Non-Greenhouse Gas Emissions Estimates Across Sectors

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1. Introduction

The World Health Organization (WHO) estimates that globally 6.7 million premature deaths annually are caused by poor air quality, with 4.2 million of those deaths caused by ambient outdoor air pollution [1]. Whereas the impacts from releasing greenhouse gasses (GHGs) are long term, air pollution can have both long-term and immediate impacts on the health of individuals and communities. Further, anthropogenic sources of air pollutants are also an issue of climate justice as the impacts of air pollution are disproportionately felt by poorer, disadvantaged communities and the Global South.

Currently there are gaps in the knowledge of the sources and magnitude of ambient air pollution, and these gaps are a major impediment to addressing critical health and environmental problems. While there are many datasets that focus on air pollution used by researchers, there is no air pollution dataset that has facility-specific emissions, global coverage, and high recency. These characteristics are necessary for direct accountability of polluters, for policy and decision-makers to regulate pollutants and improve public health more efficiently, and for activists to direct action effectively. This document describes Climate TRACE's initial efforts to fill this gap by applying their knowledge of and approaches for estimating greenhouse gas sources to air pollution.

2. Data and Methods

2.1. Overview

Estimates of emissions that take a bottom-up approach (where emissions are estimated by accounting for different consumption, energy-demand, and other activities) often lack facility-level specificity that is required for identifying polluters and holding them accountable. This includes the high-quality Emissions Dataset for Atmospheric Research (EDGAR) and the mosaic Community Emissions Data System (CEDS) which use sophisticated and granular approaches to estimating emissions and mitigation approaches for country-level emissions estimates but rely on proxies for distributing emissions spatially [2,3,4]. While these approaches are highly useful for atmospheric modeling, they ultimately lack facility-level information.

A Tier 0 non-greenhouse gas (non-GHG) emissions estimation approach was developed and applied to Climate TRACE asset-level data that leveraged country-level mitigation and reduction estimates from CEDS and EDGAR non-GHG datasets. The approach assumes a linear relationship between emissions of GHGs and non-GHGs, i.e. for every X tonnes of greenhouse gas emitted, Y tonnes of pollutant is emitted. These ratios are estimated at a country-sector-fuel level, and then applied across Climate TRACE assets – essentially utilizing CEDS/EDGAR emissions estimates but rescaled and distributed based on Climate TRACE data.

Overall, these estimates are considered Tier 0, as facilities within countries do not differ in terms of mitigation and reduction approaches; however, as Climate TRACE's effort in air quality continues, it is expected many parts of this dataset will be replaced with higher quality estimates.

2.2. Data

CEDS air pollution emissions estimates are primarily used for predicting the air pollution emissions for Climate TRACE assets. A mapping of CEDS sectors (which are IPCC code-based) and Climate TRACE sectors is needed for making this estimate and is shown in Table 2 in Supplementary Materials. In addition, as CEDS and EDGAR only estimate emissions up to 2022, forward filling is used for any date after.

Countries are matched according to ISO3 codes. CEDS does not provide estimates for 31 countries/territories that are available in Climate TRACE. Many of these are small island nations or territories, so proxy estimates are provided based on similar nearby countries or sovereign states (see Table 3 in the supplemental).

Three sectors in CEDS data (International Shipping, International Aviation, Domestic Aviation) are not provided for each country. Instead, these are provided as "Global" aggregates. To generate country-level emissions estimates, emissions values for these sectors are duplicated for all countries before merging with Climate TRACE data.

2.3. Estimation Approach

The Climate TRACE approach to estimating GHGs is based on the IPCC methodologies where an activity measurement is used in conjunction with an emissions factor (*EF)* for a given gas in order to determine the amount of emissions produced, expressed for an individual facility/asset a by,

$$EM_{a,g} = A_a \cdot EF_{a,g} \text{ (Eq. 1)},$$

where $EM_{a,g}$ is the emission for an asset for a given pollutant g, which is similar to the approach taken by EDGAR and CEDS for estimating GHGs. Given that this mirrors the approach used by EDGAR and CEDS, Climate TRACE similarly modifies Equation 1 to predict emissions from air pollution,

$$EM_{jg} = A_a \cdot \widetilde{EF}_{a,g} \text{ (Eq. 2)},$$

where $\widetilde{EF}_{a,g}$ is a modified emissions factor, which comprises the emissions of the pollutant and any mitigation approaches used.

Although these modifications are simple, the size, availability, and heterogeneity of information that needs to be collected at a facility-level poses a challenge for producing emissions estimates. So preliminary emissions factors were estimated by using EDGAR and CEDS country-level GHG and non-GHG emissions estimates. EDGAR and CEDS produce non-GHG emissions estimates by using county-level economic and technology information, and hence using their estimates would allow for the creation of consummate Climate TRACE non-GHG estimates that are consistent with the other existing inventories.

For a given pollutant g, the country-level emissions factor was determined by the ratio of its emissions to the CO_2 equivalent (CO_2eq) emissions between Climate TRACE and the comparison inventory, disaggregated by sector s and fuel f. This is expressed for country c by,

$$EM_{c,g,s,f,ClimateTRACE} = EM_{c,g,s,f,CEDS} \cdot (EM_{c,CO2eq,s,f,ClimateTRACE} / EM_{c,CO2eq,s,f,CEDS}) \text{ (Eq. 3),}$$

Dividing this estimation of the total country-level air pollution by the sum of the activity yields a constant emissions factor, defined by

$$\widetilde{EF}_{c,a,g,f} = EM_{c,g,s,f,ClimateTRACE} / \Sigma A_{c,s,f,ClimateTRACE} \text{ (Eq. 4),}$$

The outcome of this approach, although having uniform emissions factors across all facilities from the same sector and using the same fuel, is that the estimated $EM_{c,g,s,f,ClimateTRACE}$ is conserved and distributed based on facility-level activity and location directly as opposed to spatial proxies. In addition, the use of CO_2 equivalent – a weighted sum of GHG species based on their heat absorption compared to CO_2 – allows for this analysis to be applied to sectors where different GHG species are dominant and others are negligible.

Carbon monoxide (CO), ammonia (NH_3), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NOx), sulfur dioxide (SO_2), and speciated components of $PM_{2.5}$ that are byproducts of combustion – black carbon (BC) and organic carbon (OC) – were estimated in this manner and for most anthropogenic sectors. $PM_{2.5}$ itself is computed for several sectors; however, complete sector coverage for $PM_{2.5}$ is on-going.

CEDS was used for most sectors; however, an additional conversion step was needed to produce $PM_{2.5}$ as CEDS only provided the speciated BC and OC. We assume that the mitigation of BC was as equally effective for mitigating $PM_{2.5}$ since BC is a subspecies of $PM_{2.5}$. Thus, a conversion of CEDS BC emissions to $PM_{2.5}$ emissions can be made with,

$$Em_{c,\,PM2.5,\,s,f,\,CEDS} = \rho_{BC} \cdot Em_{c,BC,s,f,CEDS}, \text{ (Eq. 5),}$$

where $\rho_{BC} = \frac{1}{\%\ of\ PM2.5\ that\ is\ BC}$. The value of ρ_{BC} is computed for most sectors with the EMEP/EEA Air Pollutant Emission Inventory Guidebook [5], with the only exception being aviation where EPA Smartway is used [6].

