carbon content of each other solid input containing carbon fed to each decarburization vessel (expressed as a decimal fraction)	IVT						x			
98.177(f)(6)(viii)	Annual mass of each other solid output containing carbon produced by each decarburization vessel (mt)	IVT						x			
98.177(f)(6)(ix)	Carbon content of each other solid output containing carbon (expressed as a decimal fraction)	IVT						x			
98.177(f)(6)(x)	Annual mass of each other gaseous input containing carbon fed to each decarburization vessel (mt)	IVT						x			
98.177(f)(6)(xi)	Carbon content of each other gaseous input containing carbon fed to each decarburization vessel (expressed as a decimal fraction)	IVT						x			
98.177(f)(6)(xii)	Annual mass of each other gaseous output containing carbon produced by each decarburization vessel (mt)	IVT						x			

Rule Citation (40 CFR part 98)	Data Element Description	CBI or IVT	Q-1	Q-2	Q-3	Q-4	Q-5	Q-6	Q-7	98.173(b)	98.173(c)
98.177(f)(6)(xiii)	Carbon content of each other gaseous output containing carbon produced by each decarburization vessel (expressed as a decimal fraction)	IVT						x			
98.177(f)(6)(xiv)	Annual mass of each other liquid input containing carbon fed to each decarburization vessel (mt)	IVT						x			
98.177(f)(6)(xv)	Carbon content of each other liquid input containing carbon fed to each decarburization vessel (expressed as a decimal fraction)	IVT						x			
98.177(f)(6)(xvi)	Annual mass of each other liquid output containing carbon produced by each decarburization vessel (mt)	IVT						x			
98.177(f)(6)(xvii)	Carbon content of each other liquid output containing carbon produced by each decarburization vessel (expressed as a decimal fraction)	IVT						x			
98.177(f)(7)(i)	Annual volume of the gaseous fuel (scf at 68F and 1 atm)	IVT							x		
98.177(f)(7)(ii)	Average carbon content of the gaseous fuel, from the fuel analysis results (kg C per kg of fuel)	IVT							x		
98.177(f)(7)(iii)	Molecular weight of the gaseous fuel (kg/kg-mole)	IVT							x		
98.177(f)(7)(iv)	Annual mass of iron ore or iron pellets fed to the furnace (mt)	IVT							x		
98.177(f)(7)(v)	Carbon content of the iron ore or iron pellets, from the carbon analysis (expressed as a decimal fraction)	IVT							x		
98.177(f)(7)(vi)	Annual mass of carbonaceous materials (e.g., coal, coke) charged to the furnace (mt)	IVT							x		
98.177(f)(7)(vii)	Carbon content of the carbonaceous materials, from the carbon analysis results (expressed as a decimal fraction)	IVT							x		
98.177(f)(7)(viii)	Annual mass of each other material charged to the furnace (mt)	IVT							x		
98.177(f)(7)(ix)	Average carbon content of each other material charged to the furnace, from the carbon analysis results (expressed as a decimal fraction)	IVT							x		
98.177(f)(7)(x)	Annual mass of iron produced (mt)	IVT							x		
98.177(f)(7)(xi)	Carbon content of the iron produced, from the carbon analysis results (expressed as a decimal fraction)	IVT							x		
98.177(f)(7)(xii)	Annual mass of non-metallic materials produced by the furnace (mt)	IVT							x		
98.177(f)(7)(xiii)	Carbon content of the non-metallic materials produced, from the carbon analysis results (expressed as a decimal fraction)	IVT							x		
98.177(f)(7)(xiv)	Annual mass of air pollution control residue collected (mt)	IVT							x		
98.177(f)(7)(xv)	Carbon content of the air pollution control residue collected, from the carbon analysis results (expressed as a decimal fraction)	IVT							x		
98.177(f)(7)(xvi)	Annual mass of each other solid input containing carbon fed to each furnace (mt)	IVT							x		
98.177(f)(7)(xvii)	Carbon content of each other solid input containing carbon fed to each furnace (expressed as a decimal fraction)	IVT							x		
98.177(f)(7)(xviii)	Annual mass of each other solid output containing carbon produced by each furnace (mt)	IVT							x		

Rule Citation (40 CFR part 98)	Data Element Description	CBI or IVT	Q-1	Q-2	Q-3	Q-4	Q-5	Q-6	Q-7	98.173(b)	98.173(c)
98.177(f)(7)(xix)	Carbon content of each other solid output containing carbon (expressed as a decimal fraction)	IVT							x		
98.177(f)(7)(xx))	Annual mass of each other gaseous input containing carbon fed to each furnace (mt)	IVT							x		
98.177(f)(7)(xxi)	Carbon content of each other gaseous input containing carbon fed to each furnace (expressed as a decimal fraction)	IVT							x		
98.177(f)(7)(xxii)	Annual mass of each other gaseous output containing carbon produced by each furnace (mt)	IVT							x		
98.177(f)(7)(xxiii)	Carbon content of each other gaseous output containing carbon produced by each furnace (expressed as a decimal fraction)	IVT							x		
98.177(f)(7)(xxiv)	Annual mass of each other liquid input containing carbon fed to each furnace (mt)	IVT							x		
98.177(f)(7)(xxv)	Carbon content of each other liquid input containing carbon fed to each furnace (expressed as a decimal fraction)	IVT							x		
98.177(f)(7)(xxvi)	Annual mass of each other liquid output containing carbon produced by each furnace (mt)	IVT							x		
98.177(f)(7)(xxvii)	Carbon content of each other liquid output containing carbon produced by each furnace (expressed as a decimal fraction)	IVT							x		
98.177(f)(8)(i)	Average hourly feed or production rate, as applicable, during the test (mt/hour)	IVT								x	
98.177(f)(8)(ii)	Annual total feed or production, as applicable (mt)	IVT								x	
Total coal charged to the coke ovens for each process (mt/year)											x

Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Improvements to Manure Management Estimates

1 Introduction

The U.S. Environmental Protection Agency (EPA), with support from Eastern Research Group (ERG), prepares the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (*Inventory*) which includes livestock greenhouse gas (GHG) emissions estimates in the manure management and enteric fermentation categories. The U.S. Department of Agriculture Office of the Chief Economist (USDA OCE) is working with EPA and ERG to improve these estimates. As part of these efforts, ERG requested data from USDA Natural Resources Conservation Service (NRCS) staff concerning waste management system (WMS) data for dairy cows, swine, beef feedlots, and poultry (layers and broilers).

This memorandum describes the data collection, data processing, data integration steps, and WMS data source reconciliation within the time series for integration of the updated beef feedlot and poultry WMS data into the *Inventory*.

2 Previous Data Sources

The following sections provide a summary of the previous *Inventory's* beef feedlot, layers, and broilers WMS usage methodology and a description of the updated data received from USDA NRCS.

2.1 Previous Data Sources and Inventory Methodology

Table 1 shows the data source and description of the Inventory WMS data. See EPA (2023) for more detail.

Table 1. Inventory WMS Usage Data Sources and Description.

Animal	Year of the Inventory: Source
Beef Feedlots	1990—current: Assumed 100 percent of manure deposited in dry lots (EPA 2002). In addition, because manure also is managed in runoff ponds managed in this manure for a long period of time a small percentage is also attributed to liquid/slurry systems (ERG 2000).
Layers	1990—1992:(EPA 1992). 1993—1998: Linear interpolation 1999—current: A 1999 survey from the United Egg producers estimated operations using housing with a flush system to anaerobic lagoons or high-rise housing without bedding (poultry without bedding).
Broilers	1990—current: One percent of broiler manure is assumed to be deposited on pasture, the remaining deposited in poultry with bedding.

Source: EPA (2023)

3 Improvements

3.1 Updated Data Source Description

USDA OCE and ERG worked with NRCS staff to develop a data request spreadsheet with the goal of capturing available knowledge from regional NRCS staff. The request was meant to estimate the WMS usage for the entire state, though may be split into different operation sizes depending on animal type. ERG compiled the data request in a spreadsheet and submitted it to NRCS staff in 2019. NRCS regional staff were requested to voluntarily provide WMS data for 2018.

NRCS staff suggested edits to the data collection spreadsheet. The data request split housing/confinement type and storage treatment. Options for the confinement and storage types were decided by the NRCS staff; staff were also able to use "other" to write in systems not captured in drop down menus in the request spreadsheet. Staff were asked to estimate **the percent of operations/manure** (within the state) using the confinement or storage type as well as **the percent of time (or number of months)** the system type was used. See Table 2 for the available options provided to NRCS staff.

Table 2. NRCS Staff Data Request Selections

Animal	Operation Size	Confinement Type	Storage & Treatment
Beef Feedlot	• Small (1-99 head) • Medium (100-499 head) • Large (>500 head)	• Deep Bedded • Dry lot – roof • Dry lot – no roof • House slatted floor – scraped • House slatted floor – flush • Other	• Scraped and removed daily to field • Scrape – Solid Storage • Flush-WSP-Liquid-covered • Flush-WSP-Liquid-uncovered • Flush-WSF-Liquid-covered-AD • Flush-Lagoon-covered • Flush-Lagoon-uncovered • Flush-Lagoon-covered-AD • Flush-Pit-Shallow • Flush-Pit-Deep • Flush-Pit-Shallow-AD • Flush-Pit-Deep-AD • WSF-Liquid-covered • WSF-Liquid-uncovered • WSF-Liquid-covered-AD • Flush-WSF-Solid Separation-Solid Storage • Composted • Other
Poultry	• Any	• Pasture • House with bedding/litter • House without bedding/litter • Other	• Scraped and removed daily to field • Scraped - Solid storage • Waste Storage Facility – liquid – covered • Waste Storage Facility – liquid – uncovered • Waste Storage Facility – liquid – covered - AD • Waste Storage Facility – liquid – solid separation – solid storage • Treatment Lagoon – covered • Treatment Lagoon – uncovered • Treatment Lagoon – covered-AD

Animal	Operation Size	Confinement Type	Storage & Treatment
			- Composting - Other - N/A

a – While dairy and swine were included in the NRCS data request, USDA OCE focused on poultry and beef feedlot updates because recent, more comprehensive, USDA surveys data were available to estimate dairy and swine WMS data.
AD = anaerobic digester
N/A = not applicable
WSF = waste storage facility
WSP = waste storage pond

Table 3 presents a summary of the state-level data provided by NRCS staff. In some cases, NRCS staff may have not provided data for a given animal or operation size. Reasons for the missing data include:

- As noted, the request was voluntary.
- Specific animal types were not present in the state.
- Animals on a particular operation size were not present in the stated.
- For beef feedlot, NRCS staff were instructed to not include time for beef that were 100 percent on pasture/range.

Table 3. NRCS Data Provided

	Poultry		Beef Feedlots		
State	Layers	Broilers	<100	100-499	>500
AK	X	X	X	X	--
AR	X	X	--	--	--
CO	X	X	X	X	X
DE	X	X	X	--	--
FL	X	X	--	--	X
IA	X	--	X	X	X
ID	X	X	X	X	X
IL	X	X	X	X	X
KY	--	--	X	--	--
LA	X	X	--	--	--
MA	X	X	X	X	--
MO	X	X	X	X	X
MT	X	X	X	X	X
NC	X	X	X	X	--
ND	--	--	X	X	X
NE	X	X	X	X	X
NJ	X	X	X	X	--

State	Poultry		Beef Feedlots		
	Layers	Broilers	<100	100-499	>500
NV	--	--	X	X	X
OH	X	X	X	X	X
OR	X	X	X	X	X
VA	X	X	X	X	--
WI	X	X	X	X	--

4 Processing NRCS Staff Data

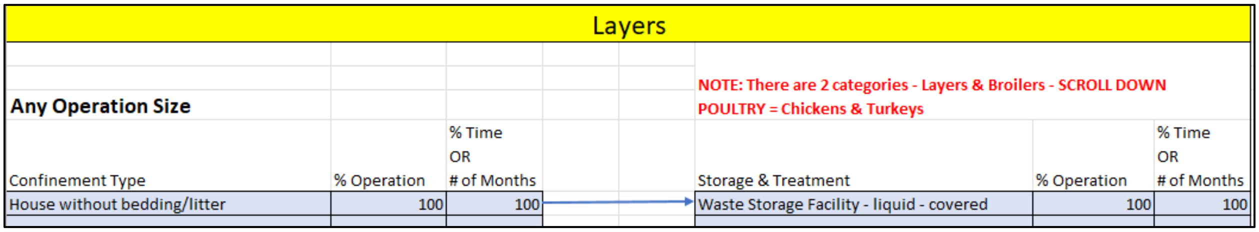
The data required multiple steps to process. Those steps are provided in Section 4.1, while Section 4.2 and 4.3 provide additional details on the regions and WMS specific steps.

4.1 General Steps

The following are the general steps ERG used to prepare the updated WMS usage data for the *Inventory*:

1) Reconciled the WMS between the data collection categories and the Inventory WMS categories (see Section 4.2 for details).
    a) For beef feedlots, where the percent of time a given percent of operations did not equal 100, ERG assumed the remaining time was spent on pasture.
2) Multiplied the percent of operations by the percent of time animals spend in a given confinement or treatment system.
3) Combined the confinement types and storage and treatment types.
    a) As noted, the NRCS staff provided data as a treatment train where manure from a confinement type (e.g., Dry Lot) routes to a given storage or treatment type (e.g., Solid Storage). The *Inventory* methodology would assume that a portion of the manure would be in confinement and a portion in storage at any one moment in time. When storage and treatment types were specific to a confinement type, ERG treated them as a percent of that confinement type.
    b) Normalized data as needed to equal 100 percent of manure.

Figure 2-1 shows a simple example where, NRCS reported 100 percent of operations with a confinement type of “house without bedding/litter” routing to storage treatment of “waste storage facility – liquid -- covered" for 100 percent of the time. ERG normalized these data to attribute 50 percent is attributed to poultry without bedding/litter and 50 percent to liquid/slurry systems.



Layers

NOTE: There are 2 categories - Layers & Broilers - SCROLL DOWN
POULTRY = Chickens & Turkeys

Any Operation Size

Confinement Type	% Operation	% Time OR # of Months		Storage & Treatment	% Operation	% Time OR # of Months
House without bedding/litter	100	100	→	Waste Storage Facility - liquid - covered	100	100

Figure 2-1. NRCS staff reported data for New Jersey Layers

4.2 WMS Reconciliation

Confinement and storage types are not treated differently within the *Inventory*—all are types of manure management and are therefore included in the WMS dataset. Table 4 provides the crosswalk ERG developed to match WMS types from the NRCS data collection to *Inventory* WMS, including when NRCS staff provided an "other" WMS or additional notes within the provided spreadsheet. For both composting and bedded pack, the most conservative *Inventory* equivalent was assumed (meaning the WMS with a middle-ground emission factor).

Table 4. Crosswalk of NRCS Confinement or Storage Type to Inventory WMS

Animal Type	NRCS Confinement/Storage Type	Inventory WMS
Layers	House without bedding/litter	Poultry without bedding
	House with bedding/litter	Poultry with bedding
	Waste Storage Facility - liquid - covered	Liquid/Slurry
	Scrape - Solid Storage	Solid storage
	Composting	Composting-static pile
	Treatment lagoon-uncovered	Anaerobic lagoon
	Pasture	Pasture
	Other: Small cage (sometimes described as housing with/without bedding), with access to outside.	Poultry with or without bedding dependent on specific notes.
Broilers	House with bedding/litter	Poultry with bedding
	Scrape to field	Pasture
	Composting	Composting-static pile
	Scrape - Solid Storage	Solid storage
	Other: Sometimes described as housing with/without bedding, with access to outside.	Poultry with or without bedding dependent on specific notes.

Animal Type	NRCS Confinement/Storage Type	Inventory WMS
Beef Feedlot	Dry lot - no roof	Dry Lot
	Dry lot - roof	Dry Lot
	Bedded Pack	Cattle Deep Litter (>1 month)
	Scrape - Solid Storage	Solid Storage
	House slatted floor - scraped	Dry Lot or Barn (with Deep Pit) depending on any notes or associated Storage/Treatment.
	Flush - Pit - Deep	Deep Pit
	Composted	Composting-static pile
	Other	Pasture
	Waste Storage Facility - liquid - uncovered	Liquid/slurry
	Waste Storage Facility - liquid – covered (Combined with Confinement Type Slatted Barn)	Deep Pit
	Scraped and removed daily to field	Daily Spread

4.3 Regional Breakdown

Where data were not provided for an individual state, ERG average available data from missing states in the region and applied to the other states in the region (see Table 5). While beef feedlot WMS usage data have not historically been available by operation size, there were differences available by region. ERG maintained those regions for this analysis, with slight variations dependent on available data.

Table 5. States within Regions

Inventory Region	Operation size (when applicable): States within region where NRCS staff provided data	Other states in region
Layers		
Central	CO, ID, MT, UT	AZ, NV, NM, OK, TX, WY

Inventory Region	Operation size (when applicable): States within region where NRCS staff provided data	Other states in region
Mid-Atlantic	DE, MA, NJ, NC, VA	CT, KY, ME, MD, NH, NY, PA, RI, TN, VT, WV
Midwest	IL, IA, MO, NE, OH, WI	IN, KS, MI, MN, ND, SD
Pacific	AK, OR	CA, HI, WA
South	AR, FL, LA	AL, GA, MS, SC
Broilers		
Central	CO, ID, MT	AZ, NV, NM, OK, TX, UT, WY
Mid-Atlantic	DE, MA, NJ, NC, VA	CT, KY, ME, MD, NH, NY, PA, RI, TN, VT, WV
Midwest	IL, IA, MO, NE, OH, WI	IN, KS, MI, MN, ND, SD
Pacific	AK, OR	CA, HI, WA
South	AR, FL, LA	AL, GA, MS, SC
Beef Feedlots		
Central	Small, Medium, Large: CO, ID, MT, NV, UT	AZ, NM, OK, TX, WY
Mid-Atlantic/South[a]	Small: DE, KY, MA, NJ, NC, VA	CT, ME, MD, NH, NY, PA, RI, TN, VT, WV
	Medium: MA, NJ, NC, VA	
	Large: FL	AL, AR, GA, LA, MS, SC
Midwest	Small, Medium: IL, IA, MO, NE, ND, OH, WI	IN, KS, MI, MN, SD
	Large: IL, IA, MO, NE, ND, OH	
Pacific	Small, Medium: AK	CA, HI, WA
	Small, Medium, Large: OR	

a –Mid-Atlantic and Southern regions were combined due to available data and application to the time series (see Section 3).

5 Time Series Application

For integration into the *Inventory*, the NRCS data need to be applied to the *Inventory* time series. The application to the time series varied for poultry and beef feedlots because beef feedlot data included operation sizes. Generally, data from NRCS were applied to 2018 and years between 2018 and the previous dataset year (e.g., 2002) were linearly interpolated (e.g., between 2018 and 2002). The following subsections present the steps to apply the updated poultry and beef feedlot WMS data to the time series. See Section 7 for next steps and acknowledgements of the reality of this methodology.

5.1 Poultry

Table 6 presents how ERG applied the various data sources to the time series. ERG applied WMS data to the *Inventory* year for which the survey or study collected data, therefore some years of the *Inventory* timeseries were updated while others were not.

Table 6. Inventory Poultry WMS Usage Data Time Series Sources and Description

Animal	Year	Year of the Inventory	Updated from Previous WMS usage?
Layers	1990-1992	EPA (1992)	No
	1993-1998	Linear interpolation	No
	1999	UEP (1999). Same as previous.	No
	2000—2017	Linear interpolation	Yes
	2018—current	NRCS staff data	Yes
Broilers	1990—1992	EPA (1992)	No
	1993—2017	Linear interpolation	Yes
	2018—current	NRCS staff data	Yes

5.2 Beef Feedlots

Historically, the WMS usage data for beef feedlots has not been available at the operation size (e.g., <100 head). ERG applied Census of Agriculture operation size data to determine a weighted average of the WMS usage for the state. The following summarize the caveats and data processing steps used to apply the WMS usage to the Census of Agriculture data, ERG:

1) Obtained Census of Agriculture beef inventory by operation size data for 2002, 2007, 2012, and 2017.
    a) 1992 and 1997 were assumed the same as 2002.
2) Used the reported operation size data into the following ranges: 500+, 200-499, 100-199, 50-99, 20-49, and 1-19 or 10-19 and 1-9 for 2002 and 2007. ERG matched these operation sizes to the operation size ranges noted in the NRCS data for the WMS usage.

3) Distributed undisclosed ("D") values in the Census for several states and operation sizes. USDA reports "D" values to avoid disclosing individual farm data, but for the purpose of the Inventory assumptions are required to determine a full accounting that is as reasonable as possible.
    a) If the D values were the total state-level value (versus an individual operation size), ERG determined a proportion between all D state-level values using the operation sizes reported for the state.
        i) For example, if Louisiana (LA) and Mississippi (MS) reported D at the state-level and there were 500 head attributed to undisclosed data state values. LA reported a D value for the 100-199 and 20-49 operations sizes, and MS reported D values for 1-9 and 10-19 operation sizes:
            (1) LA = [(100+20)/(100+20+1+10)]×500 ~ 458 head
            (2) MS = [(1+10)/(100+20+1+10)]×500 ~ 42 head.
        ii) To determine operation sizes (see step 3b) a state-level value was required.
    b) If the D values were within an operation size (e.g., >500 head), ERG distributed the total undisclosed value based on the proportion of the total state value. Estimated head counts at the operation size level is needed to calculate the weighted average of WMS usage.
        i) For example, if Alabama (AL) and Arkansas (AR) reported D values at the 500+ operation size and there were 5,000 head attributed to undisclosed data for 500+ head operations sizes. If AL had 3,000 total head, and AR had 19,000 total head:
            (1) AL = (3,000/(3,000+19,000))×5,000 ~ 682 head
            (2) AR = (19,000/(3,000+19,000))×5,000 ~ 4,318 head.
4) Determined population in states with zero reported operations. Some states reported zero feedlot operations where there are populations estimated by the Cattle Enteric Fermentation Model. In these cases, ERG applied data from the most recent year of the Census.

