Climate TRACE: Implicitly Estimated National Greenhouse Gas Inventories

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1. Introduction

Greenhouse gas (GHG) emissions inventories are crucial tools for setting mitigation targets, measuring progress toward goals and for accountability within the context of national and international commitments. There are several organizations – governments, academia and commercial entities – that are involved in data collection and preparation of inventories.

Of these, one of the most important sources of GHG data are official country inventories. All countries that are parties to the United Nations Framework Convention on Climate Change (UNFCCC) are required to prepare GHG inventories as part of their commitments toward Monitoring, Reporting and Verification (MRV) for which standardized requirements have been developed.[1] Annex 1 countries are required to provide annual inventories covering emissions and removals of direct GHGs (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3)) from five sectors (energy; industrial processes and product use; agriculture; land use, land-use change and forestry (LULUCF); and waste), and for all years from the base year (or period) to two years before the inventory is due. Non-Annex 1 countries, on the other hand, have less stringent requirements and provide inventories as part of the national reports every 2-4 years and include other information such as mitigation actions, constraints and gaps, including support needed and received. As a result, these reporting requirements create a patchwork of GHG data that has varying levels of completeness, comprehensiveness, and detail.

Apart from official country inventories, several academic and research organizations also produce inventories at varying levels of granularity and recency. These inventories rely on statistics from the International Energy Agency (IEA)[2], the BP Statistical Review of World

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1 UNFCCC Reporting Requirements, Available at: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/reporting-requirements [Accessed 2022-11-03].

2 International Energy Agency (2022), Data and Statistics, https://www.iea.org/data-and-statistics [Accessed 2022-11-03].

Energy[3], the Food and Agriculture Organization's FAOSTAT database[4], and the United Nations Statistical Division datasets[5] (all of which rely on government data sources to some degree). Examples of these inventories include the Emissions Database for Global Atmospheric Research (EDGAR)[6], PIK-Potsdam PRIMAP[7], and Global Carbon Project[8].

However, despite the existence of many global emissions inventories, several clear challenges exist for any policymaker seeking to access complete publicly available global greenhouse gas emissions estimates in practice.

The key challenges identified by Climate TRACE to accessing a complete global inventory were:

- **Geographic completeness:** Many otherwise high quality inventories informally referred to as "global" did not, upon close investigation, actually cover the entire globe. As a general rule, inventories were often relatively complete in wealthier countries, but frequently had significant gaps in the global South. EDGAR, for example, reports emissions for all sectors and countries, but sometimes has a time lag.
- **Sector completeness:** Nearly every inventory Climate TRACE was able to identify covered only certain sectors, rather than the total emissions for a geography. UNFCCC Annex 1 National Inventory Reports for example, report emissions for all sectors (but are not available in every geography and have a time lag).
- **Temporal completeness and recency:** Many existing inventories are not published every year. Most are also not published until at least 2 years after the emissions occurred. Some countries' most recent inventories–particularly the official UNFCCC inventories of non-Annex 1 countries–were as much as 10 years ago. A few exceptions exist, most notably Carbon Monitor which publishes emissions estimates only a week after the time period measured.

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[3] BP (2021), Statistical Review of World Energy, https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html [Accessed 2022-11-03].

[4] Food and Agriculture Organisation (2019), FAOSTAT Database, https://www.fao.org/faostat/en/#home [Accessed 2022-11-03].

[5] United Nations Department of Economic and Social Affairs Statistics, https://unstats.un.org/UNSDWebsite/ [Accessed 2022-11-03].

[6] Crippa, M., Guizzardi, D., Solazzo, E., Muntean, M., Schaaf, E., Monforti-Ferrario, F., Banja, M., Olivier, J.G.J., Grassi, G., Rossi, S., Vignati, E.,GHG emissions of all world countries - 2021 Report, EUR 30831 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-41547-3, https://edgar.jrc.ec.europa.eu/dataset_ghg70 [Accessed 2022-11-03].

[7] Gütschow, J.; Günther, A.; Pflüger, M. (2021): The PRIMAP-hist national historical emissions time series (1750-2019). V2.3.1, https://www.pik-potsdam.de/paris-reality-check/primap-hist/ [Accessed 2022-11-03].

[8] Friedlingstein et al (2021), Global Carbon Budget 2021, https://essd.copernicus.org/preprints/essd-2021-386/essd-2021-386.pdf, [Accessed 2022-11-03].

In addition, the lack of completeness and standardization of emissions inventories can make data harmonization and cross-validation difficult or, in some cases, impossible.

The goal of Climate TRACE is to address these challenges by providing a globally complete and comprehensive national level GHG inventory that is continually updated every year with emission values up to the preceding calendar year. In 2021, Climate TRACE released national level GHG estimates for years 2015-2020. In 2022, Climate TRACE GHG estimates have been updated to include 2021 national level emission estimates in addition to the 500 largest emitting assets per sector.

Climate TRACE uses the Intergovernmental Panel on Climate Change (IPCC) common reporting framework[9] to develop a novel technique called implicit estimation to complement other GHG measurement methods in forming a global, comprehensive greenhouse gas inventory. Climate TRACE members and contributors use several measurement and estimation techniques:

1) Machine Learning + Satellite Measurements
2) Statistical Modeling + Satellite Measurements
3) Statistical Modeling + Reported Data
4) Implicit Estimation
5) Estimation

Estimates from Climate TRACE members and contributors using techniques 1, 2, and 3 make up 40-70% of global emissions. To account for the remaining percentage, Climate TRACE's 2022 data release employed 4 and 5, leveraging the Emissions Database for Global Atmospheric Research (EDGAR) and The Food and Agriculture Organization (FAO) to estimate emissions. This methodology describes the implicit estimation techniques applied to the remaining sectoral "other" emissions.

2. Materials and Methods

The approach used for implicit estimation employs GHG inventories, projects emissions data to fill in missing years in GHG inventories, and developed sector specific equations to output implicit estimation for the sectoral "other" emissions. Sectors estimated using technique 5, are directly equal to their source dataset.

2.1 Datasets employed

[9] 2006 IPCCGuidelines for National Greenhouse Gas Inventories: https://www.ipcc-nggip.iges.or.jp/public/2006gl/ [Accessed 2022-11-03].

Climate TRACE GHG emissions inventory data[10]: Climate TRACE is a global coalition of organizations with each organization focusing on measuring CO_2, N_2O, and CH_4 GHG emissions from particular economic or land cover sectors.

Temporal coverage: Climate TRACE country level data is provided for 2015-2021. The data for the previous year is typically released in the fall of the following year. For example, 2021 data will be released in November 2022.

Sectoral coverage: Climate TRACE sectors using techniques 1, 2, and 3 (described in the Introduction) total ~60% of global emissions. Emissions that are not currently estimated using techniques 1 to 3 are measured using 4 by applying the implicit estimation. By employing all techniques, Climate TRACE country level inventory accounts for 100% of known anthropogenic greenhouse gasses.

Geographic coverage: Emissions estimates for Climate TRACE measured sectors are available for every country in the world. Comprehensive data are not available in some disputed territories due to lack of data availability.

Food and Agriculture Organization of the United Nations (FAOSTAT) is a specialized agency of the United Nations that focuses on agriculture and food security. FAO is also tasked with collecting food, agriculture and land use, land-use change and forestry (LULUCF) data from countries around the world regarding their agricultural and forestry activities and emissions.

Temporal coverage: FAOSTAT data is available from 1990 - 2019. Data is released on a two year delay. For example, 2019 data was released in 2021.

Sectoral granularity and coverage: FAOSTAT data is available only for agriculture and LULUCF sectors.

Geographic coverage: FAOSTAT data is global and covers 194 countries and 38 territories.[11]

The Emissions Database for Global Atmospheric Research (EDGAR) is an independent database of anthropogenic GHG emissions, providing both national totals and gridmaps. Though the gridmaps are highly granular, we only use the national totals for the purposes of this exercise.