The $PM_{2.5}$ from a handful of sectors were computed with Equations 3 and 4 but using EDGAR air pollutant emissions estimates instead of CEDS: enteric fermentation, manure management, rice cultivation, and solid waste disposal. These sectors produce $PM_{2.5}$ with non-combustion emissions, and hence BC emissions are negligible and not computed by CEDS.

Most industrial sectors are also impacted by CEDS only producing combustion based $PM_{2.5}$ emissions as their estimates only reflect the emissions from fuel use and not the underlying industrial process. EDGAR does provide non-combustion related $PM_{2.5}$ for many of these sectors; however, in order to properly estimate $PM_{2.5}$ emissions using Equation 3, fuel and process GHG emissions needed to be disaggregated in Climate TRACE. This is only the case for cement, and hence emissions for coal mining and manufacturing of paper and pulp, chemicals, aluminum, and petrochemicals are only "partial" estimates containing only the $PM_{2.5}$ from fuel use.

Cement $PM_{2.5}$ emissions utilize both CEDS and EDGAR to produce emissions estimates for fuel and non-combustion emissions. This is performed with a modified version of Equation 3 which is combined with Equation 5, yielding

$$Em_{c,PM,\,cement,CT} = \rho_{BC}\left(\frac{Em_{c,BC,\,cement,f,\,CEDS}}{Em_{c,CO2e,\,cement,f,\,CEDS}} \cdot Em_{c,CT,\,CO2e,\,s,f}\right) + \frac{Em_{c,PM,\,cement,process,\,EDGAR}}{Em_{c,CO2e,cement,\,process,\,EDGAR}} \cdot Em_{c,CO2e,\,cement,process,\,CT}$$
(Eq. 6).

For emissions from open waste-burning, the global median of the emissions ratio in Equation 3 is used instead of a country-by-country approach. At a country-level, this value for Portugal and Spain is 4 orders of magnitude larger than the median which is caused by relatively small CO_2e estimates but nominal-sized non-GHG estimates. This may be potentially erroneous, and the impact of using the country-level CEDS values is that the Climate TRACE CO estimates are 5 times larger globally, with 80% of emissions arising from these countries. The rationale for using the median is that it is expected that mitigation of open burning likely does not vary much country-by-country, nor does not the composition of waste.

Finally, certain sectors have already begun to produce non-GHG estimates: road transportation, shipping, and electricity generation. These replace estimates produced here. A matrix of sectors and approach for emissions estimates for each gas is shown in Table 4 in the supplement. In all, non-GHGs emissions estimates are provided from 2021 to 2024.

2.4. Uncertainty & Confidence

Uncertainty analysis was not performed for this initial development of air quality datasets; however, as the dataset matures, uncertainty of activity for sectors will be incorporated with the uncertainty of emissions factors and mitigation approaches. As UQ was not performed and country-level mitigation and reduction technologies are considered constant across facilities, the confidence of these estimates are considered *Very Low*.

3. Results

The total asset-level emissions estimate for each species predicted is in Table 1 as well as a comparison to CEDS and EDGAR global non-GHG emissions. Comparatively, the order of magnitude of Climate TRACE non-GHG emissions estimates is fairly aligned with the comparable inventories for most gasses. EDGAR and CEDS substantially differ on global emissions estimates for SO_2 and OC, with Climate TRACE naturally aligning more with the latter. The largest noticeable differences of the remaining gasses are NO_X and $PM_{2.5}$. The difference in NO_X estimates is due to the provision of NO_X estimates from the Climate TRACE leads for road transportation, shipping, and electricity generation as the NO_X estimates are 114 MT if these supplemented estimates are not used. The lack of sectoral coverage is the cause of the smaller PM estimates.

Table 1. Global emissions estimate for each species per inventory.

Species	Climate TRACE (MT)	CEDS (MT)	EDGAR (MT)
BC	6.8	5.3	4.7
CO	563	425	450
NH_3	46	64	57.3
NMVOC	151	134	138
NO_X	91	113	110
OC	16	13	93
SO_2	84	73	37
$PM_{2.5}$	33	N/A	58

A sector-to-sector, country-to-country comparison to CEDS/EDGAR is shown in Figure 1. Emissions quantities between Climate TRACE and the comparison inventory are correlated; however, deviations occur with differences in estimated CO2 equivalents.

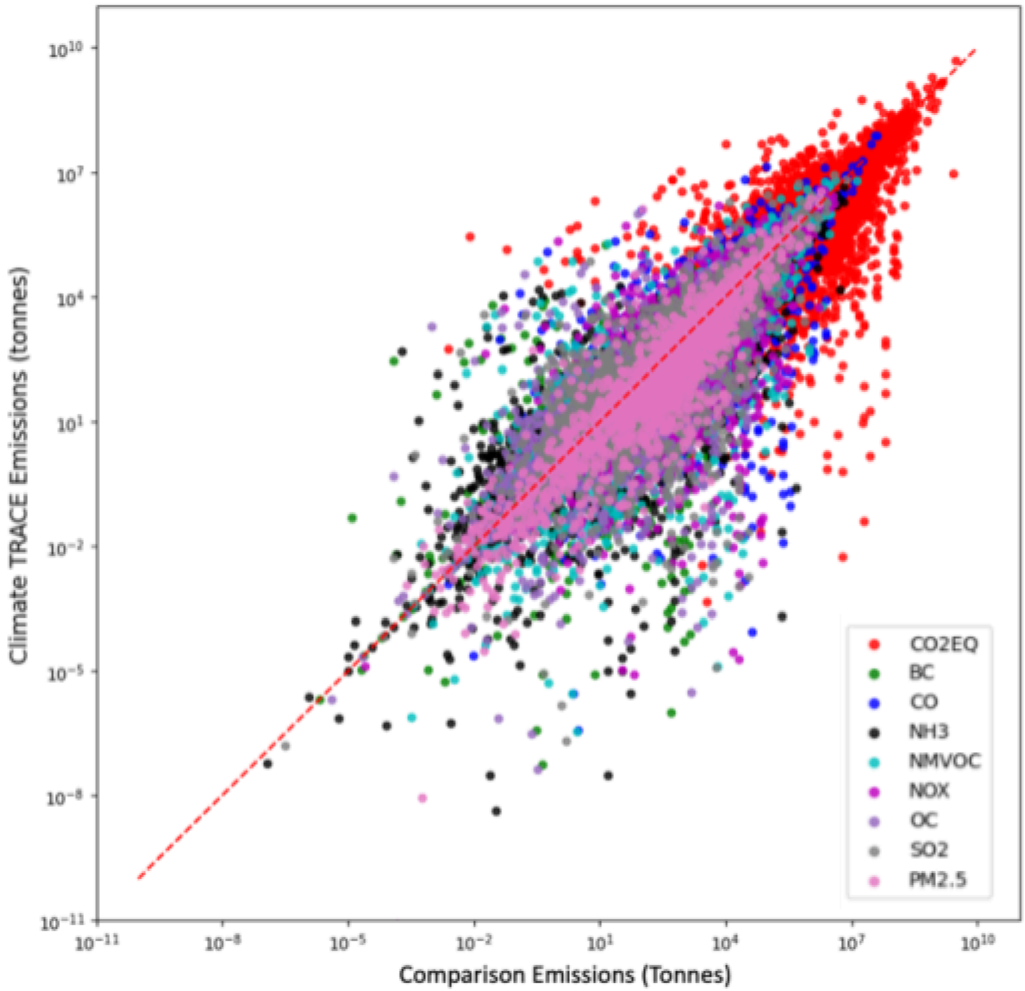

Figure 1. Country-to-country, sector-to-sector comparison between Climate TRACE and the comparable inventory emissions for 2022. CEDS is the comparison inventory for most gases, with the only exception being $PM_{2.5}$. Each dot represents a country and a sector, and while Climate TRACE and the comparison inventory are correlated, differences arise from differences in CO_2 equivalent estimates. See Figures 4 and 5 for a country and sector breakdown of non-GHG emissions.