ERG interpolated the weighted average of the WMS usage for non-Census years (e.g., 2016) to create the timeseries. Table 7 provides the updated sources for the timeseries of beef feedlot WMS usage data. ERG recognizes that applying the data to the time series in this way has the potential to create unrealistic data trends due to the inconsistent number of practices reported in each data source. While this also occurs for poultry, because the previous Inventory data are older, the change occurs over a longer period of time so there is less of a sharp contrast between different parts of the time series.

Table 7. Inventory Beef Feedlot WMS Usage Data Time Series Sources and Description

Animal	Year	WMS usage Source	Census of Agriculture	Updated from previous WMS usage?
Beef Feedlot	1990—2002	EPA (2002), normalized to 100%	2002	No[a]
	2003—2006	Linear interpolation between normalized EPA (2002) and NRCS staff data	Linear interpolation between 2002 and 2007	Yes
	2007		2007	
	2008—2011		Linear interpolation between 2007 and 2012	
	2012		2012	

Animal	Year	WMS usage Source	Census of Agriculture	Updated from previous WMS usage?
	2013—2017		Linear interpolation between 2012 and 2017	
	2017		2017	
	2018—current	NRCS staff data		

a – ERG normalized beef WMS to 100% to avoid creating an incidental decreasing trend between a WMS distribution slightly > 100% of manure (i.e., EPA 2002) and = 100% (i.e., NRCS dataset).

6 Impacts of Proposed Improvements on Emissions Estimates

The proposed changes in data sources and methodology will increase nitrous oxide (N_2O) emissions for poultry and decrease emissions for beef feedlot. This change is in conjunction with an update to the solid storage direct N2O emission factor from IPCC (2006) to IPCC (2019) - which increases the emission factor from 0.005 to 0.01 kg N_2O-N/kg nitrogen excreted, and results in increased solid storage emissions. As compared to the 1990-2020 *Inventory* (2022 submission):

- For beef feedlot, the national average percent change over the time series was -9.5%.
- For broilers, the national average percent change over the timeseries was an +41.3%.
- For layers, the national average percent change over the timeseries was +22.6%.

Overall, these changes result in a minor decrease in total N_2O manure management emissions. Table 8 presents the changes between the 1990-2021 *Inventory* (2023 submission) and the draft 1990-2022 *Inventory* (2024 submission) for the year 2021.

Table 8. Proposed Changes Impact on 2021 Total N_2O Emissions

Category	**2021 N_2O Emissions MMT CO_2e/year**		**Difference**
	1990-2021 *Inventory*	**1990-2022 *Inventory***	
Dairy Cows	3.20	4.01	25%
Dairy Heifers	2.26	2.27	0%
Dairy Calves	NA	NA	
Swine	1.79	1.79	0%
Beef Cattle	8.33	6.40	-23%
Sheep	0.27	0.27	0%
Goats	0.02	0.02	-5%
Horses	0.07	0.07	0%
Poultry	1.46	2.30	58%
Mules	0.00	0.00	0%
Bison	NA	NA	
Total	**17.41**	**17.15**	**-2%**

Changes to methane are still pending as of November 2023. The updated data include more beef feedlot and poultry on liquid systems (e.g., liquid/slurry or anaerobic lagoons) than the previous data. Because liquid systems have higher methane conversion factors than dry systems, the CH_4 emissions on average are expected to increase.

7 Further Work in Future Cycles

There is a need for continued work to refine the earlier time series (1990-2002) for beef feedlots. While EPA (2002) was previously the best available data source, there is further refinement needed to harmonize the WMS practices reported in the EPA (2002) source and the updated WMS collected from NRCS. ERG suggests reaching out to experts who are aware of the practices in the 1990s or 2000s to confirm the practices reported in EPA (2002).

ERG could also further investigate the differences between the Census of Agriculture reported operation beef feedlot size data and the population data estimated for the Inventory (based on USDA National Agricultural Statistics Service data). For example, the 2017 Census of Agriculture reported zero beef feedlot operations for Alabama, but there is 2017 population data estimated. The discrepancies may be because operations may have existed but did not meet the $1,000 threshold[1] for Census reporting (USDA, 2017), or there are no populations in those size categories for certain years (which would be a greater implication for the Inventory). ERG made assumptions (e.g., carried over older Census data) to estimate in cases where operation size is absent to avoid creating gaps or inconsistencies in the *Inventory* data.

8 Request for Feedback

EPA seeks technical expert feedback on the updates under consideration discussed in this memo and the questions below. Please provide input on:

1. Reasonableness of the application to the time series method given the limitations of the datasets.
2. Any additional sources of poultry or beef feedlot WMS, to better capture any changes over the time series.
3. Whether there are data to create U.S. specific emission factors using the NRCS confinement types (rather than the more general IPCC management types).

9 References

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[1] The USDA Census of Agriculture covers a “target population of all farms and ranches selling or intending to sell $1,000 or more of agricultural products including horticulture”, https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Census_of_Agriculture/index.php.

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Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Proposed Methodology for Production of Fluorochemicals other than HCFC-22

This memorandum discusses updates under consideration for the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (GHGI) to include emissions of fluorinated GHGs[1] from production and transformation of fluorinated gases[2] other than HCFC-22. (Emissions from production of HCFC-22 are already included in the GHGI.) Emissions of fluorinated GHGs from production and transformation of fluorinated gases other than HCFC-22 will be reported in Chapter 4 of the GHGI, and data for the full time series will be reported under Category 2B9 in the Common Reporting Tables (CRT).

1 Introduction/Background

Emissions of fluorinated GHGs from production or transformation of fluorinated gases other than HCFC-22 are not currently included in the GHGI. The *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (2019 Refinement) notes that emissions from fluorochemical production may include emissions of the intentionally manufactured chemical as well as reactant and by-product emissions.[3] The compounds emitted depend upon the production or transformation process, but may include, e.g., hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride, nitrous oxide, nitrogen trifluoride, and many others. The 2019 Refinement also notes that potential sources of fluorinated GHG emissions at fluorochemical production facilities include process vents, equipment leaks, and evacuating returned containers.[4] Production-related emissions of fluorinated GHGs occur from both process vents and equipment leaks. Process vent emissions occur from manufacturing equipment such as reactors, distillation columns, and packaging equipment. Equipment leak emissions, or fugitive emissions, occur from valves, flanges, pump seals, compressor seals, pressure relief valves, connectors, open-ended lines, and sampling connections. In addition, users of fluorinated GHGs may return empty containers (e.g., cylinders) to the production facility for reuse; prior to reuse, the residual fluorinated GHGs (often termed "heels") may be evacuated from the container and are a potential emission source. In many cases, these "heels" are contaminated and are exhausted to a treatment device for destruction. In other cases, however, they are released into the atmosphere. To improve the

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[1] Under the Greenhouse Gas Reporting Program (GHGRP), "fluorinated GHGs" include sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), and any fluorocarbon except for substances with vapor pressures below 1 Torr at 25 degrees C and substances that are regulated as "controlled substances" under EPA's ozone-protection regulations at 40 CFR part 82, subpart A (e.g., chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], and halons). This definition includes hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), hydrofluoroethers (HFEs), fully fluorinated tertiary amines, perfluoropolyethers, and hydrofluoropolyethers, and others. In this analysis, we present emissions totals for HFCs, PFCs, SF6, NF3, and "other" fluorinated GHGs.

[2] Under the GHGRP, "fluorinated gases" include the fluorinated GHGs detailed in the first footnote as well as CFCs and HCFCs. HCFC-22 is considered a fluorinated gas under the GHGRP, but emissions from HCFC-22 production are reported separately from emissions from production of other fluorinated gases. The discussion here addresses the GHGRP requirements for facilities that produce fluorinated gases other than HCFC-22.

[3] IPCC 2019, *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

[4] The totals presented below also include emissions from destruction of previously produced fluorinated GHGs that are shipped to production facilities for destruction, e.g., because they are found to be irretrievably contaminated.

completeness of the source category in the GHGI, EPA is proposing methods to include emissions from fluorinated gas production other than HCFC-22 production in GHGI, based on methods recommended in the 2019 Refinement, data submitted under the Greenhouse Gas Reporting Program (GHGRP), and other data sources detailed below.

2 Methodology

The 2006 IPCC Guidelines as elaborated by the 2019 Refinement include Tier 1, Tier 2, and Tier 3 methods for estimating F GHG emissions from production of fluorinated compounds. The Tier 1 method calculates emissions by multiplying a default emission factor by total production. Specific default emission factors exist for production of sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3); a more general default emission factor covers production of all other fluorinated GHGs. (The more general default emission factor was developed based on data from U.S. facilities collected under the GHGRP between 2011 and 2016.) The Tier 2 method calculates emissions using a mass-balance approach. The Tier 3 method is based on the collection of plant-specific data on the types and quantities of fluorinated GHGs emitted from vents, leaks, container venting, and other sources, considering any abatement technology. The Tier 3 method is often implemented by developing and applying facility-specific emission factors indexed to production.

Based on available data on emissions and activity, EPA is proposing to use a form of the IPCC Tier 3 method to estimate fluorinated GHG emissions from most production of fluorinated compounds. Emissions from some production for which there are fewer data are based on the Tier 1 method.

Overview of Greenhouse Gas Reporting Program Data for this Source Category

As discussed further below, much of the data used to develop the estimates presented here comes from the Greenhouse Gas Reporting Program (GHGRP). The data were collected under two sections of the GHGRP regulation—subpart L, Fluorinated Gas Production, and subpart OO, Suppliers of Industrial Greenhouse Gases. Under subpart L, certain fluorinated gas production facilities must report their emissions from a range of processes and sources, detailed further below. Data collected under subpart L include emissions data for calendar years 2011 through 2022. Under subpart OO, fluorinated GHG suppliers (including fluorinated GHG producers) must report the quantities of each fluorinated GHG that they produce, transform, destroy, import, or export. Data collected under subpart OO include production and transformation data for calendar years 2010 through 2022.

Emissions Reported Under Subpart L of the GHGRP

Under subpart L, facilities that produce a fluorinated gas must report their GHG emissions if the facility emits 25,000 metric tons CO_2e or more per year in combined emissions from fluorinated gas production, stationary fuel combustion units, miscellaneous uses of carbonate, and all other applicable source categories listed in the rule. (For purposes of calculating emissions from fluorinated gas production for inclusion in the total that is compared to the threshold, emissions are assumed to be uncontrolled.) Facilities must report their fluorinated GHG emissions from the production and transformation of fluorinated gases, from venting of residual fluorinated GHGs from containers, and from destruction of previously produced fluorinated GHGs. The emissions reported from production and transformation include both emissions from process vents and emissions from equipment leaks.

Facilities calculate emissions from process vents using one of two methods. For vents that emit 10,000 $mtCO_2e$ or more (considering controls) of fluorinated GHGs from continuous processes, facilities must use emissions testing to establish an emission factor at least every ten years, or sooner if the process changes in a way that will significantly affect emissions from the vent. For other process vents, facilities may use emissions testing, engineering calculations, or engineering assessments to establish the emission factor. Facilities then calculate their annual emissions based on the measured or calculated emission factor and related activity data, considering the extent to which the process is controlled and any destruction device or process malfunctions.

To calculate emissions from equipment leaks, facilities that report under subpart L are required to collect information on the number and type of pieces of equipment; service of each piece of equipment; concentration of each fluorinated GHG in the stream; and the time period each piece of equipment was in service. Facilities use one or more of the following methods to calculate emissions from leaks:

- Average Emission Factor Approach in EPA Protocol for Equipment Leak Estimates.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with EPA Method 21.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with site-specific leak detection methods.
- Site-specific leak detection methods.

Most emissions are reported by chemical; the exceptions are (1) fluorinated GHGs that are emitted in quantities of 1,000 mt CO_2e or less across all production and transformation processes at a facility and (2) fluorinated GHGs that are emitted from facilities that produce only one fluorinated GHG, where the emitted fluorinated GHG is not the fluorinated gas produced. In these cases, the emissions are reported in CO_2e by fluorinated GHG group. There are 12 fluorinated GHG groups, each of which encompasses a set of GHGs with roughly similar atmospheric behavior, including similar GWPs and atmospheric lifetimes. These include, e.g., fully fluorinated GHGs such as PFCs and SF_6, saturated HFCs with two or fewer hydrogen-carbon bonds, saturated HFCs with more than two carbon-hydrogen bonds, unsaturated HFCs and PFCs, and others (see Table A-1 for a full list).

Two other datasets reported under subpart L are relevant to estimating uncontrolled emission factors. (As discussed further below, such uncontrolled emission factors are applied to years before subpart L reporting began (for CY 2011) and before emission controls were put into place.) First, in addition to reporting emissions by chemical at the facility level, facilities report emissions from each production and transformation process at the facility in tons of CO_2e by fluorinated GHG group. To calculate CO_2e emissions, facilities use a chemical-specific 100-year GWP where one is available for the compound of interest. If no chemical-specific 100-year GWP is available for the compound of interest, facilities use the

GHGRP default GWP for the fluorinated GHG group of which the compound is a member. These default GWPs are shown in Table A-1 of the Appendix.[5,6]

Second, for each process, facilities also report the extent to which emissions are abated (the effective destruction efficiency or EDE) as a range. The EDE is calculated as follows:

$$EDE = 1 - \frac{CE_{PV}}{UE_{PV}}$$

Where

EDE = Effective destruction efficiency of the process

CE_{PV} = Actual GWP-weighted controlled emissions from all vents for the process, $mtCO_2e$

UE_{PV} = Hypothetical GWP-weighted uncontrolled emissions from all vents for the process, $mtCO_2e$. (CE_{PV} will equal UE_{PV} if the process is not controlled, resulting in a calculated EDE of 0).

Note that the EDE is based on the extent to which emissions from process vents are controlled. Emissions from equipment leaks are not included in the EDE calculation. Table 1 provides the EDE ranges available for facilities to report and the arithmetic means of each range. The use of these datasets to calculate uncontrolled emission factors is discussed in more detail in the "1990-2010 Emissions Estimates" section below.

Verification of GHGRP Reports

Data reported under the GHGRP, including emissions and production, are electronically verified using range checks, internal consistency checks, and time-series consistency checks. Where the data fail a preliminary check, EPA contacts the facility to see whether there is an explanation for the issue or whether the data are indeed erroneous. In the latter case, facilities are required to correct the data. Where one or more of the anomalous data elements is not explained or corrected, the report for that facility for that year is considered unverified.

2011-2022 Emissions Estimates

For the 17 fluorinated gas production facilities that have reported their emissions under the Greenhouse Gas Reporting Program (GHGRP), 2011-2022 emissions are estimated using the fluorinated GHG emissions reported under subpart L of the GHGRP.

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[5] Specifically, facilities use the chemical-specific 100-year GWP from the IPCC Fourth Assessment Report (AR4) if AR4 includes a chemical-specific GWP for the compound of interest. If AR4 does not include a chemical-specific GWP for the compound of interest, facilities use the chemical-specific 100-year GWP from the IPCC Fifth Assessment Report (AR5) for the compound. If no chemical specific GWP is available in either AR4 or AR5, facilities use the GHGRP default GWP for the fluorinated GHG group of which the compound is a member.

[6] Note that the CO_2-equivalent estimates in this memorandum are based on the 100-year GWPs in AR5 if AR5 includes a chemical-specific GWP for the compound of interest. If AR5 does not include a chemical-specific GWP for the compound of interest, this analysis uses the chemical-specific 100-year GWP from the IPCC Sixth Assessment Report (AR6) for the compound. If no chemical specific GWP is available in either AR5 or AR6, this analysis uses the GHGRP default GWP for the fluorinated GHG group of which the compound is a member.

As discussed above, most emissions reported under subpart L are reported by chemical, but some emissions are reported only by fluorinated GHG group in $mtCO_2e$. Between 2011 and 2022, the share of total CO_2e emissions reported only by fluorinated GHG group has ranged between 1 and 2 percent. In this analysis, to ensure that all emissions are reported by species, emissions that are reported only by fluorinated GHG group are assumed to consist of the fluorinated GHGs in that group that are reported by chemical at the facility. As discussed further in the Uncertainty section, this is likely to result in incorrect speciation of some emissions, but the impact of this incorrect speciation is expected to be small.

For a sulfur hexafluoride (SF_6) production facility that ceased production in 2010, the year before emissions from fluorinated gas production were required to be reported under the GHGRP, SF_6 emissions were estimated using historical production capacity, the global growth rate of SF_6 sales reported in RAND 2008, and the Tier 1 default emission factor for production of SF_6 in the 2019 Refinement. For this plant, a 1982 SF_6 production capacity of 1,200 short tons (Perkins 1982) was multiplied by the ratio between the RAND survey SF_6 sales totals for 2006 and 1982, 1.52 (RAND 2008), resulting in estimated production of 1,652 metric tons in 2006. This production was assumed to have declined linearly to zero in 2011.

We are still in the process of developing estimates for other fluorinated gas production facilities that do not report their emissions under the GHGRP (e.g., because their uncontrolled emissions fall below the 25,000-$mtCO_2e$ threshold). Based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement, we expect that emissions from these facilities will account for less than twenty percent of total U.S. emissions from fluorinated gas production and transformation.

1990-2010 Emissions Estimates

For the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 1990-2010 emissions are estimated using (1) facility- and chemical-specific emission factors based on the emissions data discussed under "2011-2022 Emissions" above, (2) reported or estimated production and transformation of fluorinated GHGs at each facility in each year, and (3) reported and estimated levels of emissions control at each facility in each year.

Facility- and Chemical-Specific Emission Factors Reflecting Emissions Controls

Facility- and chemical-specific emission factors were developed based on the 2011-2015 emissions reported under the GHGRP (discussed above) and the 2011-2015 production and transformation of fluorinated GHGs reported under the GHGRP. (Production and transformation of CFCs and HCFCs are not reported under the GHGRP.) For each emitted fluorinated GHG at each facility, emissions of the fluorinated GHG were summed over the five-year period. This sum was then divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility over the five-year period.[7] As discussed further below in the "Uncertainty" section, emissions of any particular fluorinated GHG are

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[7] Permit data for two facilities indicated that they began controlling emissions at some point between 2011 and 2015. However, the actual emissions reported by these facilities did not change substantially after the date when the permit indicated that controls were imposed. For this reason, the reported 2011-2015 emissions and emission factors are believed to be representative of emissions for these facilities before 2011.

likely to occur only from a subset of the production or transformation processes at each facility, but in the absence of information on chemical-specific emissions at the process level, we made the simplifying assumption that all fluorinated GHG production and transformation processes at the facility emit all fluorinated GHGs at the facility. This yielded the emission factors for each fluorinated GHG at each facility. Both emissions and activity (production + transformation) totals were summed over the five-year period to account for the intermittent and variable nature of some emissions and production/transformation processes. Compounds that were not emitted or produced/transformed between 2011 and 2015 but that were emitted or produced/transformed later were assumed not to have been emitted or produced/transformed (as applicable) before 2011.

Facility- and Chemical-Specific Emission Factors Reflecting No Emissions Controls

The 2011-2015 emissions reported under the GHGRP reflect emissions controls to the extent those are implemented at each facility. Because facilities have not always controlled their fluorinated GHG emissions since 1990, we developed uncontrolled emission factors for each facility to apply to years when the facility's emissions were not believed to be controlled. To estimate uncontrolled emissions, we first used GHGRP data to assess the 2011-2015 levels of control for each production or transformation process at each facility.

To calculate uncontrolled emissions from each process and fluorinated GHG group, we required a point estimate of the effective destruction efficiency (EDE, described above), which we estimated using the arithmetic mean of the lower and upper bounds of the EDE range reported for the process.[8] (This was consistent with the approach taken in the 2019 Refinement to develop the Tier 1 factor for fluorinated gas production facilities.) We divided the reported vented emissions for each process and fluorinated GHG group by (1 - arithmetic mean) to obtain the estimated uncontrolled emissions from process vents for that process and fluorinated GHG group. For each fluorinated GHG group, we then summed the controlled emissions across processes (including emissions from both vents and leaks) and the uncontrolled emissions across processes (including emissions from both vents and leaks) and divided the first by the second. This yielded an average level of control for each fluorinated GHG group at each facility. We assumed that all fluorinated GHGs within each fluorinated GHG group at each facility were controlled to the same level. To estimate the uncontrolled emissions of each fluorinated GHG within each group at each facility, we divided the emissions of each fluorinated GHG by the level of control estimated for its fluorinated GHG group at the facility. We then used the same procedure to estimate uncontrolled emission factors as we had to estimate controlled emission factors: we summed the estimated uncontrolled 2011-2015 emissions of each fluorinated GHG and divided this sum by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility from 2011 to 2015.

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[8] Note that facilities would report a range of 0% to 75% even if they do not abate emissions at all; thus, the assumption that emissions are 37.5% controlled may overestimate the hypothetical uncontrolled emissions of some facilities, e.g., those that do not abate any emissions.