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[10] Climate TRACE - Tracking Real-time Atmospheric Carbon Emissions (2022), Climate TRACE Emissions Inventory: https://climatetrace.org [Accessed 2022-11-03].

[11] FAOSTAT domain Emissions shares. Methodological note, release November 2021. Available at: https://fenixservices.fao.org/faostat/static/documents/EM/EM_e.pdf

Temporal coverage: EDGAR data is available for the years 1970-2021 (EDGAR v7.0). The complete data is published on an irregular lag. For example, 2018 data was published in May of 2021 and data for 2019, 2020 and 2021 was published in September of 2022. Smaller subsets of data, such as fossil fuel emissions are available more frequently.

Sectoral granularity: EDGAR data covers all IPCC emissions except for LULUCF. However, the sectors are not as granular as the most granular IPCC categories. For example, EDGAR reports emissions for 1.B.1 Solid Fuels but does not break it down into 1.B.1.a Coal Mining, 1.B.1.b Solid Fuel Transformation, 1.B.1.c Other.

Geographic coverage: EDGAR data is globally comprehensive.

Table 1 Climate TRACE sectors with IPCC equivalent sector coverage. Sector specific global emission contributions (based on Annex 1), estimation method (from Introduction), data sources are provided.

Sector	Subsector	IPCC Coverage	% of Global Emissions (Annex 1)	Estimation Method	Data Source
power	electricity-generation	1.A.1.a.i Electricity Generation 1.A.1.a.ii Combined Heat and Power Generation	21.00%	1	WattTime & Transition Zero
power	other-energy-use	1.A.1.a.iii Heat Plants 1.A.1.a.iv Other	1.90%	4	WattTime analysis of EDGAR data
buildings	residential-and-commercial-onsite-fuel-usage	1.A.4 Residential and other sectors	12.50%	5	EDGAR
buildings	other-onsite-fuel-usage	1.A.5 Non-Specified	1.70%	5	EDGAR
manufacturing	steel	1.A.2.a Iron and Steel 2.C.1 Iron and Steel Production	2.50%	1	Transition Zero
manufacturing	cement	1.A.2.f Non-metallic Minerals 2.A.1 Cement Production	3.10%	1	Transition Zero
manufacturing	chemicals	1.A.2.c Manufacture of Solid Fuels and Other Energy Industries 2.B.1 Ammonia Production 2.B.7 Soda Ash Production 2.B.8.a Methanol	2.40%	3	Transition Zero
manufacturing	aluminum	1.A.2.b Non-Ferrous Metals 2.C.3 Aluminium Production	0.40%	3	Transition Zero
manufacturing	pulp-and-paper	1.A.2.d Pulp, Paper and Print 2.H.1 Pulp and Paper	0.70%	3	Transition Zero

manufacturing	other-manufacturing	1.A.2.b Non-Ferrous Metals (excluding aluminum) 1.A.2.e Food Processing, Beverages and Tobacco 1.A.2.f Non-metallic Minerals (excluding cement) 1.A.2.g. Other (excluding bauxite, iron, copper, rock and sand) 2.A.2 Lime Production 2.A.3 Glass production 2.A.4 Other Process Uses of Carbonates 2.B.2 Nitric Acid Production 2.B.3 Adipic Acid Production 2.B.4 Caprolactam, Glyoxal and Glyoxylic Acid Production 2.B.5 Carbide Production 2.B.6 Titanium Dioxide Production 2.B.8.b Ethylene 2.B.8.c Ethylene Dichloride and Vinyl Chloride Monomer 2.B.8.d Ethylene Oxide 2.B.8.e Acrylonitrile 2.B.8.f Carbon Black 2.B.8.g Other 2.C.2 Ferroalloys Production 2.C.4 Magnesium Production 2.C.5 Lead Production 2.C.6 Zinc Production 2.C.7 Other 2.D Non-energy Products from Fuels and Solvent Use 2.E Electronics Industry 2.G Other Product Manufacture and Use 2.H.2. Food and Beverages Industry 2.H.3 Other	9.80%	4	WattTime analysis of Transition Zero and EDGAR data
fossil-fuel-operations	oil-and-gas-refining	1.A.1.b Petroleum Refining 1.B.2.a.iv Oil Refining / Storage 1.B.2.a.v Oil Distribution of Oil Products 1.B.2.b.v Natural Gas Distribution	2.90%	2	RMI
fossil-fuel-operations	oil-and-gas-production-and-transport	1.B.2.a.i Oil Exploration 1.B.2.a.ii Oil Production 1.B.2.a.iii Oil Transport 1.B.2.b.i Natural Gas Exploration 1.B.1.b.ii Natural Gas Production 1.B.1.b.iii Natural Gas Processing 1.B.2.c Venting and Flaring	3.00%	2	RMI

fossil-fuel-operations	solid-fuel-transformation	1.B.1.b Solid Fuel Transformation 1.B.2.c Other	0.04%	4	WattTime analysis of Global Energy Monitor and EDGAR data
fossil-fuel-operations	coal-mining	1.B.1.a Coal Mining and Handling	1.40%	3	WattTime analysis of Global Energy Monitor
fossil-fuel-operations	other-fossil-fuel-operations	1.A.1.c Manufacture of Solid Fuels and Other Energy Industries 1.B.2.a.vi Refining / Storage 1.B.2.b.vi Other 1.B.2.d Other	2.60%	4	WattTime analysis of RMI and EDGAR data
mineral-extraction	copper-mining	1.A.2.g.iii Mining (Excluding Fuels) and Quarrying		3	Hypervine
mineral-extraction	iron-mining	1.A.2.g.iii Mining (Excluding Fuels) and Quarrying		3	Hypervine
mineral-extraction	bauxite-mining	1.A.2.g.iii Mining (Excluding Fuels) and Quarrying		3	Hypervine
mineral-extraction	sand-quarrying	1.A.2.g.iii Mining (Excluding Fuels) and Quarrying		3	Hypervine
mineral-extraction	rock-quarrying	1.A.2.g.iii Mining (Excluding Fuels) and Quarrying	0.10%	3	Hypervine
transportation	domestic-aviation	1.A.3.a Domestic Aviation	1.10%	3	WattTime
transportation	international-aviation	7.A International Aviation	2.60%	3	WattTime
transportation	road-transportation	1.A.3.b Road Transportation	20.90%	1 (asset) 5(country)	Johns Hopkins Applied Physics Laboratory (Asset Level) EDGAR (Country Level)
transportation	shipping	1.A.3.d. Domestic Navigation 7.B International Navigation	1.40%	2	OceanMind
transportation	railways	1.A.3.c Railways	0.40%	5	EDGAR
transportation	other-transport	1.A.3.e Other Transportation	1.10%	5	EDGAR
agriculture	rice-cultivation	3.C Rice Cultivation	0.20%	2	University of Malaysia
agriculture	cropland-fires	3.F Field Burning of Agricultural Residues	0.01%	2	Blue Sky Analytics
agriculture	enteric-fermentation	3.A Enteric Fermentation	4.20%	1 (asset) 5 (country)	WattTime analysis of Synthetaic and FAOSTAT