SO_2 is a significantly impactful pollutant on both the environment and human health, and hence understanding the sources of SO_2 is important for reducing its impact. As shown by Figure 2, SO_2 emissions are dominated by countries with large energy demand and where coal use is prevalent. When broken down by industry, industrial sectors and power dominate the emissions, as shown by Figure 3. Country-level and sector-level comparisons of the remaining gasses are in the Supplement section shown in Figures 4 and 5.

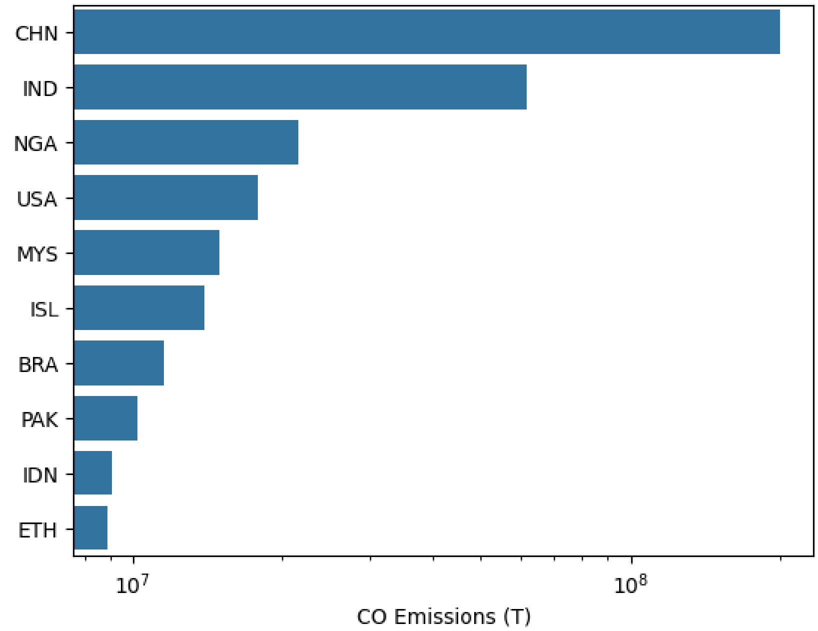

Figure 2. Top ten countries with the largest SO_2 emissions in 2022.

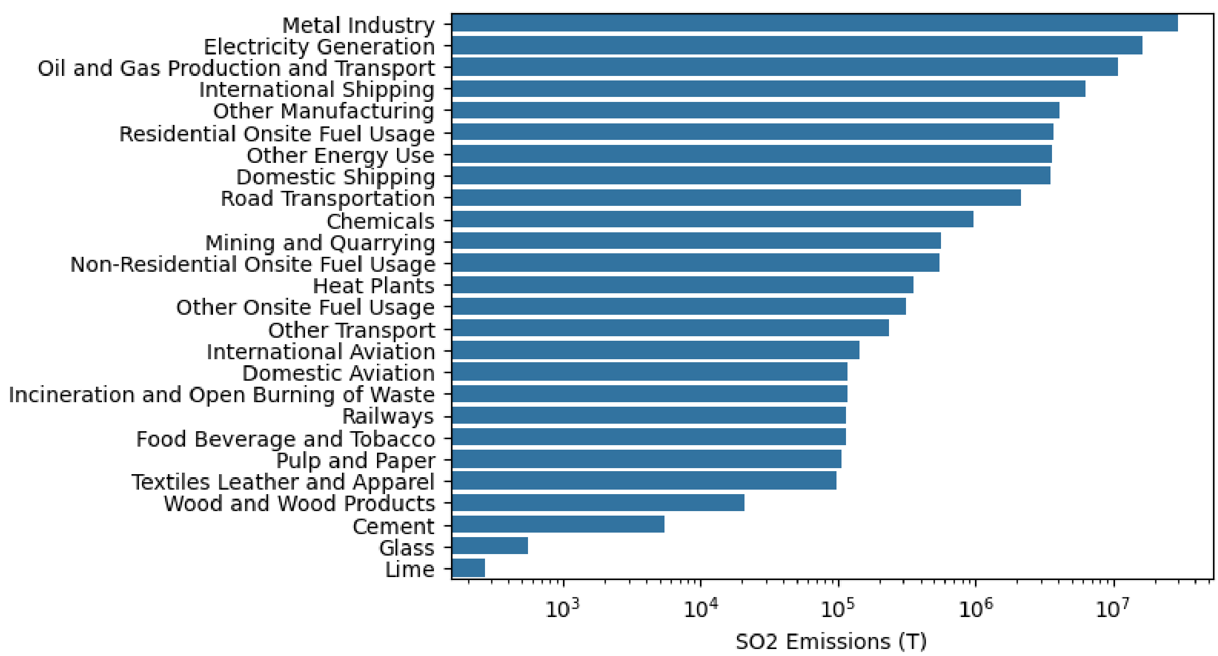

Figure 3. All sources of SO_2 that are estimated and non-zero. The largest sources of SO_2 pollution are from the metal (primarily from fuel use) and energy industry in 2022.

4. Conclusions

Climate TRACE has heretofore primarily focused on greenhouse gas emissions estimation and advanced the field of bottom-up inventories by providing precise location estimates for sources of emissions. These sources of greenhouse gas emissions are often also sources of air pollution, and knowledge of the precise location of sources of air pollution can provide insight for decision-makers, scientists, activists alike. Hence, the data approach described here is the first steps into non-greenhouse gas emissions modeling by Climate TRACE.

The air pollution signatures of a region are heavily affected by regulation, and to incorporate regulatory effects into emissions estimates, this model leverages emissions estimate ratios at a country-sector-fuel level from EDGAR and CEDS which have already performed a country-by-country analysis of pollution reduction and mitigation trends. Overall, these emissions estimates align well with these inventories with differences arising from disparate CO_2 equivalent emissions.

However, there are many limitations of this dataset that should be noted. First, this dataset does not have complete sector coverage of PM, which significantly impacts human health. In the future, Climate TRACE intends to fill this gap. Second, emissions estimates are aligned at a country-sector level, which essentially assumes a linear relationship between emissions of GHGs and non-GHGs for each facility at that level. This is likely not true, and a planned higher tier estimate intends to incorporate facility-level differences in mitigation technology. Lastly, many large sources of air pollution are non-anthropogenic, like forest fires, which are not estimated here; however, future versions of this dataset intend to include more natural sources of emissions in addition to anthropogenic.