Table 1. Destruction Efficiency Range Values Used to Estimate Pre-Abatement Emissions for Production and Transformation Processes

DE ranges	Lower Bound	Upper Bound	Arithmetic Mean of Bounds
>=0% to <75%	0.0	0.75	0.375
>=75% to <95%	0.75	0.95	0.85
>=95% to <99%	0.95	0.99	0.97
>=99%	0.99	0.9999	0.995

Estimated Levels of Emissions Controls

As discussed above, both uncontrolled emission factors and controlled emission factors were developed for each facility and fluorinated GHG; these emission factors were developed for estimating emissions from production and transformation processes for years 1990 – 2010. The following information and assumptions were used to determine whether and when emissions from facilities were likely to have been controlled from 1990 to 2010.[9]

- Facilities with publicly available information on the presence and use of control devices were assumed to control their emissions starting in the year specified in the publicly available information. Publicly available information included operating permits, news articles on facility modifications, company press releases, etc. Where the publicly available information documents that a control device was in place beginning in a certain year, the facility was assumed to control process emissions beginning in that year, and the controlled emission factor was used in estimating emissions for that year and the following years. The uncontrolled emission factor was used to estimate emissions in earlier years.
- In the absence of other control information, facilities that never reported DRE ranges other than ">=0% to <75%" for their production and transformation processes during reporting years 2011 and 2012 were assumed to have no control devices in place during the time period 1990-2012.
- Facilities that reported DRE ranges other than ">=0% to <75%" for at least one production or transformation process for 2011 or 2012 but for which other control information was not available were assumed to have begun controlling their emissions in 2005.

Activity Data

The activity data for production and transformation of fluorinated compounds for 1990-2010 are based on production and transformation data reported to EPA by certain facilities for certain years, on production capacity data, and on fluorinated GHG production and consumption trends estimated for the various fluorinated GHG-consuming industries.

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[9] For the estimated status of emissions controls at each facility reporting under subpart L, and, where relevant, the starting year for those controls, see Table A-3.

Production and production capacity data

Production data are available from reporting to the U.S. GHGRP under subpart OO, Suppliers of Industrial Greenhouse Gases, and from an industry survey conducted by U.S. EPA in 2008 and 2009. Production and transformation data were reported under subpart OO for 2010 and later years. The responses to the industry survey included production data for certain fluorinated gases at certain facilities for the years 2004, 2005, and 2006. 2004-2006 production data are available for 15 fluorinated compounds. Year 2006 production at an SF_6-producing facility was estimated based on production capacity data as described above. Production of certain compounds at one other facility was estimated based on 2003 production capacity estimates from SRI 2004.

Estimated production

Estimated production for facilities and fluorinated GHGs for which production or production capacity data were available for some years before 2010

For facilities and fluorinated GHGs for which production or production capacity data were available for 2006 or 2003, production between 2006 or 2003 (as applicable) and 2010 (or 2011) was estimated by interpolating between the 2006 production or 2003 production capacity value and the 2010 (or 2011) production value reported under subpart OO.

For the years before the earliest year with production or production capacity data (e.g., years 1990 to 2002 or 2003), production was estimated based on growth or consumption trends for the major industries using each fluorinated GHG.

- For fluorinated compounds that are commonly emitted in the semiconductor industry, estimates of U.S. layer-weighted semiconductor production (Total Manufactured Layer Area, or TMLA) were used to inform the fluorinated compound production estimates. Fluorinated compound production values were assumed to vary with TMLA from 1990 to 2002 or 2003. For example, 1998 production of PFC-14 at a particular facility was estimated by multiplying the 2003 production of PFC-14 at that facility by the ratio between the TMLA estimated for 1998 and the TMLA estimated for 2003. Fluorinated compounds for which TMLA was used to estimate production include PFC-14, PFC-116, PFC-218, perfluorocyclobutane (c-C_4F_8), and NF_3. (Note that the TMLA data were also extrapolated from year 1995 to 1990 based on the average change per year from 1995 to 2009.)
- SF_6 is commonly used in electric power systems, magnesium production, and electronics manufacturing. SF_6 consumption estimates across these three industries for 1990 to 2003 were used to inform the SF_6 production data; SF_6 production was assumed to vary with consumption totals from 1990 to 2003.
- For HFCs commonly used as replacements for ozone-depleting substances (ODS), such as HFCs used as substitutes for CFCs and HCFCs in air-conditioning and refrigeration equipment, HFC production data for certain fluorinated compounds from the Vintaging Model were used to inform the HFC production estimates. (VM 2023) HFC production values were assumed to vary with the VM estimates of production. The industry trend data were applied to the list of HFCs in Table A-2 in the Appendix.

Estimated production for facilities and fluorinated GHGs for which production data before 2010 were not available

In the absence of production data for years 1990 to 2009, the production data reported to the GHGRP under subpart OO were extrapolated backward based on the industry trends discussed above. For compounds for which industry trend data were unavailable, production was assumed to have remained constant over the time series.

In both cases, we estimated 2009 production by conducting a trend analysis on the subpart OO production data for years 2010 to 2015. In instances where there did not appear to be a trend, the average of the production values for years 2010 to 2015 was used as the estimated production for year 2009. In instances where there was a trend, the year 2010 (or 2011) production value was used as the estimated production for year 2009.

If the industry trend information discussed above was applicable to a fluorinated compound, we assumed that production varied with the industry trend from 1990 to 2009. If no industry trend information was available, we assumed that production from 1990 to 2008 remained constant at the 2009 value.

For facilities and fluorinated compounds where information was available on annual production capacity, the estimated activity data was reviewed and compared to the known production capacity. For instances where the estimated activity data exceeded known production capacity for a certain year, the production estimate was set equal to the capacity value.

3 Preliminary F-GHG Emissions Estimates

Total emissions of HFCs, PFCs, SF_6, and NF_3

The fluorinated GHG emissions reported under the GHGRP include emissions of HFCs, PFCs, SF_6, NF_3, and numerous “other” fluorinated GHGs, such as octafluorotetrahydrofuran (C_4F_8O), trifluoromethyl sulphur pentafluoride (SF_5CF_3), and hexafluoropropylene oxide. Because they are not included among the seven UNFCCC-reportable gases or gas groups, the “other” fluorinated GHGs will not be included in inventory totals. However, their emissions are presented below because they often have high GWPs and large GWP-weighted emissions.

Total emissions of HFCs, PFCs, SF_6 and NF_3 are estimated to have increased from 39 million $mtCO_2e$ (4,400 mt) in 1990 to a peak of 44 million $mtCO_2e$ (6,200 mt) in 2002, declining to 3.3 million $mtCO_2e$ (730 mt) in 2022. These trends reflect estimated changes in fluorinated gas production and increasing use of control devices. Prior to 2002, only 2 facilities are known to have operated control devices to destroy fluorinated GHG emissions. After 2002, additional production facilities began to install and use control devices to destroy fluorinated GHG emissions,[10] and fluorinated GHG emissions declined sharply from 44 million $mtCO_2e$ (6,200 mt) in 2002 to 9.8 million CO_2e (1,900 mt) in 2005. There was a small upward trend in emissions from 2006 to 2009. An additional 2 facilities installed controls in 2011 and 2012, resulting in a decline of emissions from 9.7 million $mtCO_2e$ (2,500 mt) in 2010 to 6.7 million $mtCO_2e$ (1,300 mt) in 2012. Another 2 facilities installed controls in 2015 and 2016. Total fluorinated

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[10] One facility installed controls in 2003, and four facilities are assumed to have installed controls in 2005.

GHG emissions have continued to trend downward from 2014 (4.7 million mtCO2e [980 mt]) to 2022 (3.3 million mtCO_2e [730 mt]).

HFC emissions

Because facilities that produce HFCs also tend to emit them, estimated emissions of HFCs have generally tracked estimated production of HFCs except where controls have been imposed. Production of saturated HFCs is estimated to have increased from around 0.3million mtCO2e (2,000 mt) in 1990 to over 300 million mtCO_2e (100,000 mt) by 2010 as HFCs replaced ozone-depleting substances, which were being phased out under the Montreal Protocol and Clean Air Act (U.S. EPA, 2023a, U.S. EPA, 2023b). Estimated emissions of HFCs consequently increased from 9.2 million mtCO_2e in 1990 to 15 million mtCO_2e in 2004 (1,200 to 3,200 mt) as production increased. (Emissions in 1990 were largely from facilities producing compounds other than saturated HFCs.) However, estimated emissions declined sharply in 2005 to 4.8 million mtCO_2e (1,500 mt) due to the assumed addition of controls in that year. Estimated emissions of HFCs resumed their increase from 2005 to 2010 at 6.9 million mtCO_2e (2,300 mt), but again declined sharply in 2011 to 4.2 million mtCO2e (1,200 mt) based on addition of controls. Since 2012, HFC emissions have continued to trend downward. With the phase-out of HFCs (Kigali Amendment, and U.S. AIM program), the downward trend of HFC emissions is expected to continue.

PFC emissions

Overall emissions of PFCs were relatively steady from 1990 to 2002 but dropped sharply from 25 million mtCO_2e (2,900 mt) in 2002 to 1.6 million mtCO2e (180 mt) in 2005, reflecting the addition of controls at high-emitting facilities. Overall PFC emissions from 2005 to 2022 have remained steady, oscillating around 1.5 million mtCO_2e. The quantities of fluorinated GHGs produced or transformed at facilities emitting PFCs are estimated to have remained generally steady between 1990 and 2009 and therefore do not contribute to the emissions trend before 2010. For most of the fluorinated GHGs produced at these facilities, there was no available industry information to inform the activity estimates for 1990 to 2009 and therefore available activity data from the GHGRP was used. The estimated activity for 1990 to 2009 for these compounds reflects the 2010 GHGRP information.

SF_6 emissions

Emissions of SF_6 are estimated to have been steady from 1990 to 2002 (at roughly 3.8 million mtCO_2e [160 mt]), declining to 3.0 million mtCO_2e in 2003 due to the imposition of controls at one facility. Emissions declined more sharply between 2006 and 2011 (3.0 million to 0.030 million mtCO_2e [130 to 1.3 mt]) due to the phaseout of production at the major SF_6-producing facility. SF_6 emissions have continued to decline from 2011 to 2022, with the exception of 2013 and 2014, when emissions increased briefly. (See **Figures A.2a** and **A.2b** in the Appendix for a detailed view of SF_6 and NF_3 trends in mtCO_2e and mt.) The largest source of SF_6 emissions from 1990 through 2010 was an SF_6 producer that ceased producing SF_6 in 2010. In this analysis, SF_6 production is assumed to follow the trend of SF_6 consumption except where facility production capacity caps production at a lower level. SF_6 is used in several industries, including for Electric Power Transmission and Distribution (T&D) equipment, Magnesium Production, and Semiconductor Manufacturing. The use and consumption of SF_6 follows the consumption trend of these industries, with the trend in consumption by Electrical T&D dominating early in the time series. The estimated consumption of SF_6 in Electrical T&D declined significantly from its peak in 1990 to 1998 and has fluctuated over a relatively stable range over the rest of the time series.

Total SF_6 consumption, i.e., considering the trend based on all three industries combined, is estimated to have decreased from 1990 to 1999, fluctuated through 2006, and declined through 2010.

NF_3 emissions

Estimated emissions of NF_3 had a slight upward trend from 1990 to 2002 (0.69 million $mtCO_2e$ to 0.83 million $mtCO_2e$ [43 mt to 52 mt]), declined sharply in 2003 to 0.28 million $mtCO_2e$ (17 mt) due to one facility installing controls, and then resumed a steady climb through 2010 to 0.70 million $mtCO_2e$ (43 mt). (See **Figures A.2a** and **A.2b** in the Appendix for a detailed view of SF_6 and NF_3 trends in $mtCO_2e$ and mt.) After 2010, NF_3 emissions decreased through 2018 to 0.11 million $mtCO_2e$ (6.7 mt), and then increased between 2018 and 2022 to 0.50 million $mtCO_2e$ (31 mt). NF_3 may be emitted both from the production of NF_3 and from the production of other fluorochemicals. For 1990 through 2009, the NF_3 that is emitted from the production of NF_3 is assumed to be influenced by the trajectory of NF_3 production, which is generally assumed to follow production trends in the semiconductor industry except where NF_3 facility capacity limits production further. Semiconductor production increased steadily from 1995 to 2007 but is estimated to have declined from 2007 through 2010. The NF_3 that is emitted from production of other fluorochemicals is affected by the production trends of the fluorochemicals at the emitting facility, which are assumed to have been flat before 2009 in most cases.

Other fluorinated GHG emissions

Other fluorinated GHGs, i.e., those not included in the UNFCCC-reportable gases or gas groups, are also emitted in significant quantities from fluorinated gas production and transformation processes. Estimated emissions of these other fluorinated GHGs have declined over the time series, primarily due to the installation of control devices. Emissions of other fluorinated GHGs were steady from 1990 to 2002, at roughly 9.6 million $mtCO_2e$ (800 mt). These emissions declined sharply in 2003 to 0.88 million $mtCO_2e$ (120 mt) due to the installation of controls at a major emitting facility, and they continued to slightly decline through 2012 to 0.82 million $mtCO_2e$ [110 mt]. As is the case at facilities emitting PFCs, the quantities of fluorinated GHGs produced or transformed at facilities emitting other fluorinated GHGs are estimated to have remained generally steady between 1990 and 2009 and therefore do not contribute to the emissions trend before 2010. From 2013 through 2019, emissions of other fluorinated GHGs fluctuated. They declined sharply in 2020 to around 0.13 million $mtCO_2e$ due to a decrease in the emission rate at one facility, and they remained near this value through 2022.

Tables and Figures

Data for 1990 and 2017 to 2022 are shown in Tables 2 and 3. Total process fluorinated GHG emissions in $mtCO_2e$ and mt for the full time series are shown in **Figures 1a** and **1b**, respectively. Emissions data are shown for individual groups of fluorinated GHGs (HFCs, PFCs, SF_6, and NF_3) over the time series in $mtCO_2e$ and mt in **Figures 2a** and **2b**, respectively.

More detailed emissions estimates are shown in the Appendix. **Table A.4** and **Table A.5** show estimated 1990 and 2000-2022 emissions in metric tons and $mtCO_2e$ of the 28 fluorinated GHGs with the highest total GWP-weighted 2011-2022 emissions from fluorinated gas production. The emissions of these compounds account for 99 percent of the total GWP-weighted fluorinated GHG emissions from fluorinated gas production from 2011 through 2022. **Table A-6** shows total fluorinated GHG emissions from fluorinated gas production by facility for 2011-2022 in $mtCO_2e$.

Table 1. Preliminary National Fluorinated GHG Emissions Estimates from Production of Fluorinated Gas for 1990 and 2017-2022 (Tg CO_2e)

Fluorinated GHG	1990		2005	2018	2019	2020	2021	2022
HFCs	9.2		4.8	1.9	1.7	1.2	1.0	1.4
PFCs	25		1.6	1.3	1.7	1.3	1.6	1.4
SF_6	3.8		3.0	0.0034	0.0039	0.0056	0.0050	0.0024
NF_3	0.69		0.42	0.11	0.56	0.72	0.49	0.50
Subtotal	**39**		**9.8**	**3.3**	**3.9**	**3.3**	**3.1**	**3.3**
Other F-GHGs	9.6		0.89	0.58	0.61	0.14	0.13	0.13
Total Including Other	**49**		**11**	**3.9**	**4.5**	**3.4**	**3.2**	**3.5**

Table 3. Preliminary National Fluorinated GHG Emissions Estimates from Production of Fluorinated Gas for 1990 and 2017-2022 (mt)

Fluorinated GHG	1990		2005	2018	2019	2020	2021	2022
HFCs	1,200		1,500	580	580	460	460	520
PFCs	3,000		180	160	190	160	190	170
SF_6	160		130	0.15	0.17	0.24	0.21	0.10
NF_3	43		26	6.7	35	45	31	31
Subtotal	**4,400**		**1,900**	**750**	**810**	**670**	**690**	**730**
Other F-GHGs	810		120	120	130	43	43	45
Total Including Other	**5,200**		**2,000**	**870**	**940**	**710**	**730**	**770**

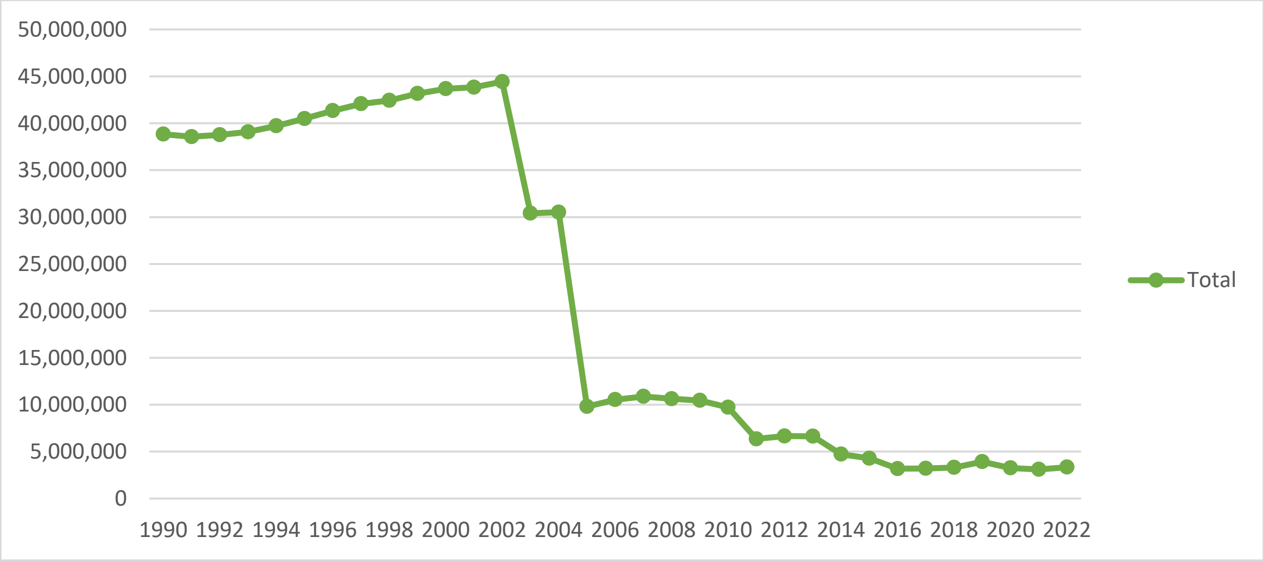

Figure 1a. Total Process Emissions from Fluorinated Gas Processes for 1990-2022 (UNFCCC-reportable gases or gas groups only), $mtCO_2e$.

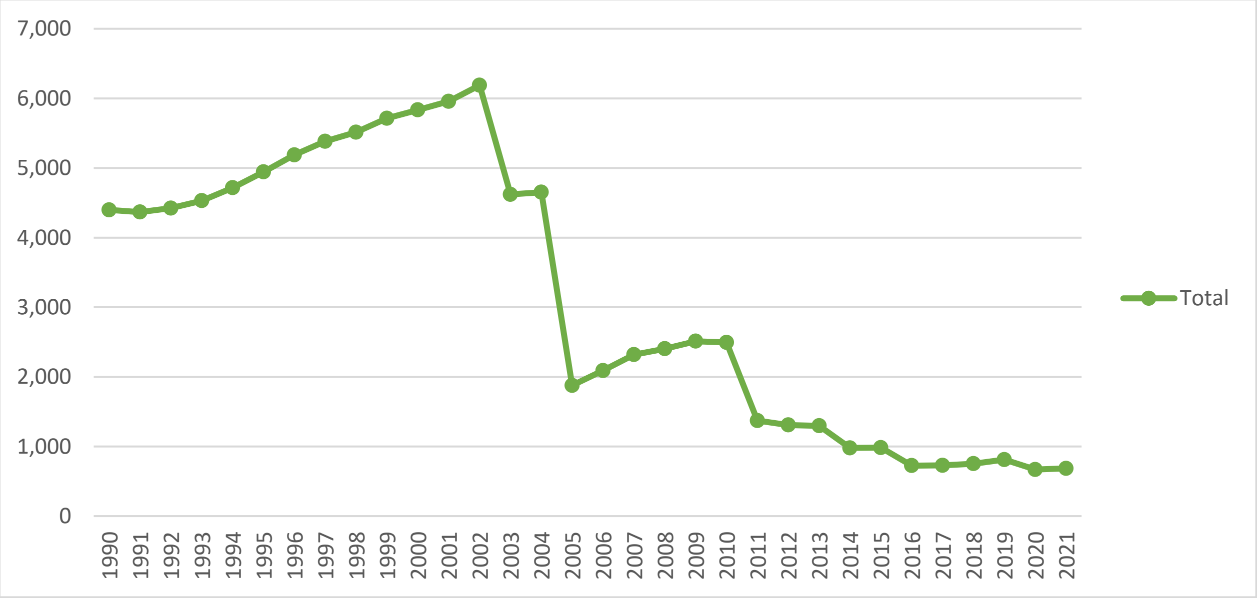

Figure 1b. Total Process Emissions from Fluorinated Gas Processes for 1990-2022 (UNFCCC-reportable gases or gas groups only), mt.