agriculture	manure-management	3.B Manure Management	1.40%	1 (asset) 5 (country)	WattTime analysis of Synthetaic and FAOSTAT
agriculture	synthetic-fertilizer-application	3.D.1.a Inorganic N Fertilizers	1.20%	3	Michigan State University
agriculture	other-agricultural-soil-emissions	3.D.1.b Organic N Fertilizers 3.D.1.c. Urine and Dung Deposited by Grazing Animals 3.D.1.d Crop Residues 3.D.1.e Mineralization/Immobilization Associated with Loss/Gain of Soil Organic Matter 3.D.1.f Cultivation of Organic Soils 3.D.1.g Other 3.D.2 Indirect N_2O Emissions From Managed Soils 3.G Liming 3.H Urea Application 3.I Other Carbon-containing Fertilizers 3.J Other	3.00%	4	FAOSTAT
waste	solid-waste-disposal	5.A Solid Waste Disposal	2.50%	5	WattTime analysis of Global Plastics Watch data and EDGAR
waste	biological-treatment-of-solid-waste-&-biogenic	5.B Biological Treatment of Solid Waste	0.10%	5	EDGAR
waste	incineration-and-open-burning-of-waste	5.C Incineration and Open Burning of Waste	0.10%	5	EDGAR
waste	wastewater-treatment-and-discharge	5.D Wastewater Treatment and Discharge	0.90%	5	EDGAR
fluorinated-gasses	fluorinated-gasses	2.B Chemical Industry (HFCs and PFCs) 2.C Metal Industry (HFCs and PFCs) 2.E Electronics Industry (HFCs and PFCs) 2.F Product Uses as Substitutes for Ozone Depleting Substances (HFCs and PFCs) 2.G Other Product Manufacture and Use (HFCs and PFCs)	2.90%	5	EDGAR
forestry-and-land-use	net-forest-carbon-stock-change	4.A	15.10%	1	CTrees
forestry-and-land-use	net-grassland-carbon-stock-change	4.B	2.00%	1	CTrees
forestry-and-land-use	net-wetland-carbon-stock-change	4.C	0.01%	1	CTrees

2.2 Methods

2.2.1 Projection approach

Not all GHG inventories have the most recent emissions estimates. EDGAR v7.0 currently provides data up to 2021, and FAOSTAT published data up to 2019. In order to utilize the FAOSTAT data for implicit estimation, the data was forward filled. This method uses the last available estimate as the future projected values. This approach was adopted to ensure all GHG inventories described in section 2.1 match temporally.

2.2.2 Implicit Estimation approach -- equations

An immediate practical challenge in implicit estimation is that different global emissions inventories do not use one consistent standardized hierarchy of definitions for emitting sectors and subsectors. Thus, Climate TRACE's first step was to define a crosswalk of all emitting sub-sectors from all inventories it could find, to enable comparison between Climate TRACE sector lead results and those of existing publicly available global emissions inventories. This crosswalk can be found in Table S1 in the Supplementary section.

With the knowledge of what is covered by Climate TRACE vs. EDGAR and FAOSTAT, we were able to write equations to describe the emissions that are not currently estimated using techniques 1, 2, or 3.

Example: Other Manufacturing

The emissions associated with manufacturing and mining are reported in two places within the IPCC Framework. Emissions associated with on-site energy use for manufacturing are reported under 1.A.2 Manufacturing Industries and Construction. Separately, process emissions from manufacturing are reported under 2. Industrial Processes and Product Use.

Climate TRACE members TransitionZero and Hypervine's manufacturing and mining emissions are reported by product: cement, chemicals, steel, aluminum, pulp-and-paper, bauxite-mining, copper-mining, iron-mining, rock-quarrying, and sand-quarrying. Adding additional complexity, these sectors for manufacturing include energy use and process emissions in one number. Consequently, it is not possible to simply republish EDGAR's data for missing sectors such as 2.A.2 Lime production.

The sector estimates generated by TransitionZero (manufacturing) and Hypervine (mining) cover 54% of 1.A.2 Manufacturing Industries and Construction and 47% of 2. Industrial Processes and Product Use[12]. In order to provide estimates that cover all manufacturing and mining emissions, Climate TRACE used the following equation to account for the remaining emissions for "other-manufacturing":

[12] All coverage percentages for this methodology are calculated by using UNFCCC values for Annex I countries.

Eq. Climate TRACE other-manufacturing =

EDGAR 1.A.2 Manufacturing Industries and Construction
\+ *EDGAR 2.A.1 Cement Production*
\+ *EDGAR 2.A.2 Lime Production*
\+ *EDGAR 2.A.3 Glass Production*
\+ *EDGAR 2.A.4 Other Process Uses of Carbonates*
\+ *EDGAR 2.B Chemical Industry*
\+ *EDGAR 2.C Metal Industry*
\+ *EDGAR 2.D Non-Energy Products from fuels and Solvent Use*
\- *TransitionZero Cement*
\- *TransitionZero Chemicals*
\- *TransitionZero Steel*
\- *TransitionZero Aluminum*
\- *TransitionZero Pulp and Paper*
\- *Hypervine Bauxite Mining*
\- *Hypervine Copper Mining*
\- *Hypervine Iron Mining*
\- *Hypervine Rock Quarrying*
\- *Hypervine Sand Quarrying*

By aggregating up, the equation above allows us to capture the emissions not measured by techniques 1, 2, and 3, despite the mismatch of sectoral definitions between EDGAR, Transition Zero, and Hypervine.

Example: Solid Fuel Transformation

Another example is solid fuel transformation. WattTime and Global Energy Monitor are measuring emissions from coal mining activities and Transition Zero is measuring only CO_2 emissions from steel manufacturing, but neither of these models include emissions from solid fuel transformation. Within the IPCC framework, coal mining is a subset of 1.B.1 Solid Fuels. EDGAR reports data for 1.B.1 Solid Fuels but does not report at the more granular levels such as 1.B.1.a Coal Mining and Handling. Figures 1 and 2 show the WattTime/Global Energy Monitor and EDGAR coverage, respectively for this sector.

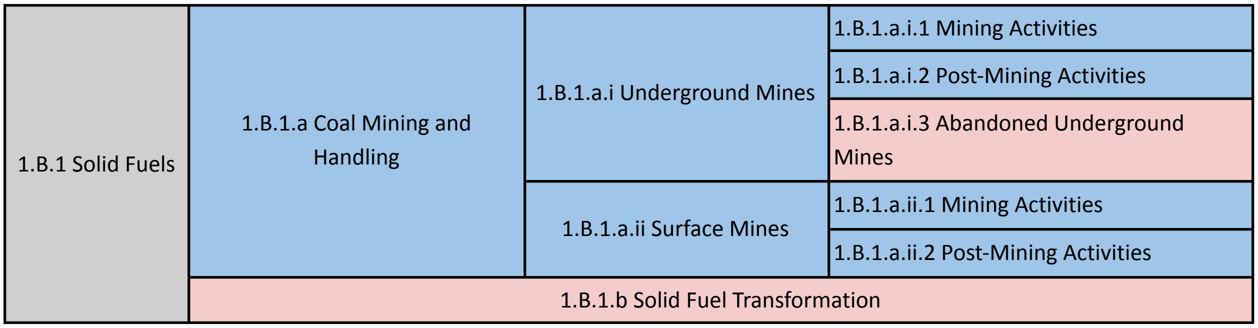

Figure 1 WattTime/Global Energy Monitor 1.B.1 Solid Fuels and subsectors coverage. Fully covered (in blue), not covered (in red), and partially covered (in gray)

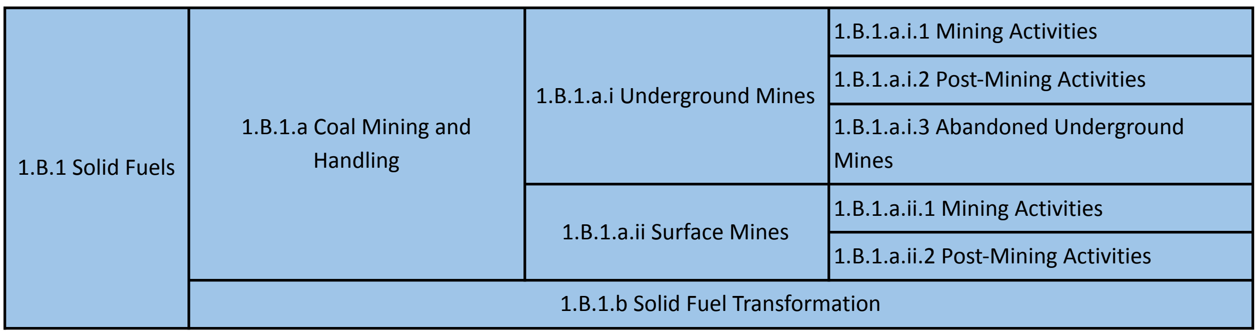

Figure 2 EDGAR 1.B.1 Solid Fuels and subsector coverage. Full covered (in blue), not covered (in red), and partially covered (gray).

