

C Air Pollutant Emissions Database

Maksym Chepeliev¹²

C.1 Overview

With a major contribution to premature mortality and morbidity levels, ambient air pollutant emission is one of the most severe global health risk factors (Hay et al. 2025). Representation of air pollutant emission flows in global economic models is thus an important element of a consistent assessment of health and environmental policies. Still, while greenhouse gas emissions are usually well represented in many global economic databases and models, air pollutant emission accounts in most cases are not included. In this chapter, we describe the methodology used to produce a global air pollutant emissions dataset consistent with the GTAP Data Base version 12. The developed air pollutant emission accounts are largely based on the EDGAR v8.1 database (Joint Research Centre, European Commission 2024), include seven reference years (2004, 2007, 2011, 2014, 2017, 2019, and 2023), cover 163 regions and 65 sectors. Emissions are linked to economic activities and three sets of emission sources: consumption (by intermediate and final users), endowment use (land) and output. In addition to the non-land use sources, emissions from land use activities are estimated by land cover type, based on the volume of burned biomass and emission factors. The emissions database can be readily incorporated in GTAP-based computable general equilibrium models, enabling assessments of a wide range of policy questions, including the health co-benefits from climate mitigation policies.

C.2 Introduction

In recent years, a number of studies have contributed to the assessment of air pollutant emissions-related externalities at the regional and global scales. According to the Health Effects Institute (Health Effects Institute 2025), in 2023, ambient PM_{2.5} emissions caused 4.9 million deaths and a loss of 124 million disability-adjusted life-years, making it the fourth-ranked global risk factor.

With such a high magnitude of air pollutant emissions-related externalities, implementing more stringent environmental policies (e.g., emissions taxation or elimination of energy subsidies) may result in significant co-benefits from reduced mortality and morbidity, as well as increased labor productivity (Vandyck et al. 2018; Markandya et al. 2018). While CO₂ and non-CO₂ greenhouse gas (GHG) emissions are usually well represented in many global economic databases and models, air pollutant emission accounts in many cases are not included. One of the reasons behind this situation is that, unlike carbon budget estimates from changes in GHG emissions, health impacts from changes in air pollutant emissions have to be assessed using specialized modelling tools and techniques (e.g., Van Dingenen et al. 2018; IIASA 2017).

In this chapter, we describe the methodology used to produce an air pollutant emissions dataset consistent with the Global Trade Analysis Project (GTAP) 12 Data Base (Aguiar et al.

¹²Center for Global Trade Analysis, Purdue University. Email: mchepeli@purdue.edu. This Chapter incorporates materials from Chepeliev 2021.

2025), which reports data for seven benchmark years: 2004, 2007, 2011, 2014, 2017, 2019 and 2023. This effort complements the complementary GTAP GHG emission accounts (Chapter 13B) and CO₂ emissions data from fossil fuels combustion, integrated in the standard GTAP Data Base (Chapter 13A).

Several sources for the global air pollutant emissions data are available, which can be used for the construction of GTAP-consistent emission accounts either separately or combined. In our effort to construct the air pollutant emission accounts consistent with the GTAP Data Base, we impose several criteria on the source data. First, we are aiming for a global dataset with (at least) country-level coverage. Second, the underlying emissions dataset should be based on a standardized methodology and with regular updates, to support future releases of the GTAP Data Base. Third, the database should distinguish sources of air pollutant emissions, which can be further linked to economic activities, as presented in the GTAP Data Base.