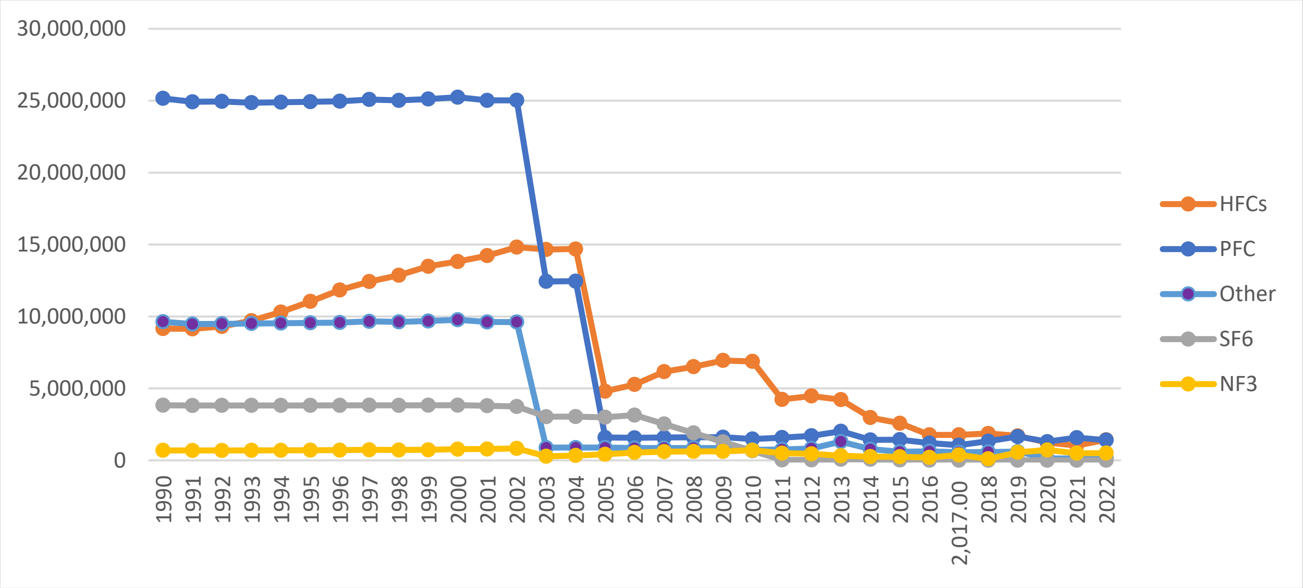

Figure 2a. Process Emissions by Individual Group from Fluorinated Gas Processes for 1990-2022 (all compounds), $mtCO_2e$.

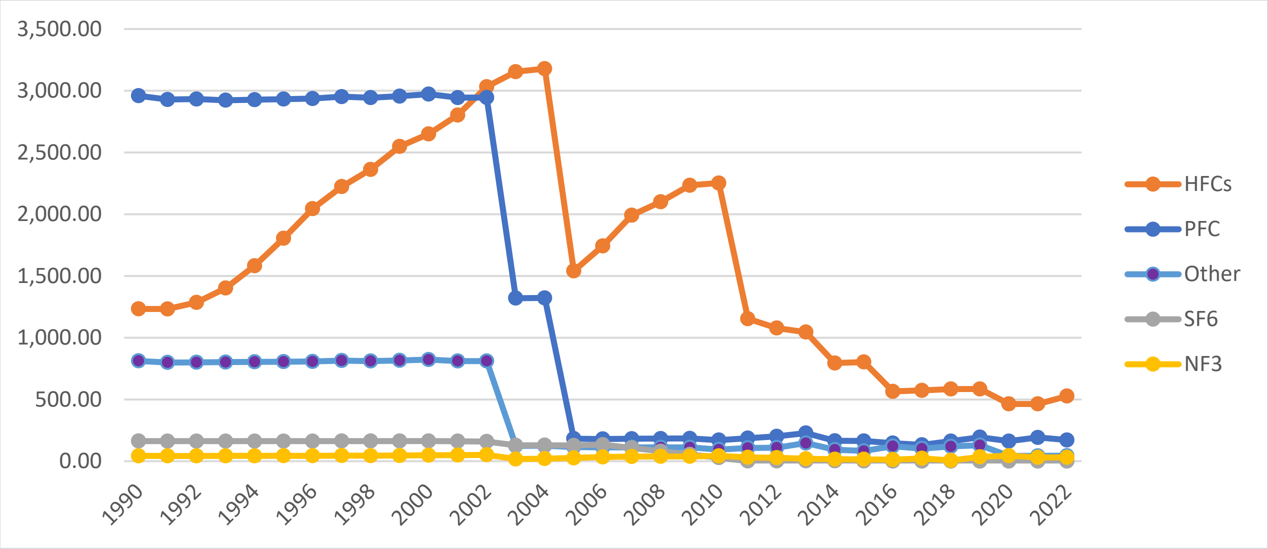

Figure 2b. Process Emissions by Individual Group from Fluorinated Gas Processes for 1990-2022 (all compounds), mt. (Note: One facility-reported, anomalous data value for 2017—for trifluoroethylene, an unsaturated HFC with an estimated GWP of 1–was removed from the graph because it appears likely to be an error. This value remains in the graph showing emissions in mtCO$_2$e and in the emission data tables.)

4 Uncertainty

The estimates in this memo are subject to a number of uncertainties. These uncertainties are generally greater for years before 2011, when reporting of fluorinated GHG emissions from fluorinated gas production began under the GHGRP, than for 2011 and following years. However, the emissions estimated from 2011-2022 are also subject to various uncertainties. The uncertainties for both the 1990-2010 and 2011-2022 periods are discussed in more detail below.

2011-2022 uncertainty

Emissions from 2011 to 2022 reflect reporting by fluorinated gas production facilities under the GHGRP. As discussed above, emissions reported under the GHGRP are based on facility- and process-specific measurements or calculations and are therefore expected to be reasonably accurate for the reporting facilities. (Emissions from the largest sources, process vents emitting 10,000 metric tons CO2e or more annually, are estimated using Tier 3 methods.)

Unverified reports

Ninety-five percent (171/180) of the subpart L reports submitted by fluorinated gas production facilities from 2011 to 2022 are considered to be fully verified; five percent (9/180) of the reports include one or more data elements that are not verified. One facility accounts for two thirds (6/9) of the unverified reports. Many of the issues in the unverified reports for this facility relate to time-series inconsistencies that have arisen as the facility updates reports for recent years, but not previous years, to reflect refinements to estimated emission rates. This facility has accounted for between 6 percent (in 2011) and 29 percent (in 2022) of the GWP-weighted emissions reported for this source category. The uncertainties for this facility therefore have an appreciable impact on the uncertainty of the estimates for the source category as a whole.

Facilities that produce fluorinated gases but do not report their emissions to the GHGRP

As noted above, EPA is still in the process of estimating emissions for fluorinated gas production facilities that do not report their emissions under subpart L of the GHGRP. The estimates presented here for 2011-2022 are therefore incomplete. Based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement, we expect that emissions from non-reporting facilities will account for less than twenty percent of total U.S. emissions from fluorinated gas production and transformation.

Facilities that do not produce fluorinated gases but may emit fluorinated GHGs from other fluorochemical production processes

Under the GHGRP, EPA collects information from facilities that produce fluorinated gases. While we believe this includes most, and possibly all, U.S. facilities that produce fluorochemicals of any kind, it is possible that some fluorochemical producers do not report either their production of fluorochemicals or their emissions of fluorinated GHGs to EPA under the GHGRP. In this case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

At fluorinated gas production facilities that currently report their emissions under the GHGRP, it is possible that some processes that emit fluorinated GHGs neither produce nor transform a fluorinated gas, in which case their emissions would not be reported under the GHGRP. In that case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

Exclusion of nitrous oxide

The GHGRP does not currently require facilities to report emissions of nitrous oxide (N_2O) from fluorinated gas production or transformation, but the IPCC 2019 Refinement includes a default emission factor for N_2O from production of NF_3, implying such emissions may occur. The GHGRP data (and this analysis) may therefore underestimate emissions of N_2O from fluorinated gas production. Because the GWP of N_2O is considerably lower than that of saturated HFCs, PFCs, and other fluorinated GHGs, any underestimate is expected to be relatively small.

Identity of emitted compounds

In this analysis, we have assumed that emissions that are reported only in mtCO_2e by fluorinated GHG group consist of the compounds in that group that are reported by species by the facility. However, if that were actually the case, emissions of those compounds would have been included in the speciated emissions rather than reported separately in mtCO_2e. This analysis therefore incorrectly speciates some emissions. However, as noted in the Methodology section, the share of total CO_2e emissions reported only by fluorinated GHG group is small, ranging between 1 and 2 percent. Moreover, while the emissions are not assigned to the exact species emitted, they are assigned to a species that is closely related and likely to have similar atmospheric impacts (e.g., another saturated HFC with two or fewer carbon-hydrogen bonds). The impact of this uncertainty is therefore very limited.

1990-2010 uncertainty

The uncertainty of emissions estimated for 1990 through 2010 is considerably greater than that for emissions for 2011 through 2022 because emissions were not reported under the GHGRP. EPA has estimated emissions using estimated emission rates, fluorochemical production and transformation activity, and levels of control, and each set of estimates is subject to uncertainty.

Uncertainty regarding activity data

Identity of emitting processes

In reality, emissions of particular fluorinated GHGs are linked to production and/or transformation of particular fluorinated gases at facilities. However, GHGRP information/data does not link emissions of specific fluorinated GHGs to production or transformation of specific fluorinated gases. For the estimates presented here, therefore, we index all emissions to total production across all fluorinated gases. This may not capture trends in emissions that are driven by trends in production or transformation of subsets of the fluorinated gases produced at a facility.

Produced and emitted gases change over time

The set of gases produced at a facility, and therefore the set of fluorinated GHGs that are emitted by that facility, may change over time. It is likely that certain production and transformation processes that existed from 2011 to 2015 (the basis of the emission factors used to back-cast emissions in this analysis) did not exist throughout the entire previous time series (1990-2010). In such cases, emissions of the fluorinated GHGs emitted from the new processes will be overestimated by this analysis for certain years before 2011. On the other hand, it is also likely that some production and transformation processes, and their associated fluorinated GHG emissions, occurred only during the 1990-2010 period and not later, meaning that their emissions are not represented in the emission factors developed based on the 2011-2015 emissions and production data collected under the GHGRP. Such emissions will therefore not be captured by this analysis. The most prominent example of the second situation is probably production of CFCs and HCFCs other than HCFC-22 between 1990 and 2009, which has declined steadily since 1990 as the production of CFCs and HCFCs for emissive uses has been phased out under the Montreal Protocol and Clean Air Act. Production of CFCs and HCFCs can sometimes result in emissions of HFCs or PFCs.

Quantity of produced gases

Where production or production capacity data were available for certain fluorinated gases, facilities, and years before 2010, we have incorporated that data into this analysis. However, even for facilities and compounds for which data were available in certain years, there were several years for which data were not available. For multiple produced compounds, data were available only in 2010. To estimate trends in production of compounds for years before production or production capacity data were available, we have indexed production of certain compounds to known national production or consumption trends for those compounds. This is the case for most HFCs, several PFCs, SF_6, and NF_3. National production estimates are available for HFCs, increasing confidence in country-level production estimates, but the distribution of production among the various HFC-producing facilities is uncertain. Where we have indexed estimated production to consumption (for several PFCs, SF_6, and NF_3), the uncertainty is larger than for HFCs because changes in net imports/exports (which are not known) may also affect the production trend.

For certain fluorinated gases, trend information was not available, and we therefore back-cast production by assuming that it had remained constant at the 2010 level from 1990 through 2009. This is a highly uncertain assumption.

Some production and transformation activity are not reported under subpart OO or modeled in back-casting

Under subpart OO, quantities of fluorinated GHGs that are produced and transformed at the same facility are not reported to us, although any emissions from such processes are reported under subpart L. Such unreported production and transformation are therefore not captured in the 1990-2010 activity estimates used to estimate 1990 through 2010 emissions. To the extent that such unreported production and transformation drive emissions and change over time, the trends will not be captured by this analysis.

Facilities that no longer produce fluorinated gases or that started producing them after 1990

Some facilities may have produced fluorinated gases at some point between 1990 and 2010 that no longer produced those compounds after 2010. We are aware of one SF_6 producer that falls into this category and have estimated its 1990-2010 emissions, but there may be other facilities that are not included in this analysis. On the other hand, some facilities for which we have estimated 1990-2010 emissions may not have produced them over the entire time series, in which case we could be overestimating emissions of the compounds those facilities are assumed to have emitted.

Uncertainty regarding emission factors

Emission rates change over time

The emission factors used to estimate 1990-2010 emissions are based on the emissions and production reported from 2011-2015, reflecting emission rates during that period. For processes that have been used throughout the timeseries, emission rates may have changed over time as the process was optimized to increase efficiency, decreasing by-product emissions, or alternatively, as the process was optimized to maximize production, which sometimes increases by-product emissions. Emission rates also depend on the extent to which emissions are controlled at the facility, the uncertainties for which are discussed further below.

Emissions from container venting and destruction may not scale with production

In this analysis, we have included emissions from container venting and destruction of previously produced fluorinated GHGs in the emission factors used to estimate 1990-2010 emissions. This implicitly assumes that such emissions scale with production and transformation. While this seems likely to be broadly true, there may be exceptions. However, since emissions from container venting and destruction are generally a small share of facility emissions (2%, on average), the impact of such exceptions is expected to be small.

Uncertainty regarding levels of control

In this analysis, we use the arithmetic mean of the DRE range reported by each facility for each process to estimate the DRE for that process and the uncontrolled emissions for that process. Since the emissions implied by the bounds of each DRE range span at least a factor of four,[11] this is an uncertain

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[11] For example, the DRE range 0 to 75% implies emissions of (1-0) x uncontrolled emissions to (1-75%) x uncontrolled emissions, or, rearranging and calculating, 0.25 x uncontrolled emissions to 1 x uncontrolled emissions, a factor of four.

assumption. The uncertainty is mitigated somewhat by the fact that there are generally several processes at each facility, meaning that departures from the assumed mean average out to some extent. There is also uncertainty in the assumptions that (1) all fluorinated GHGS within a particular fluorinated GHG group are abated to the same extent and (2) facilities for which control device start dates are unavailable began to control emissions in 2005.

Quantitative uncertainty estimate for uncontrolled emission factors from 2019 Refinement

As noted above, 2011-2016 data from the GHGRP was used to develop the Tier 1 default uncontrolled emission factor for the 2019 Refinement, using methods similar to those described here. A Monte Carlo analysis performed to assess the uncertainty of the Tier 1 default factor indicated that the uncertainty for each facility's uncontrolled emission factor was less than 50 percent. This uncertainty estimate considered the uncertainty regarding the levels of control, but not the uncertainty of applying factors from one time period at the facility to much earlier time period (although the variability of each facility's emission factor over the 6-year span of the 2019 Refinement analysis was found to be relatively low).

5 Request for Feedback

EPA seeks technical expert feedback on the updates under consideration discussed in this memorandum and the questions below.

1. For all the years from 1990 through 2022, but especially for the years 1990 through 2010, are you aware of data or information that could be used to develop emissions estimates for one or more facilities that are more accurate, precise, or complete than the emissions estimates presented here? Such data could include emissions data, emission factors, activity (i.e., production and transformation) data, and data on levels of control. If so, we would appreciate it if you could share this data or information with us. Data for any part of the 1990 through 2010 time series would be appreciated. Please note that if you share emissions data or estimates without underlying activity data or emission factors, we cannot use the estimates unless you can explain how the estimates were developed, what is driving trends, and reasons for any major differences between the estimates you provide and those provided in this memorandum.
2. We are still in the process of developing emissions estimates for facilities that produce fluorinated GHGS but do not report their emissions under subpart L of the GHGRP. We are likely to use the Tier 1 emission factor from the 2019 IPCC Refinement to estimate these emissions. Are you aware of data or information for these facilities that could be used to develop emissions estimates that are more accurate, precise, or complete than emissions that would be calculated for them using the Tier 1 factor? If so, we would appreciate it if you could share this data or information with us. Data for any part of the 1990 through 2022 time series would be appreciated. Please note that if you share emissions data or estimates without underlying activity data or emission factors, we cannot use the estimates unless you can explain how the estimates were developed and what is driving trends.
3. For the years 1990 through 2010, are you aware of general usage or production data for any group of fluorinated GHGs other than the usage/production data discussed in the Methodology section above for HFCs, PFCs, NF_3 and SF6? For example, are you aware of usage or production data for fluoropolymers for 1990 through 2010?

4. Are you aware of fluorochemical production processes that emit fluorinated GHGs but whose emissions are not reported under the GHGRP because the processes are not fluorinated gas production or transformation processes or do not occur at a fluorinated gas production facility?
5. Were there any fluorinated gas production or transformation processes that were significant contributors to fluorinated GHG emissions at any point between 1990 and 2010 that are not represented in the 2011 through 2015 data? If so, it would be helpful if you could identify the processes, the fluorinated GHGs they emitted, and the approximate magnitudes and trends of the emissions.
6. Are you aware of emission factors for specific fluorinated GHGs from the production or transformation of specific fluorinated gases, including, for example, HFCs, PFCs, CFCs, and HCFCs (other than HCFC-22)?
7. Where general trend data were not available to back-cast production of fluorinated gases, we have assumed that production of these gases remained constant over time. Should we instead assume that production increased with the U.S. GDP or another common index? If so, please identify the index you recommend.
8. Are you aware of any fluorinated gas production facilities (other than facilities that produced SF6 or HCFC-22 only) that produced fluorinated gases before 2010 but not during or after 2010? If so, please provide any information you can on the gases produced, production capacity, and emissions or emission rates of these facilities.
9. Are you aware of any fluorinated gas production facilities that produced fluorinated gases during or after 2010 but that did not produce fluorinated gases during the entire period 1990 to 2009? If so, please provide any information you can on which facilities fall into this category and when they began producing fluorinated gases.
10. In general, are you aware of any data that could address or decrease the uncertainties listed in section 4?
11. Is the method for calculating the estimates clearly explained?
12. Are the shortcomings of available data and estimation approaches clearly articulated?

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Appendix

Table A.1 Fluorinated GHG Groups Under Which Certain Emissions Are Reported Under Subpart L of the GHGRP and Associated GWPs

Fluorinated GHG Group	GHGRP Default Global Warming Potential (100-yr.)
Fully fluorinated GHGs	10,000
Saturated hydrofluorocarbons (HFCs) with 2 or fewer carbon-hydrogen bonds	3,700
Saturated HFCs with 3 or more carbon-hydrogen bonds	930
Saturated hydrofluoroethers (HFEs) and hydrochlorofluoroethers (HCFEs) with 1 carbon-hydrogen bond	5,700
Saturated HFEs and HCFEs with 2 carbon-hydrogen bonds	2,600
Saturated HFEs and HCFEs with 3 or more carbon-hydrogen bonds	270
Fluorinated formates	350
Fluorinated acetates, carbonofluoridates, and fluorinated alcohols other than fluorotelomer alcohols	30
Unsaturated perfluorocarbons (PFCs), unsaturated HFCs, unsaturated hydrochlorofluorocarbons (HCFCs), unsaturated halogenated ethers, unsaturated halogenated esters, fluorinated aldehydes, and fluorinated ketones	1
Fluorotelomer alcohols	1
Fluorinated GHGs with carbon-iodine bond(s)	1
Other fluorinated GHGs	2,000

Table A-2. List of HFCs whose 1990-2009 Production Was Estimated Using Vintaging Model, Virgin Manufacturing by Chemical

Fluorinated Gas
HFC-23
HFC-32
HFC-125
HFC-134a
HFC-143a
HFC-152a
HFC-236fa
HFC-245fa
HFC-365mfc
HFCO-1233zdE
HFO-1234yf
HFO-1234ze
HFO-1336mzzZ
HFC-4310mee

Table A-3. Estimated Starting Years for Emission Controls at Each Fluorinated Gas Production Facility Reporting under Subpart L of the GHGRP

Facility Name	Estimated Start Year	Basis of Estimation
3M COMPANY	No controls	Never reported a DRE range other than “>=0% to <75%”
3M CORDOVA	2003	Climate News Article (https://insideclimatenews.org/news/29122022/3m-cordova-illinois-pfas-cf4-pollution/)
3M Cottage Grove Center - Site	2016	Reported a DRE range other than “>=0% to <75%” for the first time in 2016
Airgas Therapeutics LLC - Scott Medical Products	No controls	Never reported a DRE range other than “>=0% to <75%”
ANDERSON DEVELOPMENT COMPANY	No controls	Never reported a DRE range other than “>=0% to <75%”
ARKEMA, INC.	2005	Reported a DRE range other than “>=0% to <75%” in 2011
Chemours - Corpus Christi Plant	No controls	Never reported a DRE range other than “>=0% to <75%”
CHEMOURS CHAMBERS WORKS	2005	Reported a DRE range other than “>=0% to <75%” in 2011
CHEMOURS COMPANY - FAYETTEVILLE WORKS	2015	Reported a DRE range other than “>=0% to <75%” for the first time in 2015
CHEMOURS EL DORADO	2005	Reported a DRE range other than “>=0% to <75%” in 2011
CHEMOURS LOUISVILLE WORKS	No controls	Never reported a DRE range other than “>=0% to <75%”
CHEMOURS WASHINGTON WORKS	2005	Reported a DRE range other than “>=0% to <75%” in 2011
DAIKIN AMERICA INC.	1993	Title V operating permit (http://lf.adem.alabama.gov/WebLink/DocView.aspx?id=29951882&dbid=0)
HONEYWELL INTERNATIONAL INC - BATON ROUGE PLANT	2012	Title V operating permit (https://edms.deq.louisiana.gov/app/doc/view?doc=8579001)
HONEYWELL INTERNATIONAL INC - GEISMAR COMPLEX	2011	Title V operating permit (https://edms.deq.louisiana.gov/app/doc/view?doc=7812895)
Honeywell Metropolis	No controls	Never reported a DRE range other than “>=0% to <75%” (did not report under subpart L)
MEXICHEM FLUOR INC.	1993	Title V operating permit (https://edms.deq.louisiana.gov/app/doc/view?doc=1309650)
Versum Materials US, LLC	No controls	Never reported a DRE range other than “>=0% to <75%”

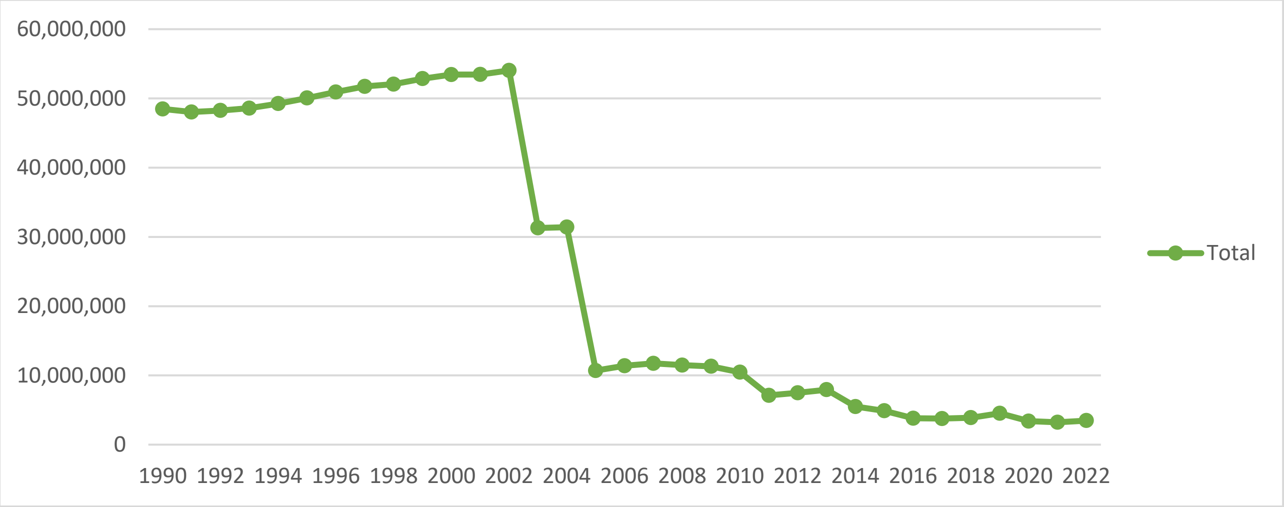

Figure A.1a Total Process Emissions from Fluorinated Gas Processes for 1990-2022 (all compounds), mtCO2e.