Because EDGAR covers all of 1.B.1, subtracting WattTime/Global Energy Monitor's coal mining values from EDGAR results in an estimate for 1.B.1.b Solid Fuel Transformation.

Eq. Climate TRACE solid-fuel-transformation =
EDGAR 1.B.1 Solid Fuels
- WattTime/Global Energy Monitor Coal Mining

The approaches highlighted in the examples were repeated for different sectors to estimate remaining emissions. All implicit estimation equations can be found in Table S2 in the Supplementary section.

2.3 Verifying results

We went through several systematic audits of the results to ensure that the implicit estimation equations were properly applied using all available relevant data. For instance, due to differences in how inventories specify country names, we ensured that standardized ISO3 (International Organization for Standardization) codes were used to match up data points for each implicit calculation.

Results were not reported in cases where inventories define the actual emitting country differently. For example, EDGAR reported data for Serbia and Montenegro as one country. Climate TRACE and FAOSTAT report them separately since they have become separate legal entities since 2006. Therefore, results relying on EDGAR data for such countries were excluded from reported results. Similarly, results for some sectors are not included for countries in the Climate TRACE dataset where EDGAR and/or FAOSTAT do not provide emissions estimates.

2.3.1 What do negative results tell us about the approach

In some cases, implicit estimation equations resulted in negative emissions estimates. We identified two main reasons for this:

1. There is a large disparity between emissions estimates from different inventories for the relevant sectors.
2. Data from relevant sectors are missing from one of the inventories.

Examining the causes of negative results can identify discrepancies that are relevant to comparing estimates between inventories. Overall, 5.7% of implicit estimation results were negative in the dataset. However, they were distributed across just 4 out of the 17 sectors in the analysis. These results are highlighted in Tables 2 and 3.

Table 2 Sum of negative implicit estimate results by sector (tonnes CO_2e)

Year	Other Energy Use	Other Fossil Fuel Operations	Other Manufacturing	Solid Fuel Transformation
2015	-418,976,021	-2,441,699,569	-35,445,915	-184,595,944
2016	-469,710,098	-2,546,012,141	-26,232,491	-183,427,582
2017	-440,633,112	-2,583,939,829	-37,855,124	-188,707,419
2018	-499,562,394	-2,781,675,464	-36,134,684	-191,554,475
2019	-537,104,921	-2,755,064,988	-43,412,952	-180,454,697
2020	-552,591,530	-2,620,050,801	-33,963,251	-155,800,106
2021	-536,874,144	-2,763,556,046	-28,524,992	-141,833,963

Table 3 Number of countries with negative implicit estimate results by sector

Year	Other Energy Use	Other Fossil Fuel Operations	Other Manufacturing	Solid Fuel Transformation
2015	128	72	16	22
2016	129	71	16	23
2017	138	72	16	23
2018	133	74	18	20
2019	133	72	19	21
2020	151	70	19	23
2021	134	68	19	22

Other Fossil Fuel Operations. The Climate TRACE Other Fossil Fuel Operations is a sector created by implicit estimation to account for all of the sub-sectors not modeled: *1.A.1.b* Petroleum Refining, *1.A.1.c* Manufacture of Solid Fuels and Other Energy Industries, and *1.B.2* Oil and Natural Gas. EDGAR reports *1.A.1.b* and *1.A.1.c* together as *1.A.1.bc* Petroleum Refining and Manufacture of Solid Fuels and Other Energy Industries. Figures 3 and 4 show the layout of these sectors, with coverage by EDGAR and Climate TRACE member RMI sub-sectors.

1.A.1.bc Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries	1.A.1.b Petroleum Refining		
	1.A.1.c Manufacture of Solid Fuels and Other Energy Industries	1.A.1.c.i Manufacture of Solid Fuels	
		1.A.1.c.ii Oil and Gas Extraction	
		1.A.1.c.iii Other Energy Industries	
		1.A.1.c.iv Other	
1.B.2 Oil and Natural Gas	1.B.2.a Oil	1.B.2.a.i Exploration	
		1.B.2.a.ii Production	
		1.B.2.a.iii Transport	
		1.B.2.a.iv Refining / Storage	
		1.B.2.a.v Distribution of Oil Products	
		1.B.2.a.vi Other	
	1.B.2.b Natural Gas	1.B.2.b.i Exploration	
		1.B.2.b.ii Production	
		1.B.2.b.iii Processing	
		1.B.2.b.iv Transmission and Storage	
		1.B.2.b.v Distribution	
		1.B.2.b.vi Other	
	1.B.2.c Venting and Flaring	1.B.2.c.i Venting	1.B.2.c.i.1 Oil
			1.B.2.c.i.2 Gas
			1.B.2.c.i.3 Combined
		1.B.2.c.ii Flaring	1.B.2.c.ii.1 Oil
			1.B.2.c.ii.2 Gas
			1.B.2.c.ii.3 Combined
	1.B.2.d Other		

Figure 3 EDGAR coverage of IPCC sectors within 1.A.1.b, 1.A.1.c and 1.B.2 where blue is fully covered, gray is partially covered, and red is not covered.