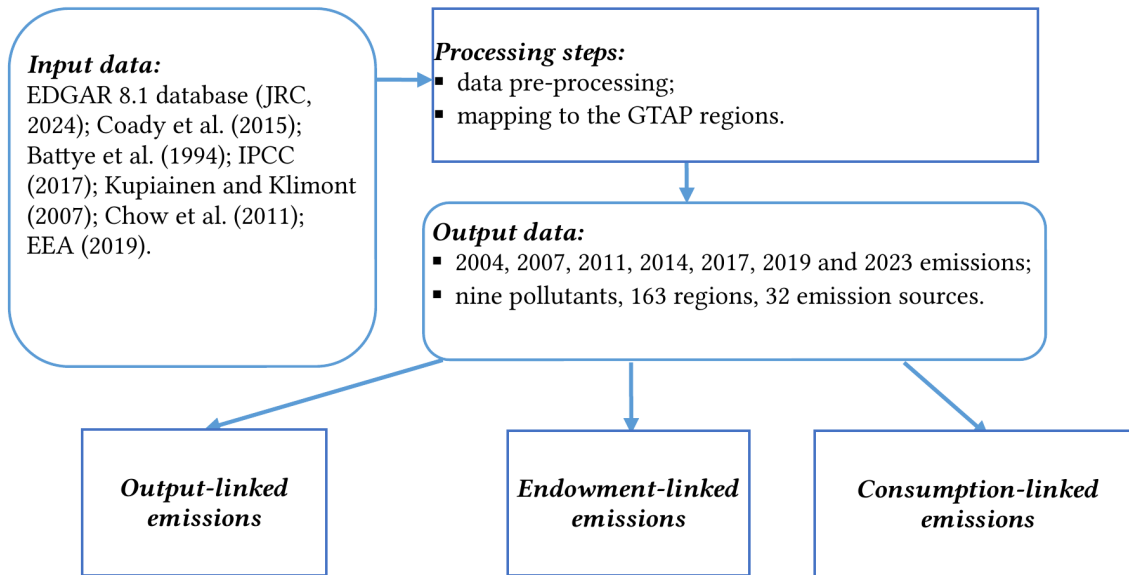
Considering the aforementioned criteria, we have chosen to rely on the EDGAR Version 8.1 database as a main source of air pollutant emissions (Joint Research Centre, European Commission 2024). The EDGAR database reports data for nine pollutants: black carbon (BC), carbon monoxide (CO), ammonia (NH₃), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), organic carbon (OC), particulate matter 10 (PM₁₀), particulate matter 2.5 (PM_{2.5}) and sulfur dioxide (SO₂). For estimates of the underlying energy volumes, both EDGAR and GTAP rely on the extended energy balances developed by the International Energy Agency (IEA).

We construct the emissions database for 9 pollutants, 163 GTAP 12 Data Base regions, and for the seven benchmark years. Emissions are linked to economic activities and three sets of emission sources: consumption (by intermediate and final users), endowment use (land and capital), and output. To assist with emissions allocation between consumption-based sources, the IIASA GAINS-based model emission factors are used (Coady et al. 2015). In addition, emissions from land use activities (biomass burning) are estimated by land cover type, based on the volume of burned biomass (FAO 2025) and emission factors. These emissions are reported separately without association with emission drivers. One particular feature of the GTAP 12 air pollution database is an expansion of the categories that represent emissions from large-scale biomass burning and activities of land use, land-use change and forestry, as documented in section C.4.

C.3 Air pollutant emissions data mapping to the GTAP Data Base

This section provides a description of the approach used to link the EDGAR-based air pollutant emissions data with the GTAP 12 Data Base. In this effort, we associate each pollution flow with one of the four sets of emission sources: output by industry, endowment by industry, input use by industry and input use by households. To provide a more accurate allocation of emissions between different types of fossil fuel consumption by industry and households, we use the GAINS-based emission factors, reported in Coady et al. 2015, IPCC-sourced emission factors provided in IPCC 2017, as well as BC and OC emission factors based on multiple data sources (Kupiainen and Klimont 2007; Chow et al. 2011; EEA 2019). Figure C.1 provides an overview of the database construction process.

Figure C.1: GTAP air pollutant emissions database construction process



Notes: This figure excludes treatment of the land use emissions (discussed separately).

Source: Author.

The EDGAR v8.1 database reports emissions from fossil fuel and bio sources. We use this distinction to provide a more consistent mapping of the emissions reported in the EDGAR to the GTAP emission drivers. As the GTAP energy database (Chapter 12) does not report energy flows for biomass or biofuels use, we apply different mappings for the fossil- and bio-based flows. These are reported in Appendices C.1 and C.2, respectively.

One particular feature of the GTAP 12 air pollution database, compared to the GTAP 11 air pollution database, is the estimation of emissions for the most up-to-date reference year, i.e., 2023. Since the most recent version of the EDGAR database available during the GTAP 12 development process reports air pollution data up to 2022 (Joint Research Centre, European Commission 2024), a growth rate approach was used to estimate emissions for 2023. In particular, it was assumed that the 2022–2023 emission growth rate is the same as the 2021–2022 growth rate for each country, emission source and pollutant case. As a result, air pollution emissions reported in GTAP 12 for the 2023 reference year are estimated. At the global level, the average growth rate for 2022–2023 ranges from 0.7–0.8% (for OC and PM₁₀) to 3–4% for SO₂ and NO_x.