5. Acknowledgements

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6. Supplementary Materials

Table 2. Mapping of Climate TRACE sectors to CEDS sectors.

Comparison Sector	Comparison Subsector	Climate TRACE Sectors	CEDS Sectors
Energy Industries and Fugitive Emissions	Electricity Generation	electricity-generation	1A1a_Electricity-autoproducer, 1A1a_Electricity-public
Energy Industries and Fugitive Emissions	Heat Plants	heat-plants	1A1a_Heat-production
Energy Industries and Fugitive Emissions	Other Energy Use	oil-and-gas-refining, other-energy-use	1A1bc_Other-transformation, 1A5_Other-unspecified

Comparison Sector	Comparison Subsector	Climate TRACE Sectors	CEDS Sectors
Energy Industries and Fugitive Emissions	Solid Fuels	coal-mining, solid-fuel-transformation	1B1_Fugitive-solid-fuels
Energy Industries and Fugitive Emissions	Oil and Gas Production and Transport	oil-and-gas-production, oil-and-gas-transport	1B2_Fugitive-petr, 1B2b_Fugitive-NG-prod
Energy Industries and Fugitive Emissions	Other Fossil Fuel Operations	other-fossil-fuel-operation s	1B2d_Fugitive-other-energy, 1B2b_Fugitive-NG-distr
Manufacturing and Industrial Processes	Cement	cement	2A1_Cement-production
Manufacturing and Industrial Processes	Metal Industry	iron-and-steel	1A2a_Ind-Comb-Iron-steel, 2C1_Iron-steel-alloy-prod
Manufacturing and Industrial Processes	Metal Industry	aluminum, other-metals	1A2b_Ind-Comb-Non-ferrous-metals, 2C3_Aluminum-production, 2C4_Non-Ferrous-other-metals
Manufacturing and Industrial Processes	Chemicals	chemicals, petrochemical-steam-crac king, other-chemicals	1A2c_Ind-Comb-Chemicals, 2B_Chemical-industry, 2B2_Chemicals-Nitric-acid, 2B3_Chemicals-Adipic-acid
Manufacturing and Industrial Processes	Pulp and Paper	pulp-and-paper	1A2d_Ind-Comb-Pulp-paper
Manufacturing and Industrial Processes	Mining and Quarrying	sand-quarrying, rock-quarrying, bauxite-mining, iron-mining, copper-mining, other-mining-quarrying	1A2g_Ind-Comb-mining-quarying
Manufacturing and Industrial Processes	Food Beverage and Tobacco	food-beverage-tobacco	1A2e_Ind-Comb-Food-tobacco
Manufacturing and Industrial Processes	Textiles Leather and Apparel	textiles-leather-apparel	1A2g_Ind-Comb-textile-leather
Manufacturing and Industrial Processes	Wood and Wood Products	wood-and-wood-products	1A2g_Ind-Comb-wood-products
Manufacturing and Industrial Processes	Lime	lime	2A2_Lime-production
Manufacturing and Industrial Processes	Glass	glass	2Ax_Other-minerals

Comparison Sector	Comparison Subsector	Climate TRACE Sectors	CEDS Sectors
Manufacturing and Industrial Processes	Other Manufacturing	other-manufacturing, fluorinated-gases	1A2f_Ind-Comb-Non-metalic-minerals, 1A2g_Ind-Comb-Construction, 1A2g_Ind-Comb-machinery, 1A2g_Ind-Comb-other, 1A2g_Ind-Comb-transpequip, 2D_Chemical-products-manufacture-processing, 2D_Degreasing-Cleaning, 2D_Other-product-use, 2D_Paint-application, 2H_Pulp-and-paper-food-beverage-wood
Transport	Domestic Aviation	domestic-aviation	1A3aii_Domestic-aviation
Transport	International Aviation	international-aviation	1A3ai_International-aviation
Transport	Domestic Shipping	domestic-shipping	1A3dii_Domestic-navigation
Transport	International Shipping	international-shipping	1A3di_International-shipping, 1A3di_Oil_Tanker_Loading
Transport	Road Transportation	road-transportation	1A3b_Road
Transport	Railways	railways	1A3c_Rail
Transport	Other Transport	other-transport	1A3eii_Other-transp
Buildings	Residential Onsite Fuel Usage	residential-onsite-fuel-usage	1A4b_Residential
Buildings	Non-Residential Onsite Fuel Usage	non-residential-onsite-fuel-usage	1A4a_Commercial-institutional
Buildings	Other Onsite Fuel Usage	other-onsite-fuel-usage	1A4c_Agriculture-forestry-fishing
Agriculture	Enteric Fermentation	enteric-fermentation-cattle-operation, enteric-fermentation-cattle-pasture, enteric-fermentation-other	3E_Enteric-fermentation
Agriculture	Manure Management	manure-management-cattle-operation, manure-management-other, manure-left-on-pasture-cattle	3B_Manure-management
Agriculture	Rice Cultivation	rice-cultivation	3D_Rice-Cultivation
Agriculture	Direct Nitrogen Emissions from Agricultural Soils	synthetic-fertilizer-application, manure-applied-to-soils, crop-residues, soil-organic-carbon	3D_Soil-emissions

Comparison Sector	Comparison Subsector	Climate TRACE Sectors	CEDS Sectors
Agriculture	Other Agriculture	other-agricultural-soil-emissions	3I_Agriculture-other, 7BC_Indirect-N2O-non-agricultural-N
Waste	Solid Waste Disposal	solid-waste-disposal	5A_Solid-waste-disposal
Waste	Other Waste	biological-treatment-of-solid-waste-and-biogenic	5E_Other-waste-handling
Waste	Incineration and Open Burning of Waste	incineration-and-open-burning-of-waste	5C_Waste-combustion
Waste	Wastewater Treatment and Discharge	industrial-wastewater-treatment-and-discharge, domestic-wastewater-treatment-and-discharge	5D_Wastewater-handling
Forestry and Land Use Change	Biomass Burning	forest-land-fires, shrubgrass-fires, wetland-fires, cropland-fires,	
Forestry and Land Use Change	Emissions and Removals Excluding Biomass Burning	forest-land-clearing, forest-land-degradation, removals, water-reservoirs	

Table 3. Country proxy used for emissions estimates. As CEDS does not provide emissions estimates for 31 regions, they are mapped to respective proxy countries based on geography, cultural ties, and governmental relationships. Countries mapped to *zero* (UNK) imply that no compatible mapping was needed.