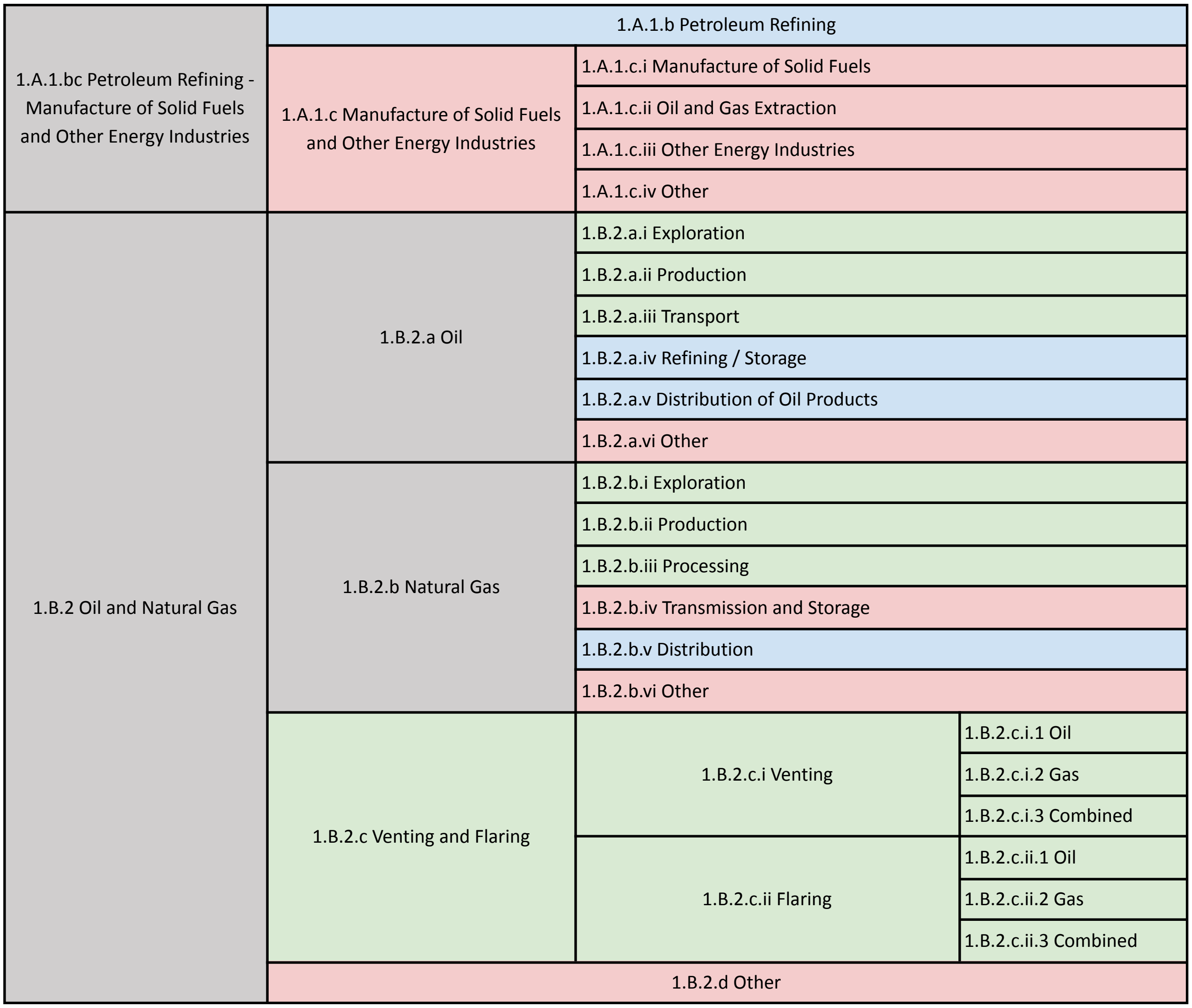

Figure 4 RMI coverage of IPCC sectors within 1.A.1.b, 1.A.1.c and 1.B.2 where blue is fully covered, gray is partially covered, and red is not covered.

To account for the sub sectors not measured by RMI, the equation for this implicit estimation is:

Eq. Climate TRACE other-fossil-fuel-operations =
EDGAR 1.A.1.bc Petroleum Refining and Manufacture of Solid Fuels and Other Energy Industries
+ EDGAR 1.B.2. Oil and Natural Gas
- RMI Oil and Gas Production and Transport
- RMI Oil and Gas Refining

Writing the EDGAR and RMI sub-sectors as their IPCC sub-sector definitions, we could see that:

Climate TRACE other-fossil-fuel-operations =
1.A.1.c Manufacture of Solid Fuels and Other Energy Industries
+ 1.B.2.a.vi Other
+ 1.B.2.b.iv Transmission and Storage
+ 1.B.2.b.vi Other
+ 1.B.2.d Other

Where the following subsectors account for the respective percentage of emissions within 1.A.1.bc + 1.B.2 (Table 4).

Table 4 Percentage of emissions within 1.A.1.bc and 1.B.2 by subsector

Subsector	% of emissions in 1.A.1.bc and 1.B.2
1.A.1.c Manufacture of Solid Fuels and Other Energy Industries	25.45%
1.B.2.a.vi Other	0.54%
1.B.2.b.iv Transmission and Storage	6.56%
1.B.2.d Other	0.30%

These percentages were calculated based on the most granular data that is currently available from the UNFCCC Annex I countries. Based on the equation and table above, it should be that other-fossil-fuel-operations is about 32% of all Climate TRACE oil and gas estimates (including oil and gas refining and oil and gas production and transport).

However, as seen above in Table 2, in many cases other-fossil-fuel-operations are negative. The country with the largest negative for other-fossil-fuel-operations is Russia, shown in Figure 5. Despite the fact that other fossil fuel operations should be some non-zero number, it is -547 million tonnes for CO_2 alone. When factoring in CH_4 and N_2O, Russia's negative other fossil fuel operations number becomes -845 million tonnes CO_2e.

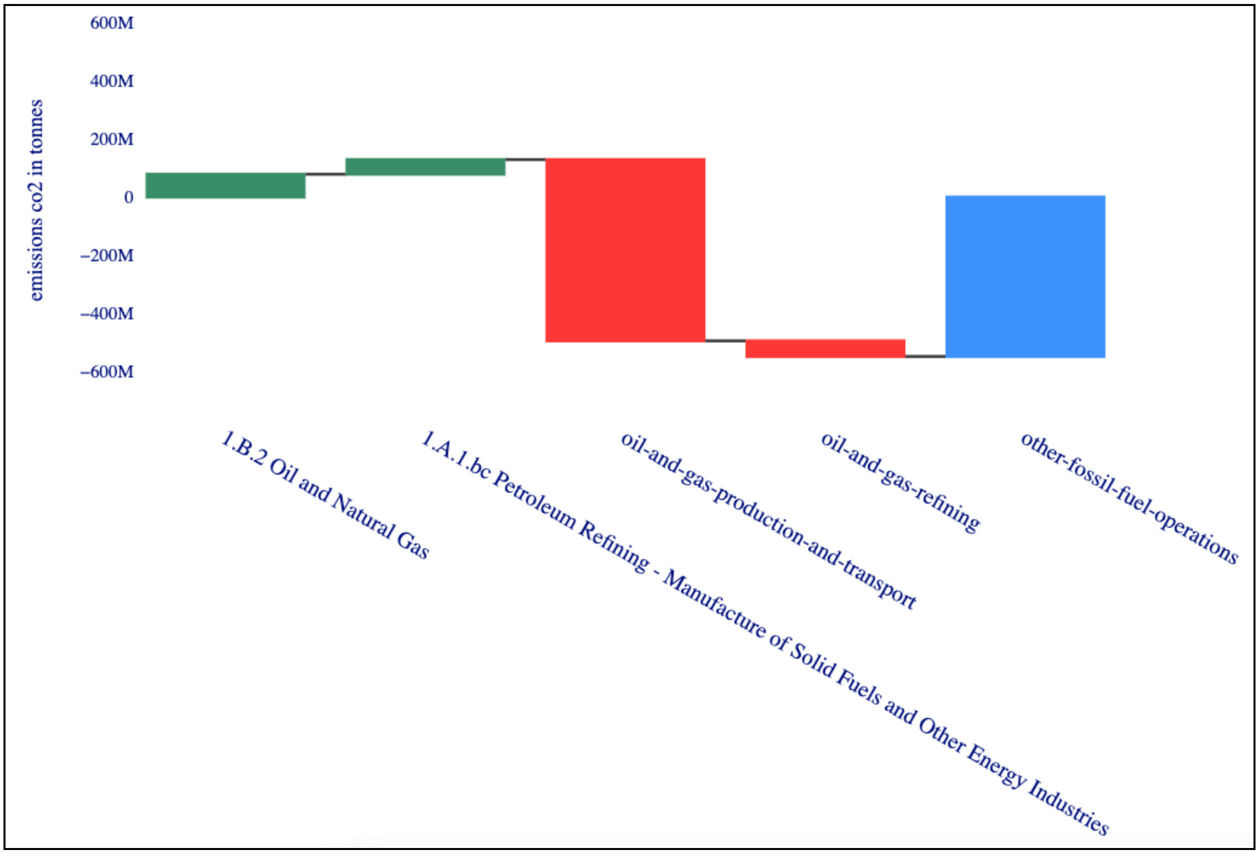

Figure 5 Waterfall chart showing the process for creating 'other-fossil-fuel-operations' (in blue) for Russia, 2021. We can see that 1.B.2 and 1.A.1.bc from EDGAR add up to 128 million tonnes (green bars). RMI estimates for oil and gas production and transport and oil and gas refining are 494 million tonnes and 53 million tonnes (red bars), respectively.