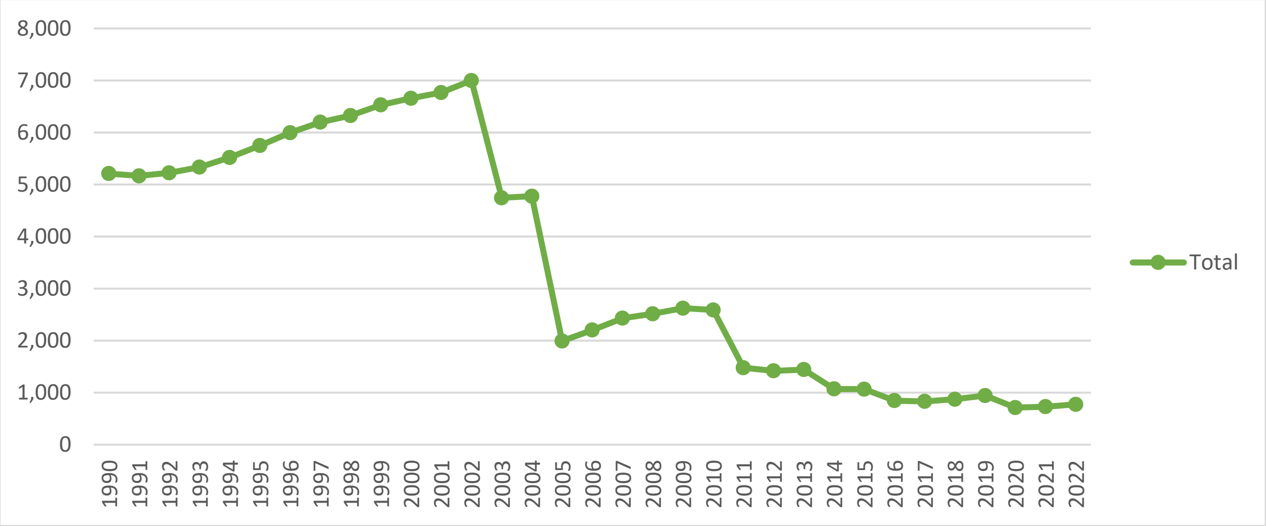

Figure A.1b Total Process Emissions from Fluorinated Gas Processes for 1990-2022 (all compounds), mt.

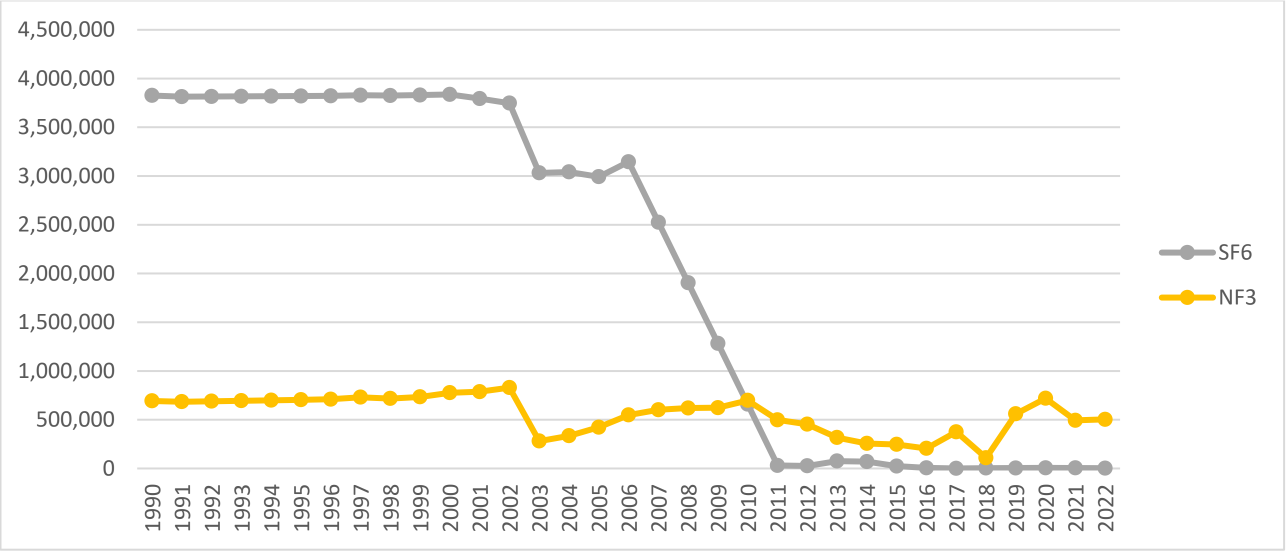

Figure A.2a **Process Emissions for SF_6 and NF_3 from Fluorinated Gas Processes for 1990-2022, mtCO₂e.**

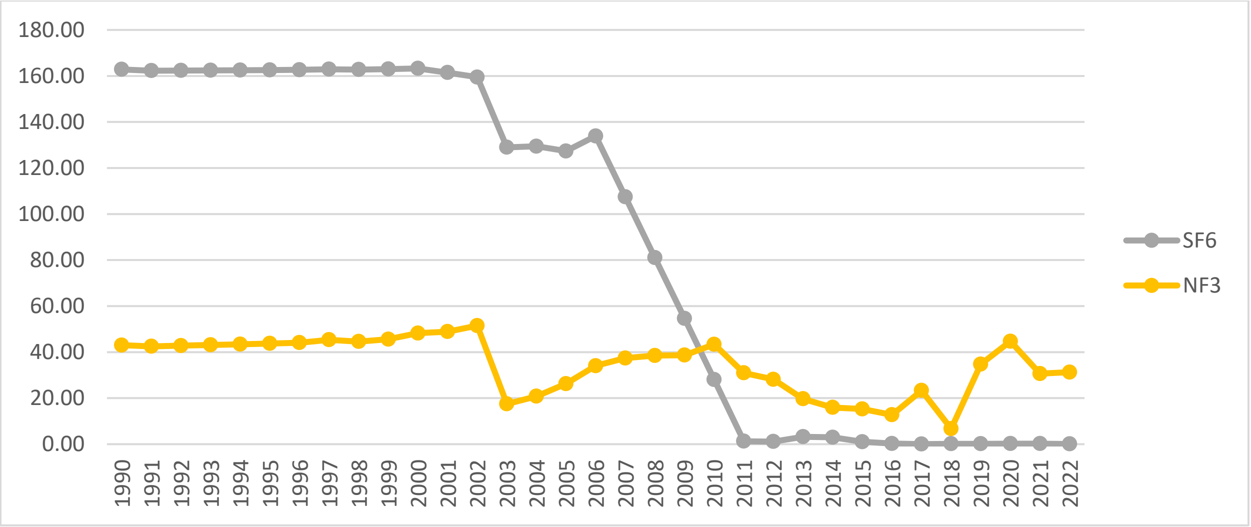

Figure A.2b **Process Emissions for SF_6 and NF_3 from Fluorinated Gas Processes for 1990-2022, mt.**

Table A-4. Preliminary National Fluorinated GHG Emissions Estimates from Production of Fluorinated Gas for 28 Compounds with Highest 2011-2022 Emissions (1990 and 2000-2022 (mt)). *For full list of compounds, see attached Excel table, Emissions by compound 1990-2022.xlsx.*

GHG	CAS	Gas Type	Emissions (mt)											
			1990	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
HFC-23	75-46-7	HFC	552	691	692	687	663	666	118	111	150	161	176	170
Perfluorocyclobutane	115-25-3	PFC	1,160	1,150	1,150	1,150	1,150	1,150	53	53	53	53	53	49
HFC-143a	420-46-2	HFC	29	144	153	162	167	175	147	159	181	185	193	174
PFC-14 (Perfluoromethane)	75-73-0	PFC	1,020	1,030	1,020	1,020	49	50	53	53	53	54	54	53
Nitrogen trifluoride	7783-54-2	NF3	43	48	49	52	18	21	26	34	37	39	39	43
HFC-125	354-33-6	HFC	43	210	269	383	491	529	584	724	771	814	857	883
HFC-134a	811-97-2	HFC	13	361	384	403	447	463	311	332	409	436	472	483
Hexafluoropropylene oxide	428-59-1	Other	35	35	35	35	34	34	33	33	33	34	34	25
Octafluorotetrahydrofuran	773-14-8	Other	398	404	397	397	20	20	21	20	20	20	19	19
PFC-116 (Perfluoroethane)	76-16-4	PFC	239	244	239	239	31	31	24	23	24	25	26	25
PFC-218 (Perfluoropropane)	76-19-7	PFC	304	308	303	303	62	62	20	19	19	19	19	18
Perfluoro(methylcyclopropane)	379-16-8	PFC	18	18	18	18	18	18	18	18	18	18	18	13
HFC-227ea	431-89-0	HFC	529	891	922	979	940	883	24	23	23	22	22	19
Trifluoromethyl sulphur pentafluoride	373-80-8	Other	145	147	144	144	8	8	8	7	8	7	7	7
HFC-32	75-10-5	HFC	7	217	222	215	222	226	88	77	128	138	155	156
PFC-5-1-14 (Perfluorohexane, FC 72)	355-42-0	PFC	137	137	135	135	9	9	10	9	9	9	9	9
HFC-245fa	460-73-1	HFC	5	60	82	124	170	184	208	260	275	290	305	314
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	3330-15-2	Other	6	6	6	6	6	6	4	4	4	4	4	3
Sulfur hexafluoride	2551-62-4	SF6	163	163	161	159	129	129	127	134	107	81	55	28
1H,4H-Perfluorobutane	377-36-6	HFC	-	-	-	-	-	-	-	-	-	-	-	-
PFC-3-1-10 (Perfluorobutane)	355-25-9	PFC	44	45	44	44	2	2	2	2	2	2	2	2
HFC-236fa	690-39-1	HFC	29	30	30	31	5	5	6	7	7	7	7	7
Trifluoromethanesulfonyl fluoride	335-05-7	Other	33	33	33	33	4	4	4	4	4	4	4	4
1H,6H-Perfluorohexane	366-07-2	HFC	-	-	-	-	-	-	-	-	-	-	-	-
Perfluorodiethyl ether	358-21-4	Other	37	37	36	36	2	2	2	2	2	2	2	2
2H-perfluoro(5-methyl-3,6-dioxanonane)	3330-14-1	Other	6	6	6	6	6	6	6	6	6	6	6	4
Hexafluorooxetane	425-82-1	Other	24	24	24	24	1	1	1	1	1	1	1	1
PFC-4-1-12 (Perfluoropentane)	678-26-2	PFC	28	28	28	28	1	1	1	1	1	1	1	1

GHG	CAS	Gas Type	Emissions (mt)											
			2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
HFC-23	75-46-7	HFC	190	215	199	120	90	53	53	55	47	35	23	28
Perfluorocyclobutane	115-25-3	PFC	51	62	51	54	53	57	45	73	95	76	95	82
HFC-143a	420-46-2	HFC	140	134	131	101	94	104	116	124	93	40	28	26
PFC-14 (Perfluoromethane)	75-73-0	PFC	60	77	58	47	46	55	64	65	62	77	83	76
Nitrogen trifluoride	7783-54-2	NF3	31	28	20	16	15	13	23	7	35	45	31	31
HFC-125	354-33-6	HFC	157	159	161	153	139	66	73	82	92	80	79	56
HFC-134a	811-97-2	HFC	351	300	227	218	241	161	116	117	146	119	123	113
Hexafluoropropylene oxide	428-59-1	Other	26	20	25	26	31	33	33	32	32	2	2	2
Octafluorotetrahydrofuran	773-14-8	Other	19	26	41	24	6	6	5	4	4	2	1	2
PFC-116 (Perfluoroethane)	76-16-4	PFC	24	24	44	20	23	2	1	4	2	1	7	5
PFC-218 (Perfluoropropane)	76-19-7	PFC	22	17	48	17	6	5	3	4	2	2	1	4
Perfluoro(methylcyclopropane)	379-16-8	PFC	10	8	10	11	19	15	8	8	23	-	-	-
HFC-227ea	431-89-0	HFC	26	25	35	24	26	23	23	27	25	33	26	23
Trifluoromethyl sulphur pentafluoride	373-80-8	Other	8	9	19	5	3	2	0	3	4	1	1	1
HFC-32	75-10-5	HFC	156	166	154	117	131	93	56	55	67	57	69	50
PFC-5-1-14 (Perfluorohexane, FC 72)	355-42-0	PFC	12	8	8	10	13	6	6	5	7	4	3	2
HFC-245fa	460-73-1	HFC	48	49	49	50	80	41	48	39	39	32	41	41
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	3330-15-2	Other	0.3	0.2	0.3	4	15	15	7	5	6	3	6	3
Sulfur hexafluoride	2551-62-4	SF6	1	1	3	3	1	0.3	0.01	0.1	0.2	0.2	0.2	0.1
1H,4H-Perfluorobutane	377-36-6	HFC	-	-	-	-	-	-	-	-	1	1	1	53
PFC-3-1-10 (Perfluorobutane)	355-25-9	PFC	2	2	6	3	1	2	3	1	1	0.5	0.5	0.2
HFC-236fa	690-39-1	HFC	2	3	5	3	2	2	1	1	1	1	1	1
Trifluoromethanesulfonyl fluoride	335-05-7	Other	4	5	7	4	2	2	-	25	30	3	0.0002	-
1H,6H-Perfluorohexane	366-07-2	HFC	-	-	-	-	-	-	-	-	1	0.5	1	41
Perfluorodiethyl ether	358-21-4	Other	2	3	2	1	2	2	1	0.4	0.2	0.01	0.005	0.002
2H-perfluoro(5-methyl-3,6-dioxanonane)	3330-14-1	Other	4	6	4	3	3	6	5	8	4	2	2	2
Hexafluorooxetane	425-82-1	Other	1	1	4	1	1	1	0.02	0.01	0.3	0.5	0.4	0.4
PFC-4-1-12 (Perfluoropentane)	678-26-2	PFC	2	1	1	1	2	1	1	1	1	1	0.4	-

Table A-5. Preliminary National Fluorinated GHG Emissions Estimates from Production of Fluorinated Gas for 28 Compounds with Highest 2011-2022 Emissions (1990 and 2000-2022 (ktCO2e)). *For full list of compounds, see attached Excel table, Emissions by compound 1990-2022.xlsx.*

		Gas	Emissions (ktCO$_2$e)											
GHG	**CAS**	**Type**	**1990**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
HFC-23	75-46-7	HFC	6,844	8,562	8,581	8,520	8,225	8,260	1,469	1,380	1,862	1,992	2,181	2,112
Perfluorocyclobutane	115-25-3	PFC	11,038	10,933	10,932	10,932	10,933	10,933	504	504	506	508	510	468
HFC-143a	420-46-2	HFC	141	690	735	778	802	838	705	761	869	890	926	836
PFC-14 (Perfluoromethane)	75-73-0	PFC	6,742	6,844	6,738	6,743	322	331	353	348	354	356	357	350
Nitrogen trifluoride	7783-54-2	NF3	693	777	787	829	281	335	423	548	602	620	623	698
HFC-125	354-33-6	HFC	136	664	853	1,213	1,556	1,675	1,852	2,295	2,443	2,579	2,717	2,798
HFC-134a	811-97-2	HFC	17	469	499	524	582	601	404	431	531	567	614	628
Hexafluoropropylene oxide	428-59-1	Other	350	352	351	351	335	336	332	332	334	335	336	249
Octafluorotetrahydrofuran	773-14-8	Other	5,536	5,615	5,524	5,523	278	281	291	272	273	271	269	257
PFC-116 (Perfluoroethane)	76-16-4	PFC	2,658	2,703	2,658	2,658	343	347	263	258	270	280	290	274
PFC-218 (Perfluoropropane)	76-19-7	PFC	2,705	2,738	2,700	2,700	552	553	178	167	168	166	165	157
Perfluoro(methylcyclopropane)	379-16-8	PFC	181	181	181	181	181	181	181	181	181	181	181	131
HFC-227ea	431-89-0	HFC	1,772	2,985	3,089	3,279	3,148	2,957	80	78	77	75	73	64
Trifluoromethyl sulphur pentafluoride	373-80-8	Other	2,519	2,555	2,513	2,513	133	135	139	130	131	130	129	123
HFC-32	75-10-5	HFC	4.7	147	150	145	150	153	59	52	86	93	105	106
PFC-5-1-14 (Perfluorohexane, FC 72)	355-42-0	PFC	1,085	1,083	1,066	1,066	74	74	76	73	73	73	72	71
HFC-245fa	460-73-1	HFC	4.5	52	71	107	146	158	179	223	236	249	262	269
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	3330-15-2	Other	39	39	39	39	39	39	25	25	25	25	25	21
Sulfur hexafluoride	2551-62-4	SF6	3,827	3,837	3,794	3,747	3,031	3,042	2,993	3,146	2,525	1,904	1,283	659
1H,4H-Perfluorobutane	377-36-6	HFC	-	-	-	-	-	-	-	-	-	-	-	-
PFC-3-1-10 (Perfluorobutane)	355-25-9	PFC	404	409	403	403	21	21	22	21	21	21	20	20
HFC-236fa	690-39-1	HFC	230	241	241	247	40	42	47	53	55	57	59	60
Trifluoromethanesulfonyl fluoride	335-05-7	Other	65	66	65	65	7.6	7.6	7.9	7.4	7.4	7.4	7.3	7.0
1H,6H-Perfluorohexane	366-07-2	HFC	-	-	-	-	-	-	-	-	-	-	-	-
Perfluorodiethyl ether	358-21-4	Other	365	370	364	364	18	18	19	18	18	18	18	16
2H-perfluoro(5-methyl-3,6-dioxanonane)	3330-14-1	Other	12	12	12	12	12	12	12	12	12	12	12	8.7
Hexafluorooxetane	425-82-1	Other	241	244	240	240	13	13	13	12	12	12	12	12
PFC-4-1-12 (Perfluoropentane)	678-26-2	PFC	237	240	236	236	9.2	9.3	10	9.0	9.1	9.0	8.9	8.6