Country	Proxy Country
AIA	GRB
ALA	FIN
AND	FRA
ATA	zero

Country	Proxy Country
MCO	ITA
MNP	ASM
MYT	LKA
NFK	AUS

ATF	SXM	NRU	ASM
BES	SXM	PCN	AUS
BLM	FRA	PSE	LBN
BVT	zero	SGS	GBR
CCK	LKA	SHN	GBR
CXR	LKA	SJM	NOR
GGY	GBR	SMR	ITA
HMD	zero	TUV	ASM
IMN	GBR	UMI	ASM
IOT	GBR	VAT	ITA
JEY	GBR	ZNC	TUR
MAF	FRA	UNK	zero

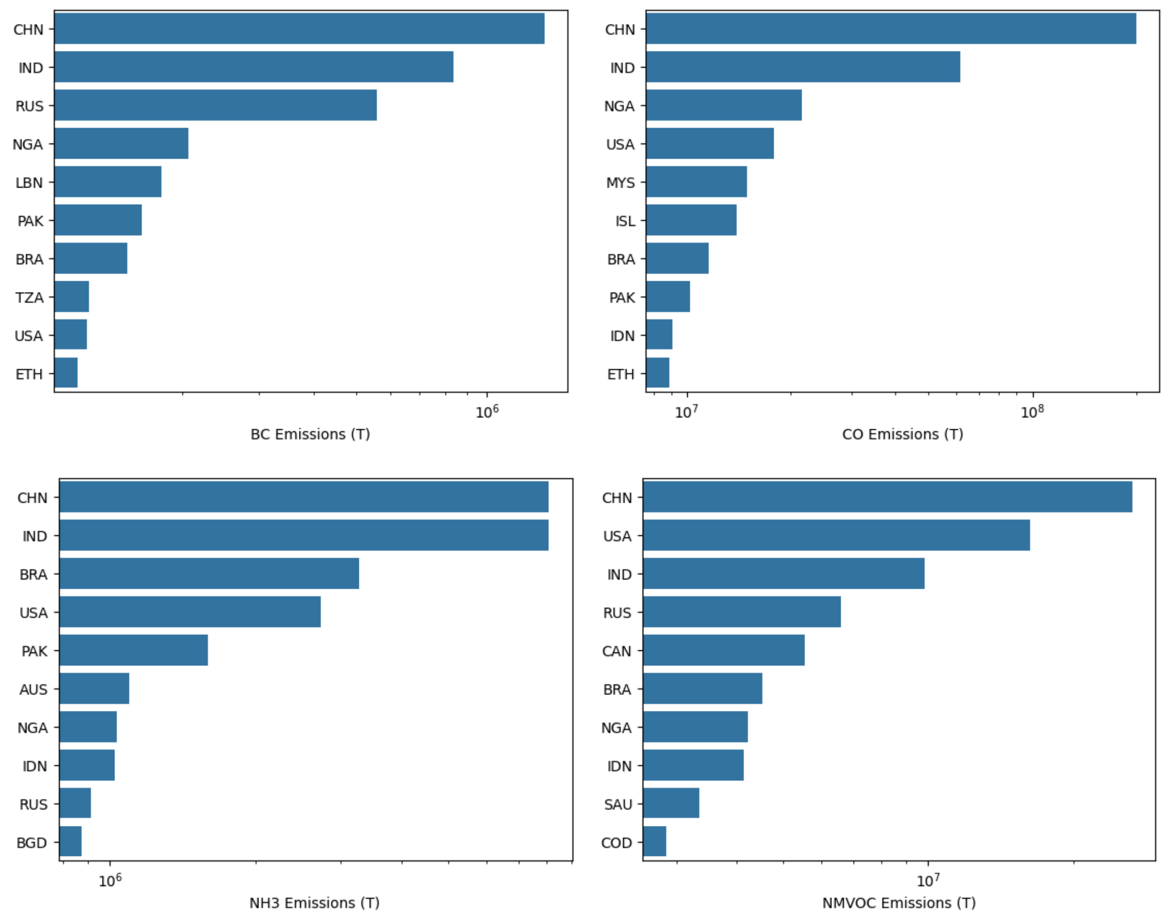
Table 4. Method used for estimating emissions. *CEDS/EDGAR* indicates they are CEDS/EDGAR-based, and *Sector Leads* indicate they are estimated by the team that estimates the GHGs of that sector. Green boxes indicate a complete emissions estimate, yellow boxes are for partial estimates, and red boxes are for sectors-gases with no estimates

Sector Name	BC	CO	NH3	NMVOC	NOx	OC	SO2	PM2.5	PM10
aluminum	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS*	Not Predicted
bauxite-mining	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
biological-treatment-of-solid-waste-and-biogenic	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
cement	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	EDGAR	Not Predicted
chemicals	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS*	Not Predicted
coal-mining	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS*	Not Predicted
copper-mining	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
crop-residues	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted

Sector Name	BC	CO	NH3	NMVOC	NOx	OC	SO2	PM2.5	PM10
domestic-aviation	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
domestic-shipping	CEDS	Sector Leads	CEDS	Sector Leads	Sector Leads	CEDS	Sector Leads	Sector Leads	Sector Leads
domestic-wastewater-treatment-and-discharge	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
electricity-generation	CEDS	CEDS	CEDS	CEDS	Sector Leads	CEDS	Sector Leads	Sector Leads	Not Predicted
enteric-fermentation-cattle-operation	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
enteric-fermentation-cattle-pasture	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	EDGAR	Not Predicted
enteric-fermentation-other	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	EDGAR	Not Predicted
fluorinated-gases	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
food-beverage-tobacco	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
glass	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
heat-plants	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
incineration-and-open-burning-of-waste	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
industrial-wastewater-treatment-and-discharge	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
international-aviation	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
international-shipping	CEDS	Sector Leads	CEDS	Sector Leads	Sector Leads	CEDS	Sector Leads	Sector Leads	Sector Leads
iron-and-steel	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
iron-mining	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
lime	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
manure-applied-to-soils	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	EDGAR	Not Predicted

Sector Name	BC	CO	NH3	NMVOC	NOx	OC	SO2	PM2.5	PM10
manure-left-on-pasture-cattle	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	EDGAR	Not Predicted
manure-management-cattle-operation	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
manure-management-other	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	EDGAR	Not Predicted
non-residential-onsite-fuel-usage	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
oil-and-gas-production	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
oil-and-gas-refining	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
oil-and-gas-transport	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
other-agricultural-soil-emissions	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
other-chemicals	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
other-energy-use	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
other-fossil-fuel-operations	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
other-manufacturing	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
other-metals	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
other-mining-quarrying	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
other-onsite-fuel-usage	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
other-transport	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
petrochemical-steam-cracking	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS*	Not Predicted
pulp-and-paper	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS*	Not Predicted
railways	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted

Sector Name	BC	CO	NH3	NMVOC	NOx	OC	SO2	PM2.5	PM10
residential-onsite-fuel-usage	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
rice-cultivation	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	EDGAR	Not Predicted
road-transportation	CEDS	Sector Leads	CEDS	CEDS	Sector Leads	CEDS	CEDS	Sector Leads	Not Predicted
rock-quarrying	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
sand-quarrying	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
soil-organic-carbon	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	EDGAR	Not Predicted
solid-fuel-transformation	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted
solid-waste-disposal	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	EDGAR	Not Predicted
synthetic-fertilizer-application	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
textiles-leather-apparel	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted	Not Predicted
wood-and-wood-products	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	CEDS	Not Predicted


CHN
IND
RUS
NGA
LBN
PAK
BRA
TZA
USA
ETH
10^6
BC Emissions (T)
CHN
IND
NGA
USA
MYS
ISL
BRA
PAK
IDN
ETH
10^7
10^8
CO Emissions (T)
CHN
IND
BRA
USA
PAK
AUS
NGA
IDN
RUS
BGD
10^6
NH3 Emissions (T)
CHN
USA
IND
RUS
CAN
BRA
NGA
IDN
SAU
COD
10^7
NMVOC Emissions (T)