While Climate TRACE was unable to make any firm conclusions about the cause for this, it is possible that EDGAR predictions for oil and gas sectors are underestimating the emissions associated with oil and gas extraction and refining. Activity data in the EDGAR dataset is partially derived from UNFCCC National Inventory Reports and emission factors are based on country-specific UNFCCC National Inventory Report data, where available, and an average value as default for all other countries for venting and IPCC default emission factors for flaring. This approach does not take 'super-emitters' into account and the emission factors are based on outdated studies that do not take local conditions into account (Rutherford et al., 2021)[13,14,15].

[13] Rutherford, J.S., Sherwin, E.D., Ravikumar, A.P., Heath, G.A., Englander, J., Cooley, D., Lyon, D., Omara, M., Langfitt, Q. and Brandt, A.R., 2021. Closing the methane gap in US oil and natural gas production emissions inventories. *Nature communications*, *12*(1), pp.1-12. Available at: https://www.nature.com/articles/s41467-021-25017-4.

[14] Lauvaux, T., Giron, C., Mazzolini, M., d'Aspremont, A., Duren, R., Cusworth, D., Shindell, D. and Ciais, P., 2022. Global assessment of oil and gas methane ultra-emitters. *Science*, *375*(6580), pp.557-561. Available at: https://www.science.org/doi/10.1126/science.abj4351

[15] See the *Oil & Gas sector: Production, Processing, Refining, and Transport Emissions* methodology on the Climate TRACE website (climatetrace.org).

Reporting Negatives. Climate TRACE replaces the negative numbers with 0 in the final inventory.

3. Results

The goal of the implicit estimation technique is to complement Climate TRACE's estimates using techniques 1, 2 and 3 with existing estimates. This serves two purposes:

1) Ensure Climate TRACE's end product is globally and sectorally comprehensive for ease of use.
2) Make Climate TRACE and other datasets interoperable enough that they can be compared statistically.

Figure 6 shows EDGAR and Climate TRACE global totals for 2015-2021. Climate TRACE totals are split into implicitly estimated and measured totals. It should be noted that the Climate TRACE's global estimates are between 3.3 and 4 Gigatonnes higher than EDGAR's. This is due primarily to RMI's oil and gas estimates which indicate vast undercounting of methane in current oil and gas estimates. Table 5 provides the EDGAR and Climate TRACE emission differences.

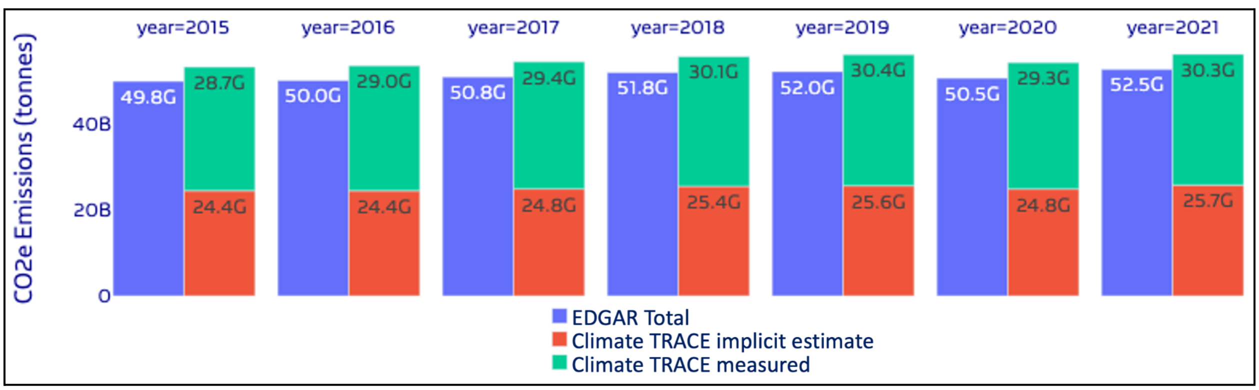

Figure 6 EDGAR global totals compared to Climate TRACE global totals for years 2015 to 2021. Climate TRACE totals are split into implicitly estimated and measured categories. Blue bars = EDGAR Totals, Red bars = Climate TRACE implicit estimate, and Green bars = Climate TRACE measured.

Table 5 Climate TRACE global totals versus EDGAR global totals, and the difference between the two.

Year	Global Climate TRACE emissions (Gigatonnes CO_2e)	Global EDGAR emissions (Gigatonnes CO_2e)	Difference (Gigatonnes CO_2e)
2015	53.08	49.78	3.30
2016	53.39	49.95	3.44
2017	54.27	50.77	3.504
2018	55.51	51.81	3.704
2019	55.97	52.03	3.94
2020	54.11	50.47	3.64
2021	56.05	52.51	3.53

Figure 7 shows EDGAR totals compared to Climate TRACE totals for the top 10 highest emitting countries for 2021. China is the highest emitter, 15.27 Gigatonnes, which is ~2.5 times more emissions than the USA (Table 6). Generally, Climate TRACE total estimates (measured and implicit estimate) result in higher emissions relative to EDGAR emissions.

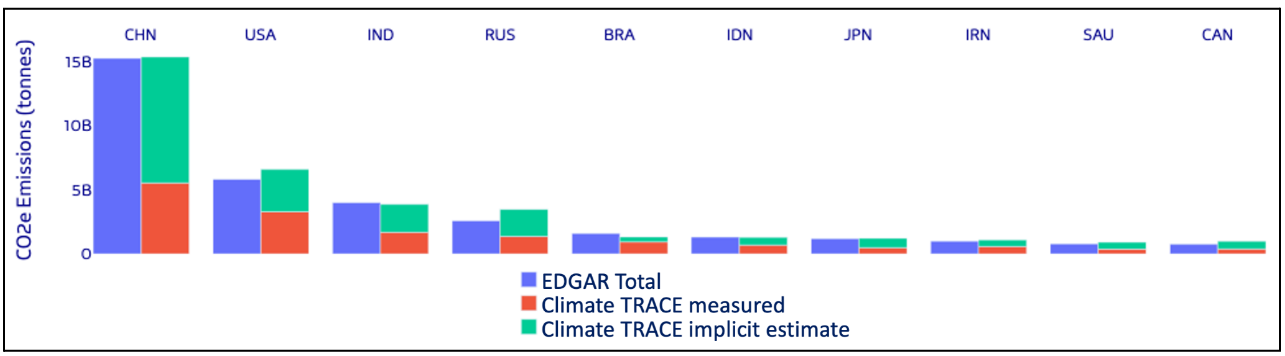

Figure 7 EDGAR totals compared to Climate TRACE totals for the top 10 highest emitting countries for 2021. Blue bars = EDGAR Totals, Red bars = Climate TRACE measured, and Green bars = Climate TRACE implicit estimate.

Table 6 EDGAR totals compared to Climate TRACE totals for the top 10 most emitting countries

Country	EDGAR Total (Gigatonnes CO_2e)	Climate TRACE Total (Gigatonnes CO_2e)	Climate TRACE estimated using techniques 1, 2 or 3 (Gigatonnes CO_2e)	Climate TRACE implicitly estimated (Gigatonnes CO_2e)
CHN	15.27	15.38	5.54	9.84
USA	5.83	6.60	3.29	3.30
IND	4.00	3.87	1.69	2.18
RUS	2.59	3.47	1.36	2.11
BRA	1.59	1.67	0.94	0.73
IDN	1.30	1.29	0.69	0.60
JPN	1.18	1.17	0.57	0.60
IRN	1.00	1.02	0.49	0.53
SAU	0.78	0.90	0.38	0.52
CAN	0.75	0.75	0.37	0.38

4. Discussion and conclusion

4.1 Strengths of the approach

Novel inventory crosswalk. By defining all third party GHG inventory sectors by their IPCC reporting categories, Climate TRACE was able to make comparisons that would have otherwise been difficult.

Combining multiple estimates increases trust. Every technique for estimating GHGs, especially at a global level has pros and cons. Some are highly granular and accurate but can be expensive (such as ground-level monitoring from CEMS units) and not comprehensive. This implicit estimation approach created by Climate TRACE for the 2022 launch lays the groundwork for more extensive Bayesian metamodeling that combines many sources of information to improve emissions estimates.