GHG	CAS	Gas Type	Emissions (ktCO$_2$e)											
			2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
HFC-23	75-46-7	HFC	2,354	2,667	2,473	1,489	1,111	661	657	679	576	432	285	342
Perfluorocyclobutane	115-25-3	PFC	489	595	487	513	502	545	433	698	910	722	906	779
HFC-143a	420-46-2	HFC	670	643	627	487	453	498	557	594	445	190	136	122
PFC-14 (Perfluoromethane)	75-73-0	PFC	399	510	384	311	306	361	422	434	411	509	552	507
Nitrogen trifluoride	7783-54-2	NF3	498	453	317	256	246	205	375	108	560	719	493	503
HFC-125	354-33-6	HFC	497	503	510	486	440	211	232	260	292	254	249	178
HFC-134a	811-97-2	HFC	457	391	295	283	314	209	151	152	190	154	159	146
Hexafluoropropylene oxide	428-59-1	Other	256	202	248	258	306	329	331	324	315	18	18	19
Octafluorotetrahydrofuran	773-14-8	Other	268	360	566	334	81	82	75	49	62	24	18	32
PFC-116 (Perfluoroethane)	76-16-4	PFC	261	269	486	219	258	20	15	41	19	7.5	73	57
PFC-218 (Perfluoropropane)	76-19-7	PFC	195	152	428	154	51	43	23	33	19	19	11	40
Perfluoro(methylcyclopropane)	379-16-8	PFC	103	82	103	112	192	148	76	76	231	-	-	-
HFC-227ea	431-89-0	HFC	88	85	117	80	86	77	77	91	84	110	87	77
Trifluoromethyl sulphur pentafluoride	373-80-8	Other	135	164	328	92	48	31	8.0	48	65	15	14	19
HFC-32	75-10-5	HFC	106	112	104	79	89	63	38	38	45	38	47	34
PFC-5-1-14 (Perfluorohexane, FC 72)	355-42-0	PFC	93	65	63	81	101	48	51	37	52	33	26	19
HFC-245fa	460-73-1	HFC	42	42	42	43	69	35	41	34	34	27	35	35
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	3330-15-2	Other	1.7	1.0	2.2	25	97	97	44	32	37	20	38	21
Sulfur hexafluoride	2551-62-4	SF6	30	27	76	70	24	6.1	0.35	3.4	3.9	5.6	5.0	2.4
1H,4H-Perfluorobutane	377-36-6	HFC	-	-	-	-	-	-	-	-	4.4	2.2	4.3	196
PFC-3-1-10 (Perfluorobutane)	355-25-9	PFC	19	14	57	24	10	20	26	5.4	5.5	4.4	4.3	1.4
HFC-236fa	690-39-1	HFC	18	27	40	24	15	13	11	8.3	8.7	5.9	4.6	7.2
Trifluoromethanesulfonyl fluoride	335-05-7	Other	7.4	10	15	8.8	3.9	3.9	-	49	59	6.8	0.00040	-
1H,6H-Perfluorohexane	366-07-2	HFC	-	-	-	-	-	-	-	-	3.4	1.7	3.3	153
Perfluorodiethyl ether	358-21-4	Other	17	30	22	14	17	17	11	4.1	2.1	0.060	0.049	0.021
2H-perfluoro(5-methyl-3,6-dioxanonane)	3330-14-1	Other	8.9	11	8.2	5.0	5.3	12	10	17	9.0	3.6	3.7	3.1
Hexafluorooxetane	425-82-1	Other	14	10	35	6.7	7.2	6.3	0.16	0.060	3.1	4.5	4.3	3.8
PFC-4-1-12 (Perfluoropentane)	678-26-2	PFC	18	7.7	8.5	5.5	15	13	7.3	4.7	7.7	4.8	3.8	-

Table A-6. Total Fluorinated GHG Emissions from Production of Fluorinated Gas by Facility for 2011-2022 ($mtCO_2e$)

	Facility Emissions ($mtCO_2e$)											
Facility Name	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
3M COMPANY	2.4	0.09	2.0	0.16	0.0054	0.021	3.0	2.7	2.3	2.1	2.2	1.9
3M CORDOVA	1,354,339	1,478,277	2,334,945	1,234,089	822,868	644,813	652,230	652,986	698,697	579,525	599,728	567,392
3M Cottage Grove Center - Site	20,083	16,466	32,016	30,981	13,135	8,804	1,451	29,468	24,652	14,609	14,677	-
Airgas Therapeutics LLC - Scott Medical Products	-	-	-	-	-	-	-	3,213	3,343	4,113	3,890	2,328
ANDERSON DEVELOPMENT COMPANY	87,674	89,613	42,845	-	-	-	-	-	-	-	-	-
ARKEMA, INC.	2,444,759	2,596,160	2,318,902	1,346,402	1,107,036	1,042,856	1,011,915	893,913	796,180	489,613	254,528	266,696
Chemours - Corpus Christi Plant	17,502	27,280	24,352	10,889	8,323	13,453	36,470	35,929	44,428	46,052	46,617	50,249
CHEMOURS CHAMBERS WORKS	683,132	721,367	851,574	626,207	542,985	34,313	77,365	38,409	31,608	17,887	32,808	34,099
CHEMOURS COMPANY - FAYETTEVILLE WORKS	446,124	351,565	422,771	444,477	589,364	562,034	453,335	496,751	626,837	15,272	16,414	15,601
CHEMOURS EL DORADO	62,563	59,219	62,599	61,168	71,493	63,248	71,775	89,819	70,869	110,402	86,878	76,204
CHEMOURS WASHINGTON WORKS	416,381	615,685	484,032	476,827	516,207	513,703	214,724	522,291	616,203	503,525	580,461	970,161
DAIKIN AMERICA INC.	273,881	232,733	241,282	276,377	234,079	272,251	383,934	424,665	617,261	405,658	626,691	668,279
DUPONT LOUISVILLE WORKS	0.14	0.10	0.09	0.07	-	-	-	-	-	-	-	-
HONEYWELL INTERNATIONAL INC - BATON ROUGE PLANT	253,590	278,213	285,869	145,476	157,832	97,239	119,205	133,498	-	-	7,309	5,948
HONEYWELL INTERNATIONAL INC - GEISMAR COMPLEX	533,472	529,581	541,771	563,301	506,629	281,061	303,005	396,799	382,763	393,698	382,337	224,085
MEXICHEM FLUOR INC.	108,786	108,112	19,068	19,114	21,174	18,266	14,318	16,851	16,633	17,869	27,922	20,542
Versum Materials US, LLC	404,142	379,571	274,081	258,223	286,337	254,864	422,438	154,650	598,879	790,722	562,445	572,169

Data Type	Sector	Subsector	Category	Units	GHG	CAS	GHGRP F-GHG Group	Gas Type	Inventory GWP	1990	2005	2018	2019	2020	2021	2022
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1,1,1,3,3,3-HEXAFLUOROPROPANE	382-24-1	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	3700	NO	NO	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1H,10H-Perfluorodecane	3492-24-	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	3700	NO	NO	NO	NO	NO	NO	11.78
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1H,4H-Perfluorobutane	377-36-6	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	3700	NO	NO	NO	1.18	0.60	1.16	53.01
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1H,6H-Perfluorohexane	366-07-2	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	3700	NO	NO	NO	0.92	0.47	0.90	41.24
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1H,8H-Perfluorooctane	307-99-3	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	3700	NO	NO	NO	0.53	NO	0.52	23.56
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1H-perfluorooctane	335-65-9	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	3700	NO	NO	0.54	0.30	0.73	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	2-Pentene, 1,1,1,2,3,4,5,5,5-nonafluoro-4-(trifluoromethyl)-	84650-68	Saturated HFCs with 3 or more carbon-hydrogen bonds	HFC	930	NO	NO	NO	NO	0.00	0.02	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-1132a; VF2	75-38-7	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	HFC	0.04	NO	NO	66.75	56.55	51.86	55.09	46.94
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-1141; VF	75-02-5	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	HFC	0.02	5.29	17.22	10.90	8.49	8.94	11.17	9.87
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-1234ze(E)	1645-83-	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	HFC	0.97	NO	NO	NO	NO	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-125	354-33-6	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	3170	43.25	601.72	131.39	134.75	116.36	111.65	105.20
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-134	359-35-3	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	1120	NO	NO	1.35	1.18	NO	1.47	1.27
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-134a	811-97-2	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	1300	37.38	335.04	197.51	216.13	178.17	176.83	192.87
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-143a	420-46-2	Saturated HFCs with 3 or more carbon-hydrogen bonds	HFC	4800	30.15	157.14	155.20	119.91	62.74	49.35	56.77
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-152a	75-37-6	Saturated HFCs with 3 or more carbon-hydrogen bonds	HFC	138	0.74	17.99	11.69	10.10	10.61	10.34	10.76
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-161	353-36-6	Saturated HFCs with 3 or more carbon-hydrogen bonds	HFC	4	NO	NO	NO	NO	0.01	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-227ca	2252-84-	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	2640	1.07	0.92	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-227ea	431-89-0	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	3350	455.49	42.41	27.23	24.93	32.74	25.85	23.00
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-23	75-46-7	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	12400	544.33	138.60	104.19	89.20	71.13	56.18	76.65
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-236ea	431-63-0	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	1330	NO	NO	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-236fa	690-39-1	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	8060	8.23	10.75	1.03	1.07	0.73	0.57	0.89
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-245cb	1814-88-	Saturated HFCs with 3 or more carbon-hydrogen bonds	HFC	4620	NO	NO	0.42	1.07	1.19	1.41	1.37
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-245fa	460-73-1	Saturated HFCs with 3 or more carbon-hydrogen bonds	HFC	858	5.26	208.33	39.29	39.25	31.91	40.69	40.60
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-32	75-10-5	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	677	21.50	102.36	104.89	109.59	92.86	102.46	99.45
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-365mfc	406-58-6	Saturated HFCs with 3 or more carbon-hydrogen bonds	HFC	804	0.03	0.40	NO	NO	0.01	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFC-43-10mee	138495-4	Saturated hydrofluorocarbons (HFCs) with 2 or fewer ca	HFC	1650	0.56	0.60	3.32	3.56	2.78	4.43	0.93
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Trifluoroethylene	359-11-5	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	HFC	0.005	NO	NO	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	butane, octafluoro-2,3-bis(trifluoromethyl)-	354-96-1	Fully fluorinated GHGs	PFC	10000	NO	NO	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C7F14	355-63-5	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	PFC	1	NO	NO	NO	0.00	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Hexafluorobenzene	392-56-3	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	PFC	1	NO	NO	NO	NO	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFP Trimer	6792-31-	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	PFC	1	NO	NO	0.02	0.01	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluoro(methylcyclopropane)	379-16-8	Fully fluorinated GHGs	PFC	10000	18.10	18.10	7.62	23.06	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluorocyclobutane	115-25-3	Fully fluorinated GHGs	PFC	9540	1,174.31	70.09	131.58	145.85	118.58	134.14	139.70
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluorocyclohexane	355-68-0	Fully fluorinated GHGs	PFC	10000	0.13	0.07	NO	NO	0.01	0.01	0.02
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PFC-1114; TFE	116-14-3	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	PFC	0.004	0.32	0.32	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PFC-116 (Perfluoroethane)	76-16-4	Fully fluorinated GHGs	PFC	11100	121.17	61.58	26.13	21.12	17.17	21.65	27.43
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PFC-1216; Dyneon HFP	116-15-4	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	PFC	0.05	1.00	1.00	2.84	1.18	2.07	2.07	1.12
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PFC-14 (Perfluoromethane)	75-73-0	Fully fluorinated GHGs	PFC	6630	359.76	214.66	146.35	131.91	136.12	137.51	156.75
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PFC-218 (Perfluoropropane)	76-19-7	Fully fluorinated GHGs	PFC	8900	199.20	79.48	17.23	13.83	11.99	10.34	17.88
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PFC-3-1-10 (Perfluorobutane)	355-25-9	Fully fluorinated GHGs	PFC	9200	17.16	9.56	0.59	0.59	0.48	0.47	0.15
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PFC-4-1-12 (Perfluoropentane)	678-26-2	Fully fluorinated GHGs	PFC	8550	8.08	4.50	0.55	0.90	0.57	0.45	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PFC-5-1-14 (Perfluorohexane, FC 72)	355-42-0	Fully fluorinated GHGs	PFC	7910	48.39	29.25	18.11	18.28	14.06	12.28	15.75
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PFC-6-1-12	335-57-9	Fully fluorinated GHGs	PFC	7820	3.83	2.14	0.15	0.22	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PFC-7-1-18	307-34-6	Fully fluorinated GHGs	PFC	7620	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Propene, Hexafluoro, Dimer	13429-24	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	PFC	1	0.35	0.01	0.01	0.00	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Nitrogen trifluoride	7783-54-	Fully fluorinated GHGs	NF3	16100	18.10	36.71	6.72	34.76	44.68	30.64	31.26
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Sulfur hexafluoride	2551-62-	Fully fluorinated GHGs	SF6	23500	247.91	138.55	0.15	0.17	0.24	0.21	0.10
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	(CF3)2-N-CF2CF2CF2CF3	103217-8	Fully fluorinated GHGs	Other	10000	NO	NO	0.00	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	[[difluoro(trifluoromethoxy)methoxy]difluoromethoxy]difluoro-ac	21703-45	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	3330-15-	Saturated hydrofluoroethers (HFEs) and hydrochloroflu	Other	6490	6.02	3.87	4.94	5.76	3.09	5.84	3.20
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1,1,1,2,3,3-Hexafluoro-4-(1,1,2,3,3,3-Hexafluoropropoxy-Pentane	870778-3	Saturated HFEs and HCFEs with 3 or more carbon-hydro	HFE	270	0.04	0.00	0.06	0.00	0.01	0.04	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1,1,1,3,3,5,5,7,7,9,9,11,11-tridecafluoro-2,4,6,8,10-pentaoxadode	21703-49	Other fluorinated GHGs	Other	2000	0.82	0.82	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1,1,2,2,3,3,3-Heptafluoro-1-propanesulfonyl Fluoride	423-40-5	Other fluorinated GHGs	Other	2000	0.14	0.00	NO	0.09	0.27	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1,1,2,2,3,3,4,4,4-NONAFLUORO-1-BUTANESULFONAMIDE	30334-69	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	NO	0.34	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1,2-Oxathiane, 3,3,4,4,5,5,6,6-octafluoro-, 2,2-dioxide	132017-5	Other fluorinated GHGs	Other	2000	NO	NO	NO	0.02	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1,4-Butanedisulfonyl difluoride, 1,1,2,2,3,3,4,4-octafluoro-	84246-31	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1-â€‹Butanesulfonamide, 1,â€‹1,â€‹2,â€‹2,â€‹3,â€‹3,â€‹4,â€‹4,â€	34455-00	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	0.30	0.08	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1-Butanesulfonamide, 1,1,2,2,3,3,4,4,4-nonafluoro-N,N-dimethyl-	207297-5	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1-Butanesulfonamide,1,1,2,2,3,3,4,4,4-nonafluoro-N-(2-hydroxyet	484024-6	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	NO	0.03	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1-BUTANOL, 2,2,3,3,4,4,4-HEPTAFLUORO-, METHACRYLATE	13695-31	Fluorotelomer alcohols	Other	1	NO	NO	0.00	0.01	0.00	0.03	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1-Ethoxy-1,1,2,2,3,3,3-heptafluoropropane	22052-86	Saturated HFEs and HCFEs with 3 or more carbon-hydro	HFE	61	NO	NO	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1-Ethoxy-1,1,2,3,3,3-hexafluoropropane	380-34-7	Saturated HFEs and HCFEs with 3 or more carbon-hydro	HFE	23	0.02	0.00	0.02	0.00	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1H,1H,6H,6H-Perfluoro-1,6-hexanediol diacrylate	132958	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1-Octanesulfonamide, N-butyl-heptadecafluoro-N-(2-hydroxyethy	132831	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	0.01	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1-Octanesulfonamide,N-ethyl-1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-hep	4151-50-	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	0.01	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1-Octanesulfonicacid,1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafl	1763-23-	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	1-propanesulfonyl fluoride, 1,1,2,2,3,3-hexafluoro-3-(trifluoromet	1227250-	Other fluorinated GHGs	Other	2000	NO	NO	NO	0.01	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	2-(perfluoropropoxy)perfluoropropyl trifluorovinyl ether	1644-11-	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	0.05	0.03	0.06	0.09	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	2,2,2-Trifluoroethanol	75-89-8	Fluorinated acetates, carbonofluoridates, and fluorinate	Other	20	0.06	0.00	0.01	0.03	NO	0.03	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	2,2,3,3,4,4,4-Heptafluorobutan-1-ol	375-01-9	Fluorinated acetates, carbonofluoridates, and fluorinate	Other	34	0.08	0.00	0.01	0.01	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	2,2,3,3,4-PENTAFLUORO-4-(TRIFLUOROMETHYL)-OXETANE	206867-8	Fully fluorinated GHGs	Other	10000	4.77	4.07	NO	0.00	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	2,2,3,3-Tetrafluoro-1-propanol	76-37-9	Fluorinated acetates, carbonofluoridates, and fluorinate	Other	13	NO	NO	0.00	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	2,3,3,3-Tetrafluoro-2-(heptafluoropropoxy)propanoyl fluoride	2062-98-	Other fluorinated GHGs	Other	2000	0.07	0.07	0.73	0.00	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	2,3,3,3-tetrafluoro-2-(trifluoromethoxy) propionyl fluoride	2927-83-	Other fluorinated GHGs	Other	2000	0.39	0.39	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	2,3,5,6-Tetrafluoro-7,7,8,8-Tetracyanoquinodimethane	29261-33	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	2-Butanone,1,1,1,3,4,4,4-heptafluoro-3-(trifluoromethyl)-	756-12-7	Fluorotelomer alcohols	Other	1	NO	NO	0.01	0.00	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	2H-perfluoro(5-methyl-3,6-dioxanonane)	3330-14-	Other fluorinated GHGs	Other	2000	6.02	6.02	8.41	4.49	1.80	1.83	1.56
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	2-propenoic acid Methyl(nonafluorobutyl)Sulfonylamino ethyl est	1017237-	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	NO	0.01	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	3,3,3-TRIFLUORO-2-(TRIFLUOROMETHYL)-PROPIONYL FLUORIDE	382-22-9	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	NO	0.01	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	3,3-Difluoropropanoic acid	155142-6	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	3-[1-[difluoro[(1,2,2-trifluoroethenyl)oxy]methyl]-1,2,2,2-tetraflu	63863-43	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	0.01	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	3-Hexanone,1,1,1,2,4,4,5,5,6,6,6-Undecafluoro-2-(trifluoro	813-45-6	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	0.00	0.00	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	4-Morpholinepropanoylfluoride,.alpha.,.beta.,.beta.,2,2,3,3,5,5,6,	122531-2	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Acetamide,N-[2,4-dimethyl-5-[[(trifluoromethyl)sulfonyl]amino]p	53780-34	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	0.01	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Acid fluoride isomer	999888-4	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	NO	0.00	NO

GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Benzamide,N-(2-piperidinylmethyl)-2,5-bis(2,2,2-trifluoroethoxy)-	54143-56	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	BIS(TRIFLUOROMETHANESULFONYL)IMIDE	82113-65	Other fluorinated GHGs	Other	2000	NO	NO	0.00	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Bis(trifluoromethyl)-methanol	920-66-1	Fluorinated acetates, carbonofluoridates, and fluorinate	Other	182	0.08	0.00	0.01	0.01	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Butane, 1,1,1,2,3,4,4,4-octafluoro-2-methoxy-3-(trifluoromethyl)-	181214-7	Saturated HFEs and HCFEs with 3 or more carbon-hydro	HFE	270	NO	NO	NO	NO	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C11F25N	86714-31	Fully fluorinated GHGs	Other	10000	NO	NO	NO	NO	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C12F23N	3M #2-31	Other fluorinated GHGs	Other	2000	NO	NO	NO	0.00	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C12F25N	14288-08	Fully fluorinated GHGs	Other	10000	NO	NO	NO	0.00	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C14F27N	109900-5	Fully fluorinated GHGs	Other	10000	NO	NO	NO	0.00	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C3F5H2COF	102526-0	Other fluorinated GHGs	Other	2000	NO	NO	0.04	0.00	0.01	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C3F6HCOF	70411-21	Other fluorinated GHGs	Other	2000	NO	NO	0.08	0.01	0.02	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C3F7-O-CF(CF3)CF=CF-O-C3F7	3M #2-32	Other fluorinated GHGs	Other	2000	NO	NO	0.02	0.05	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C4F9OCOF	55064-79	Fluorinated acetates, carbonofluoridates, and fluorinate	Other	30	NO	NO	0.04	0.00	0.01	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C5F10O	355-79-3	Fully fluorinated GHGs	Other	10000	NO	NO	0.00	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C5F11OCOF	881176-1	Other fluorinated GHGs	Other	2000	NO	NO	0.04	0.00	0.01	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C5F12O	66840-50	Fully fluorinated GHGs	Other	10000	NO	NO	0.00	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C5F13N	678-29-5	Fully fluorinated GHGs	Other	10000	0.38	0.32	NO	0.13	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C6F13COF	375-84-8	Other fluorinated GHGs	Other	2000	NO	NO	0.04	0.00	0.01	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C6F15N	131968-1	Fully fluorinated GHGs	Other	10000	0.29	0.25	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	C7F16O	92978-07	Fully fluorinated GHGs	Other	10000	1.64	1.40	0.12	0.05	0.03	0.01	0.02
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Carbonic difluoride	353-50-4	Other fluorinated GHGs	Other	0.14	1.85	1.85	1.57	1.15	NO	0.78	1.47
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	CF3-N-(CF2CF2CF3)2	103229-5	Fully fluorinated GHGs	Other	10000	NO	NO	0.00	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Difluoro-Propanedioyl Difluoride	5930-67-	Other fluorinated GHGs	Other	2000	0.00	0.00	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	F-C(O)-CF2CF2CF2-SO2F; 2,2,3,3,4,4,-hexafluoro-4-(fluorosufonyl)	83071-23	Other fluorinated GHGs	Other	2000	0.01	0.00	NO	0.02	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	FC-3283/FC-8270 (Perfluorotripropylamine)	338-83-0	Fully fluorinated GHGs	Other	9030	0.042	0.036	0.31	0.32	0.96	0.82	1.48
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	FC-3284 (Perfluoromethylmorpholine)	382-28-5	Fully fluorinated GHGs	Other	10000	0.13	0.00	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	FC-40/FC-43 (Perfluorotributylamine (PTBA))	1064698-	Fully fluorinated GHGs	Other	10000	0.33	0.27	2.22	1.70	1.27	0.15	0.13
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	FC-770 (Perfluoroisopropylmorpholine)	1093615-	Fully fluorinated GHGs	Other	10000	0.01	0.00	0.00	0.00	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Flunisolide	542449	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Fluoroalkyl alcohol	2711-81-	Fluorinated acetates, carbonofluoridates, and fluorinate	Other	30	NO	NO	0.00	0.00	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Fluoroalkylsulfonimide	999888-2	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Fluorochemical (Corrosive,Acid)	999888-0	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Fluorochemical Adduct	37338-48	Fully fluorinated GHGs	Other	10000	NO	NO	NO	NO	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Fluorosurfactant	65545-80	Fully fluorinated GHGs	Other	10000	NO	NO	NO	NO	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HEPTAFLUOROPROPYL TRIFLUOROMETHYL ETHER	59426-77	Fully fluorinated GHGs	Other	10000	0.94	0.80	NO	0.11	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Heptafluorotetrahydrofuran	24270-62	Saturated hydrofluoroethers (HFEs) and hydrochloroflu	HFE	5700	NO	NO	0.04	0.00	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Hexafluoro-1,3-propanedisulfonyldifluoride	82727-16	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Hexafluoroacetone	684162	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	0.19	0.19	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Hexafluorooxetane	425-82-1	Fully fluorinated GHGs	Other	10000	10.39	8.86	0.01	0.31	0.45	0.43	0.38
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Hexafluoropropylene (HFP) and HFPO Oligomers	N/A	Other fluorinated GHGs	Other	2000	NO	NO	NO	2.33	0.54	0.64	0.63
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Hexafluoropropylene Epoxide	60164-51	Fully fluorinated GHGs	Other	10000	NO	NO	NO	NO	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Hexafluoropropylene oxide	428-59-1	Fully fluorinated GHGs	Other	10000	34.23	33.88	32.38	31.5041	1.751	1.83	1.86
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFE-227ea	2356-62-	Saturated hydrofluoroethers (HFEs) and hydrochloroflu	HFE	6450	0.00	0.00	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFE-347mcc3	375-03-1	Saturated HFEs and HCFEs with 3 or more carbon-hydro	HFE	530	0.00	0.00	0.00	0.00	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFE-356mec3	382-34-3	Saturated HFEs and HCFEs with 3 or more carbon-hydro	HFE	387	NO	NO	0.00	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFE-356pcc3	160620-2	Saturated HFEs and HCFEs with 3 or more carbon-hydro	HFE	413	NO	NO	NO	NO	NO	0.01	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFE-449sl, (HFE-7100) Isomer blend	163702-0	Saturated HFEs and HCFEs with 3 or more carbon-hydro	Other	297	1.41	14.20	25.71	34.79	21.28	22.65	27.08
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFE-569sf2, (HFE-7200) Isomer blend	163702-0	Saturated HFEs and HCFEs with 3 or more carbon-hydro	HFE	59	0.49	0.06	0.26	0.14	0.05	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFE-7300 (1,1,1,2,2,3,4,5,5,5-decafluoro-3-methoxy-4-trifluorome	132182-9	Saturated HFEs and HCFEs with 3 or more carbon-hydro	HFE	405	0.06	0.01	0.06	0.02	0.02	0.07	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	HFE-7500 (3-ethoxy-1,1,1,2,3,4,4,5,5,6,6,6-dodecafluoro-2-trifluor	297730-9	Saturated HFEs and HCFEs with 3 or more carbon-hydro	HFE	13	0.17	0.02	0.10	0.02	NO	0.02	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Hydrofluorocarbon	No data-	Other fluorinated GHGs	Other	2000	NO	NO	0.26	0.19	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Iodonium, Diphenyl-Alkyl Derivatives Hexafluoroantimonate	155716-0	Fluorinated GHGs with carbon-iodine bond(s)	Other	1	NO	NO	NO	NO	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	isobutyryl fluoride	430-92-2	Other fluorinated GHGs	Other	2000	3.75	3.20	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Methyl 2,2,2-trifluoroacetate	431-47-0	Fluorinated acetates, carbonofluoridates, and fluorinate	Other	52	NO	NO	0.05	0.11	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Methyl heptafluoroisobutyrate	680-05-7	Other fluorinated GHGs	Other	2000	0.00	0.00	0.00	0.00	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Methyl pentafluoropropionate	378-75-6	Other fluorinated GHGs	Other	2000	0.01	0.00	0.01	0.01	0.02	0.01	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Methyl Perfluorobutyrate	356-24-1	Other fluorinated GHGs	Other	2000	0.12	0.00	0.00	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	METHYL PERFLUOROMETHOXYPROPIONATE	356-69-4	Other fluorinated GHGs	Other	2000	NO	NO	0.00	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Methyl(nonafluorobutylethyl)Methylhydrogen siloxane trimethyls	178233-6	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Morpholine, 2,2,3,3,5,5,6,6-octafluoro-4-(heptafluoropropyl)-	1704-69-	Fully fluorinated GHGs	Other	10000	NO	NO	0.00	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	N-(2-Hydroxyethyl)-Perfluorobutylsulfonamide	34454-99	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	0.21	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	NC12F24H3	3M #2-33	Other fluorinated GHGs	Other	2000	NO	NO	NO	0.00	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	n-Methyl Perfluorooctyl Sulfonamide	31506-32	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Nonafluoro-1-Butanesulfonic Acid	375-73-5	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	0.01	0.01	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Novec 649/1230, FK 5-1-12, perfluoro(2-methyl-3-pentanone)	756-13-8	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	0.11	1.52	0.00	0.19	0.14	0.00	0.40	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Octafluorotetrahydrofuran	773-14-8	Fully fluorinated GHGs	Other	13900	173.48	138.76	3.54	4.47	1.74	1.33	2.33
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Organic Fluorochemical	231620-7	Other fluorinated GHGs	Other	2000	NO	NO	NO	0.01	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	OXETANE, 2,2,3,4,4-PENTAFLUORO-3-(TRIFLUOROMETHYL)-	214119-3	Fully fluorinated GHGs	Other	10000	NO	NO	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PEM	55716-11	Fully fluorinated GHGs	Other	10000	NO	NO	NO	0.01	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Pentafluoro(trifluoromethoxy)-ethane	665-16-7	Fully fluorinated GHGs	Other	10000	21.50	7.17	NO	0.26	0.32	0.34	0.31
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PENTAFLUOROPROPANOIC ACID	422-64-0	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Pentafluorotetrahydro-methoxy-bis(tetrafluoro(trifluoromethyl)e	957209-1	Saturated HFEs and HCFEs with 3 or more carbon-hydro	HFE	270	0.00	0.00	NO	NO	NO	0.04	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluoro alkoxy acid fluoride	3M #999	Other fluorinated GHGs	Other	2000	NO	NO	NO	0.00	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluoro Compounds, C5-18	86508-42	Fully fluorinated GHGs	Other	10000	2.42	0.94	0.02	0.02	0.24	0.01	0.31
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluoro(2-methyl-3-oxahexanonic) acid	13252-13	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluoro[Butanesulfonyl Fluoride-4-Vinyl Ether]	88190-28	Other fluorinated GHGs	Other	2000	0.24	0.00	0.04	0.11	0.02	0.07	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluoro-2-(2-Fluorosulfonylethoxy) Propyl Vinyl Ether	16090-14	Other fluorinated GHGs	Other	2000	0.59	0.59	5.01	3.54	1.43	1.91	1.58
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluorobutanesulfonyl fluoride	375-72-4	Other fluorinated GHGs	Other	2000	9.46	7.67	3.26	1.80	2.57	1.70	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PERFLUOROBUTANOYL FLUORIDE	335-42-2	Other fluorinated GHGs	Other	2000	0.01	0.00	0.01	0.01	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluorobutyric Acid	375-22-4	Other fluorinated GHGs	Other	2000	0.01	0.00	0.00	NO	0.01	0.01	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluorodiethyl ether	358-21-4	Fully fluorinated GHGs	Other	10000	17.07	11.42	0.41	0.21	0.01	0.00	0.00
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PERFLUORODIETHYLSULFONE	14930-22	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluorodiisopropyl Ketone	813-44-5	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluorodimethyl sulfide - CI CAS	37305	Fully fluorinated GHGs	Other	10000	NO	NO	0.15	0.18	NO	NO	0.00
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluorodimethyl Sulfone	72971-96	Other fluorinated GHGs	Other	2000	NO	NO	NO	0.00	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluoroethanesulfonyl Fluoride	354-87-0	Other fluorinated GHGs	Other	2000	0.00	0.00	NO	0.00	0.01	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluoroethyl vinyl ether	10493-43	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	17.14	8.68	0.13	0.15	NO	0.01	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PERFLUOROISOBUTYRIC ACID FLUORIDE	677-84-9	Other fluorinated GHGs	Other	2000	0.00	0.00	0.01	0.01	0.00	0.00	NO

GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PERFLUOROMETHANESULFONIC ACID	1493-13-	Other fluorinated GHGs	Other	2000	0.01	0.00	NO	NO	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PERFLUOROMETHOXYPROPIONYL FLUORIDE	425-38-7	Other fluorinated GHGs	Other	2000	0.04	0.00	NO	0.01	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluoropropionyl fluoride	422-61-7	Other fluorinated GHGs	Other	2000	7.25	6.11	NO	0.00	0.00	0.85	1.16
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluoropropyl vinyl ether	1623-05-	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	0.40	0.40	0.23	0.34	0.03	NO	0.00
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PERFLUOROSULFOLANE	42060-64	Other fluorinated GHGs	Other	2000	0.00	0.00	0.00	0.00	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Perfluoro-tert-butanol	174-61-9	Fluorinated acetates, carbonofluoridates, and fluorinate	Other	30	NO	NO	NO	NO	NO	0.02	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PFPMIE	1309353-	Fully fluorinated GHGs	Other	10000	NO	NO	0.00	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	PMVE; HFE-216	1187-93-	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	0.17	1.96	1.96	0.50	0.16	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Poly(oxy-1,2-ethanediyl),.alpha.-[2-[ethyl[(1,1,2,2,3,3,4,4,5,5,6,6,7	68958-60	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Poly[oxy(1,1,2,2-tetrafluoro-1,2-ethanediyl)],.alpha.-(difluorohydr	114366-8	Saturated HFEs and HCFEs with 3 or more carbon-hydro	HFE	270	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Propanamide, 2,3,3,3-tetrafluoro-2-(trifluoromethyl)-	662-20-4	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	0.01	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Propane,1,1,2,2,3,3-hexafluoro-1-[(1,2,2-trifluoroethenyl)oxy]-3-(	40573-09	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Propanenitrile, 2,3,3,3-tetrafluoro-2-(trifluoromethyl)-	42532-60	Other fluorinated GHGs	Other	2750	NO	NO	NO	NO	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Propanoic acid, 2,2,3,3-tetrafluoro-3-(trifluoromethoxy)-	377-73-1	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Propanoic acid, 2,â €‹3,â€‹3,â€‹3-â€‹tetrafluoro-â€‹2-â€‹(1,â€‹1,â	13140-34	Other fluorinated GHGs	Other	2000	NO	NO	0.00	0.00	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Propanoic Acid, 3-[1-[Difluoro [(Trifluoroethenyl oxy] Methyl]-1,2	63863-43	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	0.00	0.00	NO	0.05	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Propanoicacid,2,2,3-trifluoro-3-[1,1,2,2,3,3-hexafluoro-3-(trifluoro	958445-4	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Propanoyl Fluoride	430-71-7	Other fluorinated GHGs	Other	2000	0.26	0.00	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Propanoyl fluoride, 2,2,3,3-tetrafluoro-	663-74-1	Other fluorinated GHGs	Other	2000	NO	NO	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Propanoyl fluoride, 2,â €‹3,â€‹3,â€‹3-â€‹tetrafluoro-â€‹2-â€‹[1,â€	117516-1	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	0.02	0.00	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Propanoylfluoride,2,2,3,3-tetrafluoro-3-(1,1,2,2,3,3,3-heptafluoro	356-61-6	Unsaturated perfluorocarbons (PFCs), unsaturated HFCs	Other	1	NO	NO	NO	NO	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Trifluoroacetic Acid	76-05-1	Other fluorinated GHGs	Other	2000	24.45	0.05	0.21	0.43	NO	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Trifluoroacetic Anhydride	407-25-0	Other fluorinated GHGs	Other	2000	0.00	0.00	0.00	0.00	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Trifluoroacetyl fluoride	354-34-7	Other fluorinated GHGs	Other	2000	1.75	1.75	1.18	0.82	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	TRIFLUOROMETHANESULFONIC ACID ANHYDRIDE	358-23-6	Other fluorinated GHGs	Other	2000	0.00	0.00	NO	NO	0.00	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Trifluoromethanesulfonyl fluoride	335-05-7	Other fluorinated GHGs	Other	2000	31.48	26.85	24.51	29.70	3.42	0.00	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Trifluoromethyl sulphur pentafluoride	373-80-8	Fully fluorinated GHGs	Other	17400	66.22	52.80	2.79	3.76	0.87	0.83	1.11
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Unknown FC	38042	Fully fluorinated GHGs	Other	10000	0.32	0.28	NO	NO	NO	NO	NO
GHG	Industrial Processes	Chemical Industry	Fluorochemical Productio	mt	Unknown Sulfonated Fluorochemical Compounds	38408	Fully fluorinated GHGs	Other	10000	0.27	0.23	NO	0.00	NO	0.00	0.00

***Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022*:**

Updates on Proposed Methodology for Ceramics Production

This memorandum discusses updates under consideration for the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (GHGI) to include process CO_2 emission estimates for ceramics production in current or future reports. The process CO_2 emissions from ceramics production will be reported in Chapter 4 of the GHGI, and full time series data will be available in the accompanying CSVs corresponding to the tables in the GHGI chapter, in addition to reporting time series emissions and data under Category 2A4a in the Common Reporting Tables (CRT) submitted to the UN with the report. EPA prepared a memo during the expert review cycle for the previous inventory and has updated that memo to reflect additional research This memo includes questions where EPA is requesting feedback from technical experts on the proposed methodology outlined below for estimating emissions from ceramics production.

1 Introduction/Background

Process CO_2 emissions estimates for ceramics production are currently not included in the GHGI. The *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (hereafter *2006 IPCC Guidelines*) identifies four broad source categories to consider for the process use of carbonates in the mineral industry: (1) ceramics, (2) other uses of soda ash, (3) non-metallurgical magnesia production, and (4) other uses of carbonates.[1] Currently, the Other Process Uses of Carbonate source category includes process emissions associated with the consumption of soda ash not associated with glass manufacturing and the calcination of limestone and dolomite for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, and acid neutralization. Economic data demonstrate that ceramics production has taken place over the full time series (Federal Reserve 2023). To improve completeness of the Other Process Uses of Carbonates source category within the GHGI, EPA is proposing methods to estimate and report process CO_2 estimates from ceramics production in the GHGI, based on methods recommended in the *2006 IPCC Guidelines*. Emissions from fuel used for energy at ceramics facilities are already included in the overall industrial sector energy use (as obtained from the Energy Information Administration (EIA)) and accounted for as part of energy sector emissions in Chapter 3 of the GHGI.

The ceramic industry comprises a variety of products manufactured from nonmetallic, inorganic materials, many of which are clay-based. The major end use sectors of ceramic products include bricks and roof tiles, wall and floor tiles, table and ornamental ware (household ceramics), sanitary ware, refractory products, vitrified clay pipes, expanded clay products, inorganic bonded abrasives, and technical ceramics (e.g., aerospace, automotive, electronic, or biomedical applications) (EIPPCB 2007).

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[1] *2006 IPCC Guidelines*, Volume 3 Industrial Processes and Product Use, Chapter 2 Mineral Industry Emissions, Section 2.5 Other Process Uses of Carbonates.

2 Methodology

Most ceramic products are made from one or more different types of clay (e.g., shales, fire clay, and ball clay) with varying carbonate contents. The process of manufacturing ceramic products, regardless of the product type or scale, is essentially the same. This process consists of raw material processing (grinding, calcining, and drying), forming (wet or dry process), firing (single or multiple stage firing process), and final processing. Carbon dioxide emissions are produced during the calcination process in the kiln or dryer and from any combustion sources. Process carbon dioxide emissions result from the calcination of carbonates in the raw material (particularly clay, shale, limestone, dolomite, and witherite) and the use of limestone or other additives as a flux (IPCC 2006). In the calcination process, carbonates are heated to high temperatures in a kiln or dryer, producing metal oxides and CO_2.

As noted in Section 1 of this memo, emissions from fuel used for energy at ceramics facilities are included in the overall industrial sector energy use and accounted for as part of energy sector emissions in Chapter 3 the GHGI. Emissions from the use of limestone or dolomite as a flux stone are already accounted for in the limestone and dolomite consumption under Other Process Uses of Carbonates (CRF Source Category 2A4), based on activity data obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Crushed Stone* (USGS 1995-2022a), and are not considered in these estimates to avoid double counting. Flux stone used during the production of iron and steel continues to be deducted from the Other Process Uses of Carbonates source category estimate and attributed to the Iron and Steel Production source category estimate (CRF Source Category 2C1).

The *2006 IPCC Guidelines* include Tier 1, Tier 2, and Tier 3 methodologies for estimating CO_2 emissions from ceramics production. The basic method, or Tier 1 methodology, assumes that limestone and dolomite are the only carbonates contained in the clay used for ceramics production and estimates CO_2 emissions using default limestone and dolomite CO_2 emission factors, a default fraction of limestone versus dolomite consumed, and a default carbonate content for clay if no additional information is available. The Tier 2 method requires national data on the quantity of limestone and dolomite consumed in the clay as opposed to using a default fraction. The Tier 3 method is based on the collection of plant-specific data on the types and quantities of all carbonates consumed to produce ceramics, as well as the respective plant-specific emission factors of the carbonates consumed.

Based on available activity data, EPA is proposing to use an IPCC Tier 1 method to estimate CO_2 emissions from ceramics production in accordance with the methodological framework in the IPCC Guidelines, considering this is a minor source or subcategory. EPA has not identified the data necessary to implement the Tier 2 or Tier 3 methods.

The IPCC methodology uses the equation 2.14 below to estimate CO_2 emissions from the use of carbonates.

IPCC 2006 Guidelines	Vol 3, Chapter 2	Equation 2.14 (page 2.34)

$$CO_2 = M_c \times \ (0.85\ EF_{ls} + 0.15\ EF_d)$$

Where:

CO_2 = emissions of CO_2 from other process uses of carbonates (metric tons/year)
M_c = mass of carbonate consumed (metric tons)

EF_{ls} or EF_d = emissions factor for limestone or dolomite calcination, metric tons CO_2/metric ton carbonate

According to the *2006 IPCC Guidelines*, the activity data on carbonates consumed should reflect pure carbonates and not carbonate rock. Consistent with the *2006 IPCC Guidelines*, EPA assumes a national default carbonate content of clay to be 10%, as no further published information is available.[2] The 10% carbonate content is applied to total clay consumed in the US to calculate M_c (mass of carbonate consumed) in the equation above to estimate CO_2 emissions, i.e., M_c = 10% of total clay consumed.

The *2006 IPCC Guidelines* also include the guidance that if national production data for bricks and roof tiles, vitrified clay pipes, and refractory products is used to estimate emissions, then the amount of clay consumed should be calculated by multiplying production with a default loss factor of 1.1. Where consumption data is available and used to estimate emissions, this default loss factor does not need to be applied. This proposed method uses the consumption of clay as activity data, so a loss factor does not apply.

The IPCC default emission factors for limestone and dolomite are presented in Table 1 below, taken from the *2006 IPCC Guidelines* Volume 3, Chapter 2, Table 2.1.

Table 1. CO_2 Emission Factors for Limestone and Dolomite[a]

Carbonate	**Mineral Name**	**Emission Factor (metric ton CO_2/metric ton carbonate)**[b]
$CaCO_3$	Calcite[c] or aragonite	0.43971
$CaMg(CO_3)_2$	Dolomite	0.47732

[a] Emission factors are based on stoichiometric ratios for carbonate-based minerals.

[b] The fraction of emitted CO_2 assuming 100 percent calcination.

[c] Calcite is the principal mineral in limestone. Terms like high-magnesium or dolomitic limestones refer to a relatively small substitution of Mg for Ca in the general $CaCO_3$ formula commonly shown for limestone.

Currently, only national-level activity data on the consumption of clay is available for use in estimating emissions from ceramics production over the 1990 to 2021 time series. The United States Geological Survey (USGS) publishes annual production and consumption information on six types of clay: ball clay, bentonite, common clay, fire clay, fuller's earth, and kaolin. USGS develops domestic production and consumption data based on responses from a voluntary survey of U.S operations. The number of survey respondents and the portion of the industry that the responses represent change annually. In 2018, USGS reported that 151 of the 224 domestic clay operations responded to the voluntary survey, with those respondents accounting for approximately 64% of the tonnage of total clay and shale sold or used by producers in that year. The survey respondents for the entire time series typically represent between 40 and 70% of the tonnage of total clay sold or used by producers. To address the completeness of the data, USGS estimates production data for nonrespondents based on preliminary survey data, company reports, trade reports, and/or reported prior-year production levels adjusted by industry trends and employment hours (USGS 2022).

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[2] Comments received by the Greenhouse Gas Reporting Program and shared with the EPA's GHGI staff suggest that the carbonate content of clay used for some types of ceramics (e.g., bricks) can be much lower. Available at https://www.regulations.gov/comment/EPA-HQ-OAR-2019-0424-0332.

To estimate annual process CO_2 emissions, EPA evaluated the end-use for domestic consumption of each type of clay provided by USGS to determine the emissive end-uses that fall into the ceramics production subcategory. Table A-1, included at the end of this memo, provides the list of end-uses for each clay type and indicates which end-uses are emissive. The emissive end-uses were grouped into 3 categories: ceramics, glass, and floor & tile; refractories; and heavy clay products (USGS 2023). Table A-2 provides the list of emissive categories and the end-uses that are included in each category.