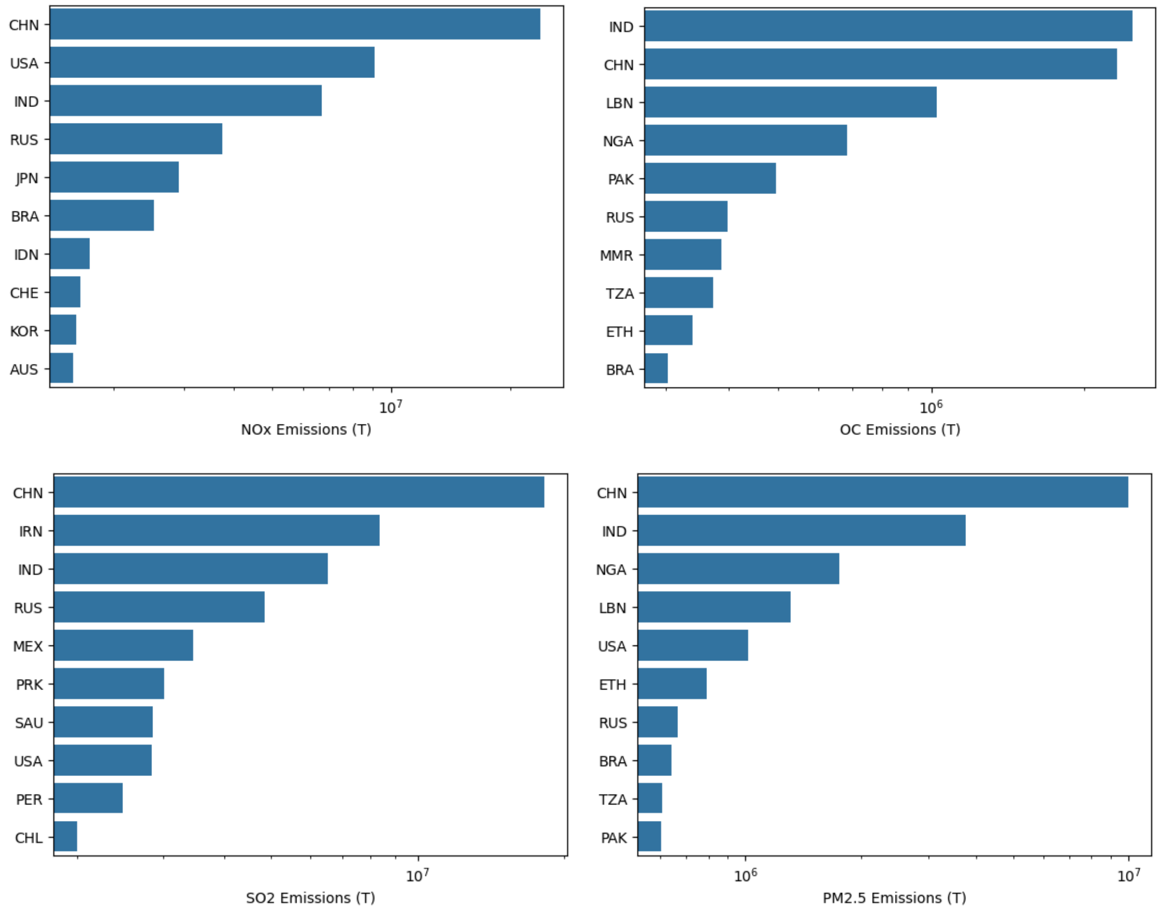
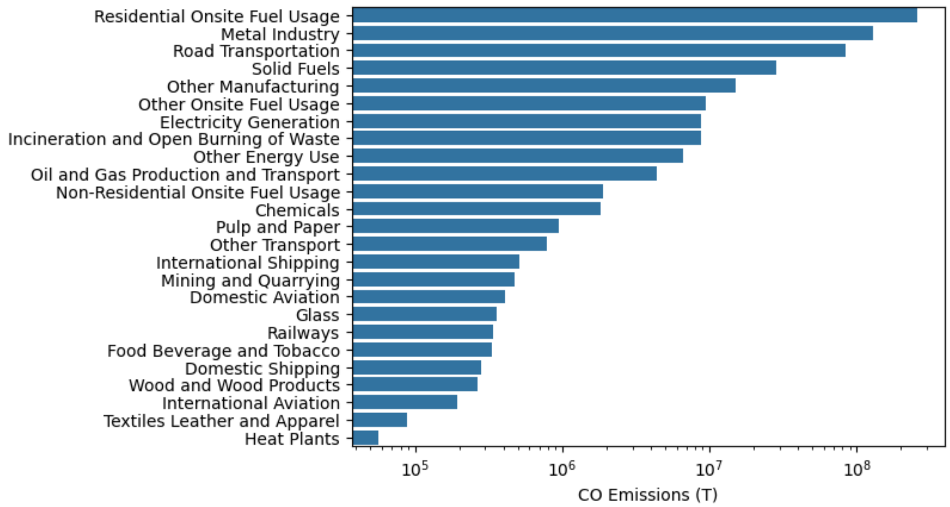
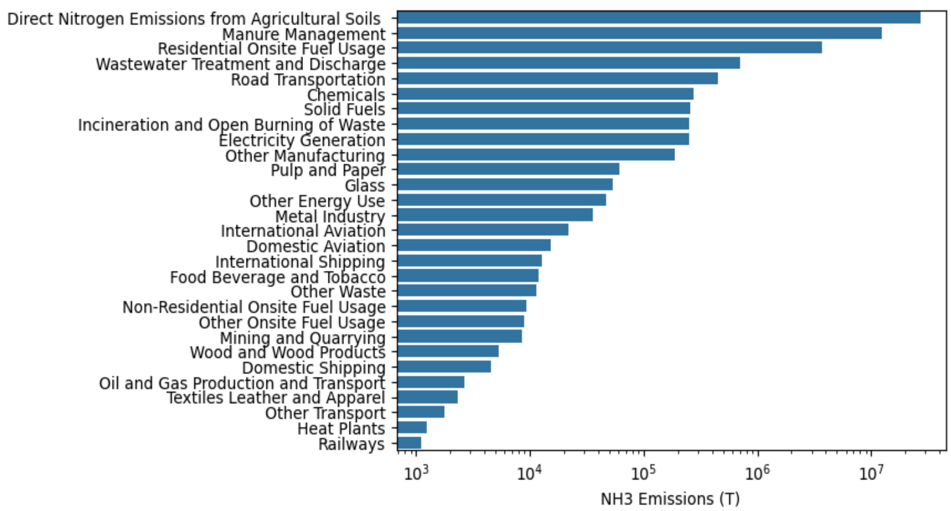
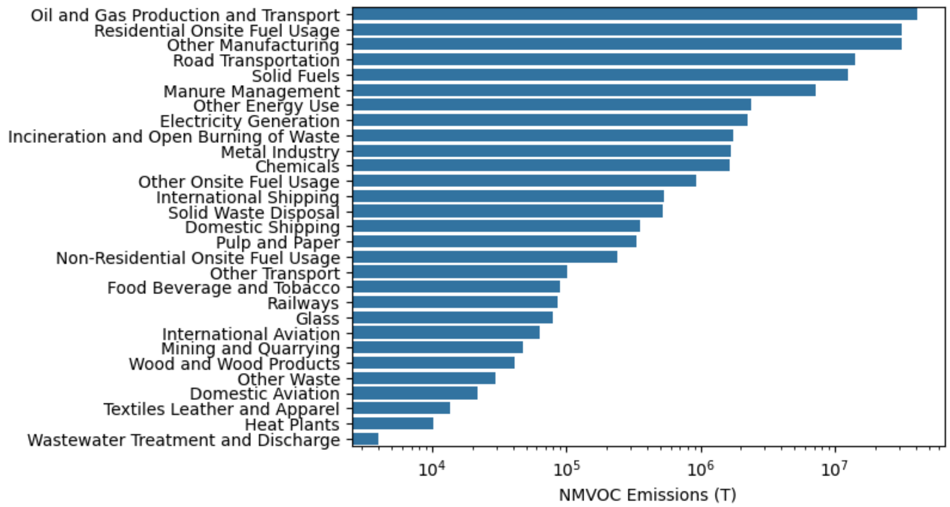
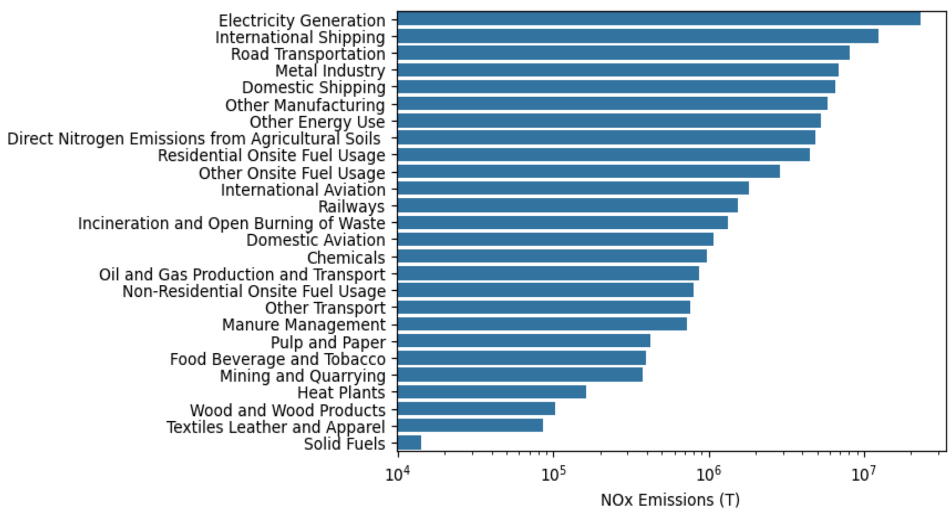