4.1 Limitations of the approach

Estimates. This method makes use of estimates that are not based on direct observations. Climate TRACE's roadmap will be to downweight such estimates in future metamodeling and upweight estimates based on direct observations.

Novel estimates. In sectors containing one or more implicitly estimated subsectors, any potential errors in the source data potentially affects the sector total, not just the implicitly estimated subsector total. As long as the sum of sub-sectors measured using techniques 1, 2, and 3 (from the introduction) are less than the sum of the implicitly measured sub-sectors, then the sector total will match exactly the source data used to implicitly estimate the remaining sectoral "other" emissions (Figure 8). For example, the sum of Hypervine and TransitionZero's mining and manufacturing sector estimates is almost always lower than the sum of the corresponding EDGAR sub-sectors. The implicitly estimated sector, Other Manufacturing, will always cause the sum of all Climate TRACE manufacturing sectors to equal the sum of EDGAR's manufacturing sectors. Therefore, this method is useful for detecting underestimates in the original source data. However, if the estimated total is an overestimate, it may not correctly detect it.

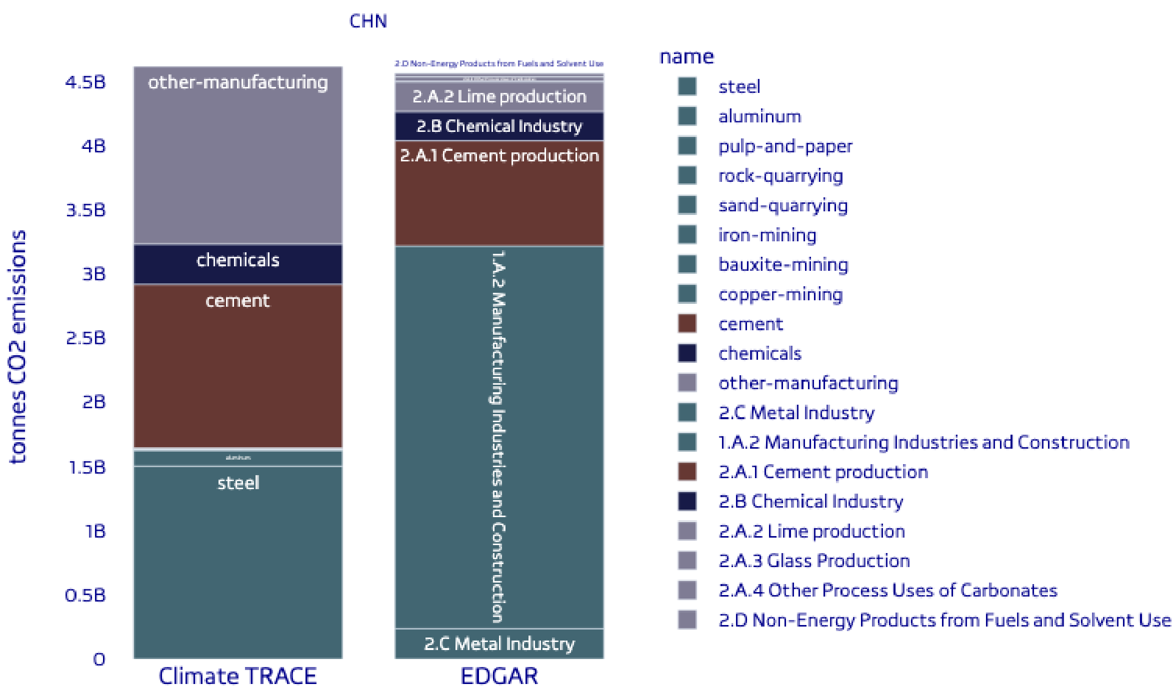

Figure 8 China manufacturing emissions as measured by Climate TRACE (left bar) and EDGAR (right bar). The sub sectors measured by Climate TRACE using techniques 1, 2 and 3 (identified as steel to chemicals, in the legend) sum to less than EDGAR total emissions. The implicitly estimated subsector, Other Manufacturing, causes the sums to be equal, potentially obscuring any overestimation in EDGAR.

Lack of specificity in implicitly estimated sectors. This method does not reveal asset level results or identify the exact cause of emissions in implicitly estimated sectors.

Reliability of source datasets. EDGAR generally publishes estimates on a lag of 2-3 years. Prior to October 2022, the last available data was from 2018. The timing of their release for 2021 data helped ensure Climate TRACE implicitly estimated sectors were fully current. However, the EDGAR release schedule is not published to the public. In the absence of up-to-date datasets for implicit estimation, Climate TRACE will need to create projections to fill in missing years using the most recently available data.

Likewise, the most recent published data from FAOSTAT is currently 2019. Climate TRACE forward fills this data for the 2020 and 2021 estimates. However, this approach is not preferred as it cannot capture major anomalies like the 2020 COVID pandemic.

Thus, Climate TRACE's priorities for future implicit estimation are to incorporate as many emissions inventories as possible, produce similar systems of equations to make them interoperable as possible, and produce parsimonious consensus results based on large numbers of independent cross-validations.

Links to data repositories and model code

All of the code used to produce implicit estimates is available on GitHub*:
https://github.com/WattTime/climate-trace-metamodeling

* note that the code will not run without database credentials. If you are interested in collaborating on this work and would like to discuss access to the Climate TRACE database, please contact christy@watttime.org

Supplementary material

Table S1 Climate TRACE, EDGAR, and FAOSTAT Data defined by UNFCCC categories.
Bolded sector codes indicate the sector partially covers that IPCC code.

Data Source	Original Inventory Sector Name	UNFCCC CRF 2006 Category
FAOSTAT	Enteric Fermentation	3.A
FAOSTAT	Manure Management	3.B
FAOSTAT	Manure applied to Soils	3.D.1.b.i
FAOSTAT	Manure left on Pasture	3.D.1.b.ii
FAOSTAT	Synthetic Fertilizers	3.D.1.a
FAOSTAT	Rice Cultivation	3.C
FAOSTAT	Burning - Crop residues	3.F

FAOSTAT	Crop Residues	3.D.1.d
FAOSTAT	On-farm energy use	1.A.4.c
FAOSTAT	Savanna fires	3.E, 4.C.1
FAOSTAT	Fires in humid tropical forests	4.B.2.a, 4.C.2.a, 4.E.2.a, 4.A.1
FAOSTAT	Forest fires	4.B.2.a, 4.C.2.a, 4.E.2.a, 4.A.2
FAOSTAT	Fires in organic soils	
FAOSTAT	Drained organic soils	3.D.1.e, 3.D.1.f
FAOSTAT	Drained organic soils	3.D.1.e, 3.D.1.f
FAOSTAT	Net Forest conversion	
FAOSTAT	Forestland	4.A
EDGAR	Main Activity Electricity and Heat Production	1.A.1.a
EDGAR	Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries	1.A.1.b, 1.A.1.c
EDGAR	Manufacturing Industries and Construction	1.A.2
EDGAR	Civil Aviation	1.A.3.a
EDGAR	Road Transportation no resuspension	1.A.3.b
EDGAR	Railways	1.A.3.c
EDGAR	Water-borne Navigation	1.A.3.d
EDGAR	Other Transportation	1.A.3.e
EDGAR	Other Sectors	1.A.4
EDGAR	Non-Specified	1.A.5
EDGAR	Solid Fuels	1.B.1
EDGAR	Oil and Natural Gas	1.B.2
EDGAR	Cement production	2.A.1
EDGAR	Lime production	2.A.2
EDGAR	Glass Production	2.A.3
EDGAR	Other Process Uses of Carbonates	2.A.4
EDGAR	Chemical Industry	2.B
EDGAR	Metal Industry	2.C
EDGAR	Non-Energy Products from Fuels and Solvent Use	2.D
EDGAR	Liming	3.G
EDGAR	Urea application	3.H
EDGAR	Other	3.J
EDGAR	Main Activity Electricity and Heat Production	1.A.1.a
EDGAR	Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries	1.A.1.b, 1.A.1.c
EDGAR	Manufacturing Industries and Construction	1.A.2
EDGAR	Civil Aviation	1.A.3.a