USGS export data is not included in total clay consumption activity data used for purposes of process CO_2 emissions estimation because industry reported quantities of exported clay whereas process emissions are associated with the end-use of clay. Limited information is provided on the end-use of imported clay. The amount of total imported clay is between 0.1% and 2.6% of the amount of clay produced across the six types of clays during the 1990 through 2021 time series, as data for 2022 was not available at the time of Expert Review. Imported clay data is not accounted for in the preliminary national-level estimates. EPA is assessing how to assess and account for the end-uses of imported clay.

3 Preliminary Process CO_2 Emissions Estimates

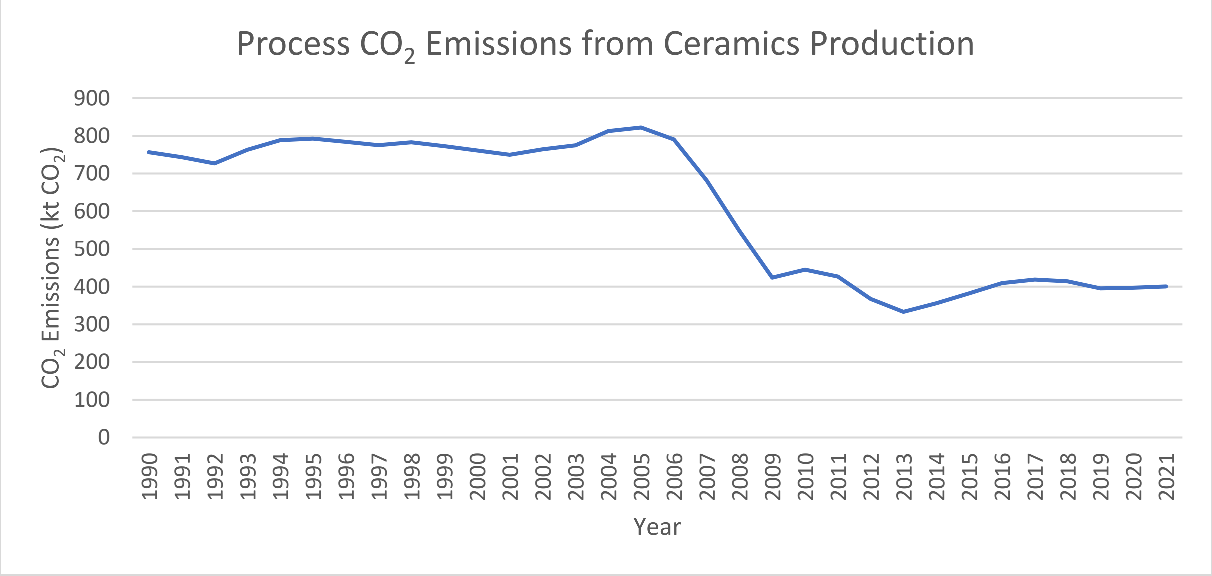
Using the IPCC Tier 1 calculation methodology and activity data from USGS on national-level clay production data per emissive category of ceramics production (USGS 2023), EPA calculated preliminary process CO_2 emissions for 1990 to 2021. Data for 1990 and 2016 to 2021 are shown in Table 2. Total process CO_2 emissions for the full time series are shown in Figure 1. USGS data for 2022 was not available during Expert Review preparation.

Table 2. Preliminary National Process CO_2 Emissions Estimates from Ceramics Production for 1990 and 2016-2021 (kt CO_2)

Clay Consumption for Emissive Category	1990		2016	2017	2018	2019	2020	2021
Ceramics, Glass, and Floor & Tile	104.7		105.1	107.3	96.2	91.3	87.3	95.3
Refractories	68.6		30.4	33.6	32.6	31.9	29.0	33.7
Heavy Clay Products	583.4		273.9	277.9	285.5	272.1	281.0	271.7
Total	**756.7**		**409.4**	**418.8**	**414.2**	**395.3**	**397.3**	**400.6**

[a] Imported clay data is not accounted for in the preliminary national-level emissions estimates.

Figure 1. Total Process CO_2 Emissions from Ceramics Production for 1990-2021.



4 Uncertainty

EPA is proposing to use a simple error propagation method to assess uncertainty of this estimate. The *2006 IPCC Guidelines* identify considerations for an uncertainty assessment of process emissions from ceramics production. Uncertainty surrounding emissions factors are inherently low, as they are based on the stoichiometric ratio of CO_2 released upon calcination. In practice, however, uncertainties arise due to variations in the chemical composition of the carbonate. Uncertainty also arises from activity data. The *2006 IPCC Guidelines* suggest the uncertainty associated with the weighing of carbonates is typically 1-3 percent, and ceramics production uses clay with an approximated carbonate content, which suggests a higher uncertainty would be appropriate. The default uncertainty in carbonate content is also indicated as 1-3 percent.

Data on clay consumption are collected by USGS through voluntary national surveys. USGS contacts the owners of U.S. clay operations (i.e., producers of various types of clay) for annual production data. The producers report the annual quantity sold to various end-users and industry types. In 2018, the response rate was approximately 67 percent of operators, representing approximately 64% of the consumption of clay and shale, and the rest is estimated by USGS. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. The accuracy of distribution by end use is also uncertain because this value is reported by the producer and not the end user.

Uncertainty in the estimates also arises in part due to the variations in the carbonate content of the various clays used for the various types of ceramics. As discussed above, as no information is available on the carbonate content for each clay, default fractions of limestone and dolomite consumed and a default carbonate content for clay are used.

The proposed approach for calculating uncertainty for process emissions from ceramics production for the full time series is to assume an uncertainty range of ±10 percent for the activity data and ±3 percent for the emission factors, consistent with uncertainty ranges for limestone and dolomite activity data and emission factors for Other Process Uses of Carbonates, respectively.

5 Request for Feedback

EPA seeks technical expert feedback on the updates under consideration discussed in this memo and the questions below.

1. EPA is considering using the IPCC assumption of 10% carbonate content value applied to total clay consumed to estimate clay carbonate content on a national level. EPA seeks feedback on additional sources of carbonate content per type of clay.
2. EPA is considering applying the IPCC Tier 1 carbonate values of 85% limestone and 15% dolomite to the emissions calculation for clay usage. EPA seeks feedback on average carbonate composition of clays, or other representations for the national level.
3. EPA intends to use the USGS production values, defined as clay sold or used by producers, to estimate process CO_2 emissions for each emissive category for clay. EPA is not currently including imported clay data in the estimated process CO_2 emissions. EPA seeks feedback on additional information regarding the end-use of imported clays.
4. EPA is seeking feedback on the uncertainty assigned to emission factors and activity data used in this estimate.
5.

6 References

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. Volume 3, Industrial Processes and Product Use, Chapter 2, Mineral Industry Emissions. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan. 2006.

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Table A-1. End Uses of Ball Clay, Bentonite, Common Clay, Fire Clay, Fuller's Earth, and Kaolin (Yes/No)

Ball Clay	Emissive?	Bentonite	Emissive?
Fillers, extenders, and binders	N	Pet waste absorbents	N
Floor and wall tile	Y	Other absorbents	N
Dinnerware	Y	Adhesives	N
Miscellaneous ceramics	Y	Animal feed	N
Pottery	Y	Drilling mud	N
Refractories	Y	Filler and extender applications	N
Sanitaryware	Y	Filtering, clarifying, decolorizing, mineral oils and greases, vegetable oils, desiccants	N
Miscellaneous:		Foundry sand	N
Chemical manufacturing	N	Pelletizing (iron ore)	N
Heavy-clay products	Y	Waterproofing and sealing	N
Waterproofing seals	N	Miscellaneous civil engineering	N
Refractories	Y	Miscellaneous refractories and kiln furniture	Y
Paint	N	**Miscellaneous:**	
Absorbents	N	Ceramics	Y
Brick (common)	Y	Chemical manufacturing	N
Flue lining	N	Clarifying and decolorizing	N
Glazes	N	Heavy-clay products	Y
Drilling mud	N	Oil and grease absorbents	N
Unknown Uses	N	Refractories	Y
		Asphalt emulsions	N
		Asphalt tile	N
		Portland cement	N
		Ceramic floor and wall tile	Y
		Face brick	Y
		Fertilizers	N
		Firebrick, blocks and shapes	Y
		Gypsum products	N
		Ink	N
		Kiln furniture	Y
		Mineral wool and insulation	N
		Oil well sealing	N
		Paper coating and filling	N
		Plastics	N
		Pottery	Y
		Roofing tile	Y
		Catalysts (oil-refining)	Y
		Rubber	N
		Unknown uses	N

Table A-1. End Uses of Ball Clay, Bentonite, Common Clay, Fire Clay, Fuller's Earth, and Kaolin (Yes/No) (continued)

Common Clay	Emissive?	Fire Clay	Emissive?
Floor and wall tile:	Y	Ceramics and glass	Y
Ceramic	Y	**Heavy-clay products and lightweight aggregates:**	
Other	Y	Common brick	Y
Heavy-clay products:		Concrete block	N
Brick, extruded	Y	Portland cement	N
Brick, other	Y	Structural concrete	N
Drain tile and sewer pipe	Y	Terra cotta	Y
Flowerpots	Y	Unknown uses	N
Flue linings	Y	**Refractories:**	
Structural tile	Y	Firebrick, block, and shapes	Y
Other	Y	Grogs and calcines	Y
Lightweight aggregate:		Other refractories:	Y
Concrete block	N	Foundry sand	N
Highway surfacing	N	Grogs and calcines	Y
Structural concrete	N	Mortar and cement	N
Miscellaneous	N	Common brick	N
Portland and other cements	N	Flue linings	N
Refractories:		Plug, tap and wad	N
Block and shapes	Y	Misc. refractories	Y
Firebrick	Y	**Miscellaneous:**	
Grogs and calcines	Y	Animal feed	N
Mortar and cement	N	Floor tile	Y
Misc. refractories	Y	Pottery	Y
Miscellaneous:		Wall tile	Y
Exports reported by producers	N	Quarry tile	Y
Misc. civil engineering and sealings	N	Misc. ceramics	Y
Misc. fillers, extenders, and binders	N	Unknown uses	N
Pottery	Y		
Roofing granules	Y		
Misc. ceramics	Y		
Asphalt emulsion	N		
Asphalt tile	N		
Wall board	N		
Pelletizing (iron ore)	N		
Unknown uses	N		

Table A-1. End Uses of Ball Clay, Bentonite, Common Clay, Fire Clay, Fuller's Earth, and Kaolin (Yes/No) (continued)

Fuller's Earth	Emissive?	Kaolin	Emissive?
Miscellaneous:		**Ceramics:**	
Catalysts (oil-refining)	N	Catalyst (oil and gas refining)	Y
Animal feed	N	Electrical porcelain	Y
Animal oils	N	Fiberglass, mineral wool	Y
Gypsum products	N	Fine china and dinnerware	Y
Miscellaneous fillers, extenders, and binders	N	Floor and wall tile	Y
Miscellaneous filtering, clarifying	N	Pottery	Y
Plastics	N	Roofing granules	Y
Wallboard	N	Sanitaryware	Y
Water treatment and filtering	N	Miscellaneous	Y
Waterproofing and sealing	N	Chemical manufacture	N
Electrical porcelain	Y	**Fillers, extenders, binders:**	
Chemical manufacturing	N	Adhesives	N
Drilling mud	N	Fertilizer	N
Fertilizers	N	Paint	N
Miscellaneous absorbents	N	Medical, pharmaceutical, cosmetic	N
Pesticides	N	Paper coating	N
Portland cement	N	Paper filling	N
Roofing granules	Y	Pesticide	N
Refractories	Y	Plastics	N
Unknown uses	N	Rubber	N
		Miscellaneous	N
		Heavy-clay products:	
		Brick (common)	Y
		Portland and other cements	N
		Refractories:	
		Firebrick, blocks and shapes	Y
		Grogs and calcines	Y
		High-alumna brick, specialties, kiln furniture	Y
		Other	
		Foundry sand	N
		Mortar	N
		Cement	N
		Misc. refractories	Y
		Miscellaneous applications:	
		Linoleum and asphalt tile	N

Table A-2. Clay Emissive End Use Categories

Ceramics, Glass, and Floor & Tile
Catalysts (Oil Refining)
Electrical Porcelain
Fiber Glass
Fine China/Dinnerware
Mineral Wool and Insulation
Pottery
Roofing Granules
Sanitaryware
Miscellaneous Ceramics
Floor and Wall Tile, Ceramic
Refractories
Firebrick, Block and Shapes
Grogs and Calcines
Kiln Furniture
Heavy Clay Products
Brick, Common
Face Brick, Other
Drain Tile
Sewer Pipe
Misc. Clay Products

***Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022*:**

Proposed Methodology for the Addition of Non-Metallurgical Magnesia Production

This memorandum discusses updates under consideration for the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (GHGI) to include process CO_2 emission estimates for non-metallurgical magnesia production. The process CO_2 emissions from non-metallurgical magnesia production will be reported in Chapter 4 of the GHGI, and full time series data will be available in the accompanying CSVs corresponding to the tables in the GHGI report, in addition to reporting the time series emissions and activity data under Category 2A4a in the Common Reporting Table (CRT) submitted to the UN with the report.

1 Introduction/Background

Process CO_2 emissions estimates for non-metallurgical magnesia production are currently not included in the GHGI. The *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (hereafter *2006 IPCC Guidelines*) identifies four broad source categories to consider for the use of carbonates in the mineral industry: (1) ceramics, (2) other uses of soda ash, (3) non-metallurgical magnesia production, and (4) other uses of carbonates.[1] Currently, the Other Process Uses of Carbonate source category includes process emissions associated with the consumption of soda ash not associated with glass manufacturing and the calcination of limestone and dolomite for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, and acid neutralization. To improve completeness of the Other Process Uses of Carbonates source category within the GHGI, EPA is proposing methods to estimate and report process CO_2 estimates from non-metallurgical magnesia production to the GHGI, based on methods recommended in the *2006 IPCC Guidelines*. Emissions from fuel used for energy at non-metallurgical magnesia facilities are already included in the overall industrial sector energy use (as obtained from the Energy Information Administration (EIA)) and accounted for as part of energy sector emissions in Chapter 3 of the GHGI.

The non-metallurgical magnesia industry comprises three categories of magnesia products: calcined magnesia, deadburned magnesia, and fused magnesia. Magnesia is produced by calcining magnesite ($MgCO_3$) which produces CO_2.

Non-metallurgical magnesia is used in agricultural, industrial, refractory, and electrical insulating applications. Specific applications include fertilizers, construction materials, plastics, and flue gas desulphurization.

2 Methodology

The *2006 IPCC Guidelines* include Tier 1, Tier 2, and Tier 3 methodologies for estimating CO_2 emissions from non-metallurgical magnesia production. Regarding activity data, the basic method, or Tier 1 methodology, assumes that magnesite and limestone are the only carbonates contained in the

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[1] *2006 IPCC Guidelines*, Volume 3 Industrial Processes and Product Use, Chapter 2 Mineral Industry Emissions, Section 2.5 Other Process Uses of Carbonates.

magnesite used for non-metallurgical magnesia production and estimates CO_2 emissions using default magnesite and limestone CO_2 emission factors. The Tier 2 method is the same as Tier 1, except it requires national data on the quantity of magnesite and limestone consumed. The Tier 3 method is based on the collection of plant-specific data on the types and quantities of carbonates consumed to produce non-metallurgical magnesia, as well as the respective emission factors of the carbonates consumed.

In accordance with the IPCC methodological decision tree and available activity data, EPA is proposing to use a Tier 1 method provided in the 2006 IPCC Guidelines to estimate process CO_2 emissions from non-metallurgical magnesia production. EPA has not identified the data necessary to implement the Tier 2 or Tier 3 methods. Additionally, the non-metallurgical magnesia production subcategory and the Other Process Uses of Carbonates category are not a key category in the GHGI.

Equation 2.14 below from the *2006 IPCC Guidelines* is used to estimate CO_2 emissions from the use of carbonates.

IPCC 2006 Guidelines	Vol 3, Chapter 2	Equation 2.14 (page 2.34)

$$CO_2 = M_c \times (0.85\, EF_{ls} + 0.15\, EF_d)$$

Where:

CO_2 = emissions of CO_2 from other process uses of carbonates (metric tons/year)
M_c = mass of carbonate consumed (metric tons)
EF_{ls} or EF_d = emissions factor for limestone or dolomite calcination, metric tons CO_2/metric ton carbonate

A 1948 United States Geological Survey (USGS) report on magnesite and brucite deposits at Gabbs, Nevada lists the carbonate content of magnesite as 98% magnesite and 1% limestone with traces of other minerals (USGS, 1948). Therefore, equation 2.14 can be modified to reflect this country-specific approach.

$$CO_2 = M_c \times (0.98\, EF_m + 0.01\, EF_{lm})$$

Where:

CO_2 = emissions of CO_2 from other process uses of carbonates (metric tons/year)
M_c = mass of carbonate consumed (metric tons)
EF_m or EF_{lm} = emissions factor for magnesite or limestone calcination, metric tons CO_2/metric ton carbonate

The IPCC default emission factors for magnesite and limestone are presented in Table 1 below, taken from the *2006 IPCC Guidelines* Volume 3, Chapter 2, Table 2.1.

Table 1. CO_2 Emission Factors for Magnesite and Limestone[a]

Carbonate	Mineral Name	Emission Factor (metric ton CO_2/metric ton carbonate)[b]
$MgCO_3$	Magnesite	0.52197
$CaCO_3$	Calcite[c] or aragonite	0.43971

[a] Emission factors are based on stoichiometric ratios for carbonate-based minerals.

[b] The fraction of emitted CO_2 assuming 100 percent calcination.

[c] Calcite is the principal mineral in limestone. Terms like high-magnesia or dolomitic limestones refer to a relatively small substitution of Mg for Ca in the general $CaCO_3$ formula commonly shown for limestone.

The USGS publishes annual production and consumption information on magnesium compounds, including magnesite, lake brines, well brines, and seawater. Only one facility in the U.S. reported producing magnesia (caustic-calcined magnesia) using magnesite as the raw material over the full time series, Premier Magnesia in Gabbs, Nevada. Magnesite consumption from the Premier Magnesia facility in Gabbs, Nevada is not published in the USGS magnesium compound reports. Production capacity for caustic-calcined magnesia produced at the Premier Magnesia facility is published in the USGS reports. To estimate annual process CO_2 emissions, EPA is proposing to use the production capacity of caustic-calcined magnesia as a proxy for activity data on magnesite consumption at the facility.

3 Preliminary Process CO_2 Emissions Estimates

Using the IPCC Tier 1 calculation methodology, EPA is proposing to use published USGS production capacity data for caustic-calcined magnesia (USGS 1994-2022) to develop preliminary process CO_2 emissions for 1990 to 2021 in Table 2. In the absence of data on consumption of magnesite for caustic-calcined magnesia production, production capacity data for caustic-calcined magnesia is assumed to be the most suitable proxy for magnesite consumption at the facility. USGS data for 2022 was not available from USGS for including in this review but will be incorporated when available.

Table 2. Preliminary National Process CO_2 Emissions Estimates from Non-metallurgical Magnesia Production for 1990 and 2016-2021 (kt CO_2)

	1990		2016	2017	2018	2019	2020	2021
Total	**51.59**		**72.23**	**72.23**	**72.23**	**72.23**	**72.23**	**72.23**

4 Uncertainty

The *2006 IPCC Guidelines* identify considerations for an uncertainty assessment of process emissions from non-metallurgical magnesia production. EPA is proposing to use a simple error propagation method to assess uncertainty of this estimate, based on the following assumptions:

- Emission factor: Uncertainty surrounding emissions factors are inherently low, as they are based on the stoichiometric ratio of CO_2 released upon calcination and assume 100 percent calcination. In practice, however, uncertainties arise due to variations in the chemical composition of the carbonates used in production of caustic-calcined magnesia production. As noted, minor quantities of other carbonates beyond limestone and magnesite are also used but unknown. These other carbonates are likely small and likely do not significantly impact the derived emission factor.
- Activity data: Uncertainty also arises from activity data. Using production capacity as a proxy for magnesite consumption adds additional uncertainty, given production could be consistent with capacity or lower. The *2006 IPCC Guidelines* suggest the uncertainty associated with the weighing of carbonates is typically 1-3 percent, but given the proposed use of production capacity in lieu of mass of carbonates, this uncertainty is not relevant. The *2006 IPCC Guidelines*

default uncertainty in carbonate content is also suggested as 1-3 percent. EPA is requesting feedback on uncertainty assigned to use of production capacity,

5 Request for Feedback

EPA seeks technical expert feedback on the updates under consideration discussed in this memo and the questions below.

1. EPA is considering using the USGS value of production capacity of caustic-calcined magnesia at Premier Magnesia as a proxy for magnesite consumption. EPA seeks feedback on use of this data as a proxy and information on additional sources of data on magnesite consumption.
2. EPA is aware of state-level data that may more closely relate to activity data for a Tier 1 method in the *2006 IPCC Guidelines*. EPA seeks feedback on additional sources of state-level information regarding magnesite consumed for non-metallurgical magnesia production for the full time series, 1990-2022.
3. EPA is considering applying carbonate content values of 98% magnesite and 1% limestone to the emissions calculations for magnesite usage. EPA seeks feedback on additional sources of magnesite carbonate content.
4. EPA is seeking feedback on the emission factor assumptions of 100 percent calcination for each carbonate. Is complete calcination a reasonable assumption for non-metallurgical magnesia production?
5. EPA is seeking feedback on the uncertainty assigned to emission factors and activity data used in this estimate.

6 References

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. Volume 3, Industrial Processes and Product Use, Chapter 2, Mineral Industry Emissions. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan. 2006.

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