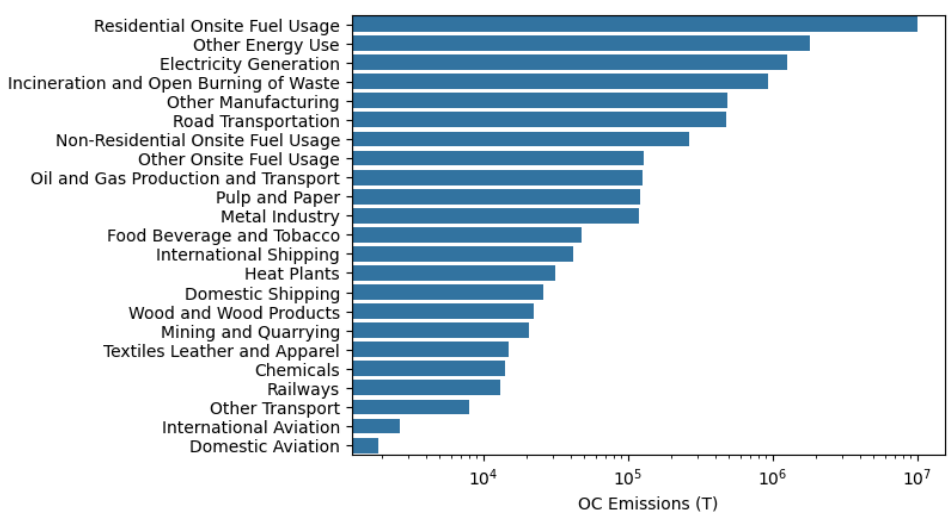
Figure 4. Countries with the largest sources of emissions per gas in 2022.

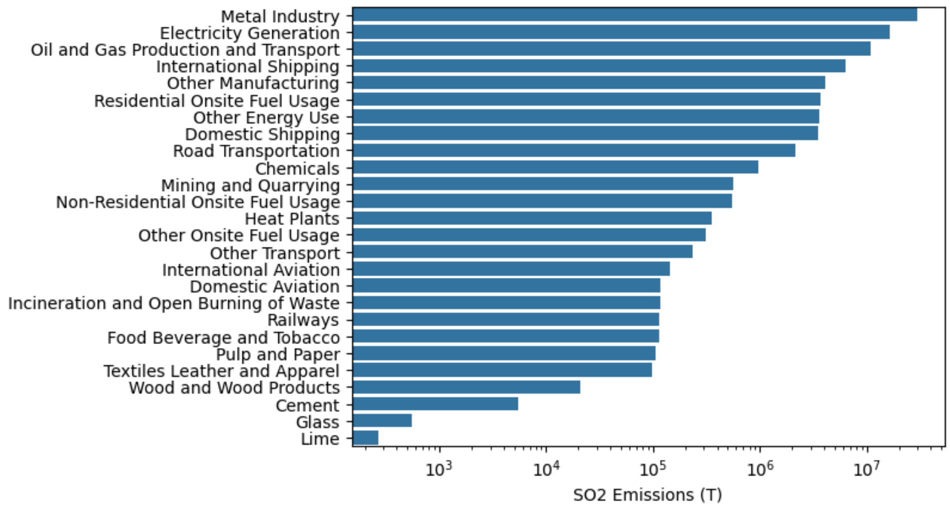

Residential Onsite Fuel Usage
Metal Industry
Road Transportation
Solid Fuels
Other Manufacturing
Other Onsite Fuel Usage
Electricity Generation
Incineration and Open Burning of Waste
Other Energy Use
Oil and Gas Production and Transport
Non-Residential Onsite Fuel Usage
Chemicals
Pulp and Paper
Other Transport
International Shipping
Mining and Quarrying
Domestic Aviation
Glass
Railways
Food Beverage and Tobacco
Domestic Shipping
Wood and Wood Products
International Aviation
Textiles Leather and Apparel
Heat Plants
10^5
10^6
10^7
10^8
CO Emissions (T)


Direct Nitrogen Emissions from Agricultural Soils
Manure Management
Residential Onsite Fuel Usage
Wastewater Treatment and Discharge
Road Transportation
Chemicals
Solid Fuels
Incineration and Open Burning of Waste
Electricity Generation
Other Manufacturing
Pulp and Paper
Glass
Other Energy Use
Metal Industry
International Aviation
Domestic Aviation
International Shipping
Food Beverage and Tobacco
Other Waste
Non-Residential Onsite Fuel Usage
Other Onsite Fuel Usage
Mining and Quarrying
Wood and Wood Products
Domestic Shipping
Oil and Gas Production and Transport
Textiles Leather and Apparel
Other Transport
Heat Plants
Railways
10^3
10^4
10^5
10^6
10^7
NH3 Emissions (T)