EDGAR	Road Transportation no resuspension	1.A.3.b
EDGAR	Railways	1.A.3.c
EDGAR	Water-borne Navigation	1.A.3.d
EDGAR	Other Transportation	1.A.3.e
EDGAR	Other Sectors	1.A.4
EDGAR	Non-Specified	1.A.5
EDGAR	Solid Fuels	1.B.1
EDGAR	Oil and Natural Gas	1.B.2
EDGAR	Chemical Industry	2.B
EDGAR	Metal Industry	2.C
EDGAR	Enteric Fermentation	3.A
EDGAR	Manure Management	3.B
EDGAR	Emissions from biomass burning	3.E, 3.F, **4.A.1.c, 4.C.1.a, 4.D.1.b**
EDGAR	Rice cultivations	3.C
EDGAR	Solid Waste Disposal	5.A
EDGAR	Biological Treatment of Solid Waste	5.B
EDGAR	Incineration and Open Burning of Waste	5.C
EDGAR	Wastewater Treatment and Discharge	5.D
EDGAR	Other	5.E
EDGAR	Main Activity Electricity and Heat Production	1.A.1.a
EDGAR	Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries	1.A.1.b, 1.A.1.c
EDGAR	Manufacturing Industries and Construction	1.A.2
EDGAR	Civil Aviation	1.A.3.a
EDGAR	Road Transportation no resuspension	1.A.3.b
EDGAR	Railways	1.A.3.c
EDGAR	Water-borne Navigation	1.A.3.d
EDGAR	Other Transportation	1.A.3.e
EDGAR	Other Sectors	1.A.4
EDGAR	Non-Specified	1.A.5
EDGAR	Oil and Natural Gas	1.B.2
EDGAR	Chemical Industry	2.B
EDGAR	Other Product Manufacture and Use	2.G
EDGAR	Manure Management	3.B
EDGAR	Emissions from biomass burning	3.E, 3.F, **4.A.1.c, 4.C.1.a, 4.D.1.b**
EDGAR	Direct N2O Emissions from managed soils	3.D.1
EDGAR	Indirect N2O Emissions from managed soils	3.D.2
EDGAR	Indirect N2O Emissions from manure management	

EDGAR	Biological Treatment of Solid Waste	5.B
EDGAR	Incineration and Open Burning of Waste	5.C
EDGAR	Wastewater Treatment and Discharge	5.D
EDGAR	Indirect N2O emissions from the atmospheric deposition of nitrogen in NOx and NH3	3.D.2.a
EDGAR	Other	6
ClimateTRACE	electricity-generation	1.A.1.a.i, 1.A.1.a.ii
ClimateTRACE	domestic-aviation	1.A.3.a
ClimateTRACE	international-aviation	7.A
ClimateTRACE	shipping	1.A.3.d, 7.B
ClimateTRACE	coal-mining	1.B.1.a
ClimateTRACE	oil-and-gas-production-and-transport	1.B.2.a.i, 1.B.2.a.ii, 1.B.2.a.iii, 1.B.2.b.i, 1.B.1.b.ii, 1.B.1.b.iii, 1.B.2.c
ClimateTRACE	oil-and-gas-refining	1.A.1.b, 1.B.2.a.iv, 1.B.2.a.v, 1.B.2.b.v
ClimateTRACE	cement	**1.A.2.f**, 2.A.1
ClimateTRACE	chemicals	**1.A.2.c**, 2.B.1, 2.B.7, 2.B.8.a
ClimateTRACE	steel	1.A.2.a, 2.C.1
ClimateTRACE	aluminum	**1.A.2.b**, 2.C.3
ClimateTRACE	pulp-and-paper	1.A.2.d, 2.H.1
ClimateTRACE	bauxite-mining	1.A.2.g.iii
ClimateTRACE	copper-mining	1.A.2.g.iii
ClimateTRACE	iron-mining	1.A.2.g.iii
ClimateTRACE	rock-quarrying	1.A.2.g.iii
ClimateTRACE	sand-quarrying	1.A.2.g.iii
ClimateTRACE	rice-cultivation	3.C
ClimateTRACE	synthetic-fertilizer-application	3.D.1.a
ClimateTRACE	cropland-fires	3.F

Table S2 The crosswalk table: Climate TRACE sector and related source data

Sector on Climate TRACE site	**Equation to calculate**	**Filled data source**
Other Energy Use	= EDGAR[“Main Activity Electricity and Heat Production”] - ClimateTrace[“electricity-generation”]	EDGAR v7.0
Railways	= EDGAR[“Railways”]	EDGAR v7.0
Road Transportation	= EDGAR[“Road Transportation no resuspension-fossil”]	EDGAR v7.0
Other Transport	= EDGAR[“Civil Aviation”] + EDGAR[“Water-borne Navigation”] + EDGAR[“Other Transportation”] + ClimateTrace[“domestic-aviation”]+ ClimateTrace[“international-aviation”] - ClimateTrace[“shipping”]	EDGAR v7.0
Residential and Commercial Onsite Fuel Usage	= EDGAR[“Other Sectors”]	EDGAR v7.0
Other Onsite Fuel Usage	= EDGAR[“Non-Specified”]	EDGAR v7.0
Solid Fuel Transformation	= EDGAR[“Solid Fuels”] - ClimateTrace[“coal-mining”]	EDGAR v7.0
Other Fossil Fuel Operations	= EDGAR[“Oil and Natural Gas”] + EDGAR[“Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries”] - ClimateTrace[“oil-and-gas-production-and-transport”] - ClimateTrace[“oil-and-gas-refining”]	EDGAR v7.0
Other Manufacturing	= EDGAR[“Manufacturing Industries and Construction”] + EDGAR[“Cement production”] + EDGAR[“Lime production”] + EDGAR[“ Glass Production”] + EDGAR[“Other Process Uses of Carbonates”] + EDGAR[“Chemical Industry”] + EDGAR[“Metal Industry”] + EDGAR[“ Non-Energy Products from Fuels and Solvent Use”] - ClimateTRACE[“aluminum”] - ClimateTRACE[“steel”] - ClimateTRACE[“chemicals”] - ClimateTRACE[“pulp-paper”] - ClimateTRACE[“cement-production”] - ClimateTRACE[“bauxite-mining”] -	EDGAR v7.0

	ClimateTRACE[“copper-mining”] - ClimateTRACE[“sand-quarry”] - ClimateTRACE[“rock-quarry”]	
Enteric Fermentation	=FAOSTAT[“enteric-fermentation”]	FAOSTAT
Manure Management	=FAOSTAT[“manure-management”]	FAOSTAT
Other Agricultural Soil Emissions	=FAOSTAT[“manure-left-on-pasture”] + FAOSTAT[“crop-residues”]+ FAOSTAT[“drained-organic-soils”]	FAOSTAT
Solid Waste Disposal	=EDGAR[“Solid Waste Disposal On Land”]	EDGAR v7.0
Biological Treatment of Solid Waste and Biogenic	= EDGAR[“Biological Treatment of Solid Waste”]	EDGAR v7.0
Incineration and Open Burning of Waste	= EDGAR[“Incineration and Open Burning of Waste”]	EDGAR v7.0
Wastewater Treatment and Discharge	= EDGAR[“4.D Wastewater Treatment and Discharge”]	EDGAR v7.0
Fluorinated Gasses	= EDGAR[fluorinated-gasses]	EDGAR v7.0