Oil and Gas Production and Transport
Residential Onsite Fuel Usage
Other Manufacturing
Road Transportation
Solid Fuels
Manure Management
Other Energy Use
Electricity Generation
Incineration and Open Burning of Waste
Metal Industry
Chemicals
Other Onsite Fuel Usage
International Shipping
Solid Waste Disposal
Domestic Shipping
Pulp and Paper
Non-Residential Onsite Fuel Usage
Other Transport
Food Beverage and Tobacco
Railways
Glass
International Aviation
Mining and Quarrying
Wood and Wood Products
Other Waste
Domestic Aviation
Textiles Leather and Apparel
Heat Plants
Wastewater Treatment and Discharge
10^4
10^5
10^6
10^7
NMVOC Emissions (T)


Electricity Generation
International Shipping
Road Transportation
Metal Industry
Domestic Shipping
Other Manufacturing
Other Energy Use
Direct Nitrogen Emissions from Agricultural Soils
Residential Onsite Fuel Usage
Other Onsite Fuel Usage
International Aviation
Railways
Incineration and Open Burning of Waste
Domestic Aviation
Chemicals
Oil and Gas Production and Transport
Non-Residential Onsite Fuel Usage
Other Transport
Manure Management
Pulp and Paper
Food Beverage and Tobacco
Mining and Quarrying
Heat Plants
Wood and Wood Products
Textiles Leather and Apparel
Solid Fuels
10^4
10^5
10^6
10^7
NOx Emissions (T)


Residential Onsite Fuel Usage
Other Energy Use
Electricity Generation
Incineration and Open Burning of Waste
Other Manufacturing
Road Transportation
Non-Residential Onsite Fuel Usage
Other Onsite Fuel Usage
Oil and Gas Production and Transport
Pulp and Paper
Metal Industry
Food Beverage and Tobacco
International Shipping
Heat Plants
Domestic Shipping
Wood and Wood Products
Mining and Quarrying
Textiles Leather and Apparel
Chemicals
Railways
Other Transport
International Aviation
Domestic Aviation
10^4
10^5
10^6
10^7
OC Emissions (T)



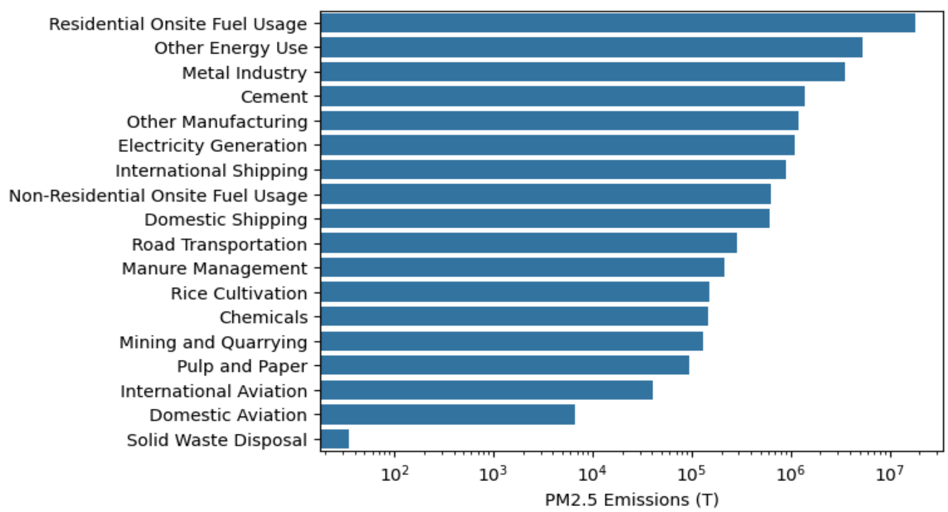


Figure 5. All sources of air-pollution estimated and larger than zero, broken-down by sector and sorted from largest to smallest for year 2022.

Data citation format: Collins, G., Robinette, M., Sridhar, L., Reilly, E, Hughes, Marisa (2024). *Non-Greenhouse Gas Emissions Estimates Across Sectors.* The Johns Hopkins University Applied Physics Laboratory (JHU/APL), USA, WattTime, USA, Climate TRACE Emissions Inventory. https://climatetrace.org [Accessed date]

Geographic boundaries and names (iso3_country data attribute): The depiction and use of boundaries, geographic names and related data shown on maps and included in lists, tables, documents, and databases on Climate TRACE are generated from the Global Administrative Areas (GADM) project (Version 4.1 released on 16 July 2022) along with their corresponding ISO3 codes, and with the following adaptations:

- HKG (China, Hong Kong Special Administrative Region) and MAC (China, Macao Special Administrative Region) are reported at GADM level 0 (country/national);
- Kosovo has been assigned the ISO3 code 'XKX';
- XCA (Caspian Sea) has been removed from GADM level 0 and the area assigned to countries based on the extent of their territorial waters;
- XAD (Akrotiri and Dhekelia), XCL (Clipperton Island), XPI (Paracel Islands) and XSP (Spratly Islands) are not included in the Climate TRACE dataset;
- ZNC name changed to 'Turkish Republic of Northern Cyprus' at GADM level 0;
- The borders between India, Pakistan and China have been assigned to these countries based on GADM codes Z01 to Z09.

The above usage is not warranted to be error free and does not imply the expression of any opinion whatsoever on the part of Climate TRACE Coalition and its partners concerning the legal status of any country, area or territory or of its authorities, or concerning the delimitation of its borders.

Disclaimer: The emissions provided for this sector are our current best estimates of emissions, and we are committed to continually increasing the accuracy of the models on all levels. Please review our terms of use and the sector-specific methodology documentation before using the data. If you identify an error or would like to participate in our data validation process, please contact us.

7. References

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[2] Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., van Aardenne, J. A., Monni, S., Doering, U., Olivier, J. G. J., Pagliari, V., and Janssens-Maenhout, G.: Gridded emissions of air pollutants for the period 1970–2012 within EDGAR v4.3.2, Earth Syst. Sci. Data, 10, 1987–2013, doi:10.5194/essd-10-1987-2018, 2018.

[3] Hoesly, R.M., Smith, S.J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J.J., Vu, L., Andres, R.J., Bolt, R.M. and Bond, T.C., 2018. Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geoscientific Model Development*, *11*(1), pp.369-408.

[4] Crippa, M., Guizzardi, D., Pagani, F., Schiavina, M., Melchiorri, M., Pisoni, E., Graziosi, F., Muntean, M., Maes, J., Dijkstra, L. and Van Damme, M., 2023. Insights on the spatial distribution of global, national and sub-national GHG emissions in edgarv8. 0. *Earth System Science Data Discussions*, *2023*, pp.1-28.

[5] European Environment Agency. 2023. EMEP/EEA Air Pollution Emission Inventory Guidebook 2023: Technical Guidance to Prepare National Emission Inventories.

[6] United State Environmental Protection Agency. 2024. 2024 SmartWay Air Carrier Partner Tool: Technical Documentation. US Version 1.0. EPA-420-B-24-008.