Air pollutant emissions associated with output by industries

In the case of output-driven categories, emissions are redistributed between corresponding emitting sectors proportionally to the value of sectoral output (Appendices C.1 and C.2). With the defined mapping between IPCC categories and the GTAP emission sources, as well as mapping between the IPCC categories and the GTAP emission drivers, output-associated emissions (APQO) are

estimated according to the following formula:

$$APQO_{t,e,k,r} = \sum_{\substack{c \in SecMap_{e,k,e} \\ c \in DriveMap_{c,Output,e}}} EmiReg_{t,e,c,r} \frac{ValRedist_{c,e} ValOutpt_{t,k,r}}{\sum_{i \in SecMap_{c,i,e}} ValRedist_{c,e} ValOutpt_{t,i,r}}. \quad (13.2)$$

where t is the set of years (2004, 2007, 2011, 2014, 2017, 2019 and 2023); e is the set of 9 air pollutants; k, i represent the 65 GTAP sectors; r represents the set of 163 GTAP regions; c is the set of IPCC emission categories. *ValRedist* identifies cases with emissions redistributed proportionally to GTAP values (such categories are indicated by “#” in Appendices C.1 and C.2). *SecMap* provides the mapping between IPCC categories and GTAP emission sources, while *DriveMap* provides the mapping between IPCC categories and GTAP emission drivers.¹³ *EmiReg* represents EDGAR-sourced emissions in million metric tonnes (Mmt) and *ValOutpt* provides value of output in million USD.

An example of the emissions associated with output includes emissions from biomass burning (IPCC code “3C1”). These emissions are redistributed proportionally to the values of output of the eight GTAP crop sectors that represent corresponding activities and are listed in Appendix C.1.

Air pollutant emissions associated with endowment by industries

Endowment sources account for the smallest share of pollution in all cases. All endowment-driven IPCC pollution categories are redistributed between drivers and sectors proportionally to the GTAP value flows (Appendix C.1), which is similar to the output-driven pollution treatment:

$$APQE_{t,e,m,k,r} = \sum_{\substack{c \in SecMap_{c,k,e} \\ c \in DriveMap_{c,m,e}}} EmiReg_{t,e,c,r} \frac{ValRedist_{c,e} Cost_{t,m,k,r}}{\sum_{\substack{i \in SecMap_{c,i,e} \\ j \in DriveMap_{c,j,e}}} ValRedist_{c,e} Cost_{t,j,i,r}}. \quad (13.3)$$

where m, j are defined over the set of endowment drivers (land and capital), used for emissions reallocation; *Costs* coefficient represents the cost structure in million USD.¹⁴

In the database, there is one case of the endowment-linked emissions—emissions from manure in pasture, land, and paddock. In the latter case, emissions are redistributed proportionally to the values of the capital endowment¹⁵ in the three GTAP livestock and animal-related sectors—cattle, raw milk, and other animal products (Appendix C.1).

¹³These mappings (*SecMap* and *DriveMap*) are generic for all air pollutants.

¹⁴The cost structure is constructed as a combination of the cost structure of firms and cost structure of consumption, as reported in the “gsdfview.har” file of the GTAP 12 Data Base.

¹⁵In the GTAP Data Base value of animal stock (e.g., cattle) is captured via the capital input in the corresponding sector (e.g., bovine cattle, sheep, goats, and horses).

Air pollutant emissions associated with consumption

C.3.3.1 Non-combustion emissions

Consumption-related pollution reallocation is treated in two ways. In the case of pollution linked to the consumption of chemical products, the treatment is similar to the endowment- and output-driven pollution, both for firms (*APQF*) and households (*APQP*):

$$APQF_{t,e,k,j,r} = \sum_{\substack{c \in SecMap_{c,j,e} \\ c \in DriveMap_{c,k,e}}} EmiReg_{t,e,c,r} \frac{ValRedist_{c,e} Costs_{t,k,j,r}}{\sum_{\substack{s \in SecMap_{c,s,e} \\ i \in DriveMap_{c,i,e}}} ValRedist_{c,e} Costs_{t,i,s,r}}, \quad (13.4)$$

where k, i, j represent the 65 GTAP sectors; s is the set of emission sources and includes traded commodities and households.

$$APQP_{t,e,k,r} = \sum_{\substack{c \in SecMap_{c,HHs,e} \\ c \in DriveMap_{c,k,e}}} EmiReg_{t,e,c,r} \frac{ValRedist_{c,e} Costs_{t,k,HHs,r}}{\sum_{\substack{s \in SecMap_{c,s,e} \\ i \in DriveMap_{c,i,e}}} ValRedist_{c,e} Costs_{t,i,s,r}}, \quad (13.5)$$

where the “HHs” label identifies households.

An example of the non-combustion consumption-related emissions associated with both firms’ and households’ consumption includes emissions from the Non-energy products from fuels and solvent use (IPCC code “2D”). In this case, emissions are redistributed between various sectors and households proportionally to the value of the use of chemical products by these agents.

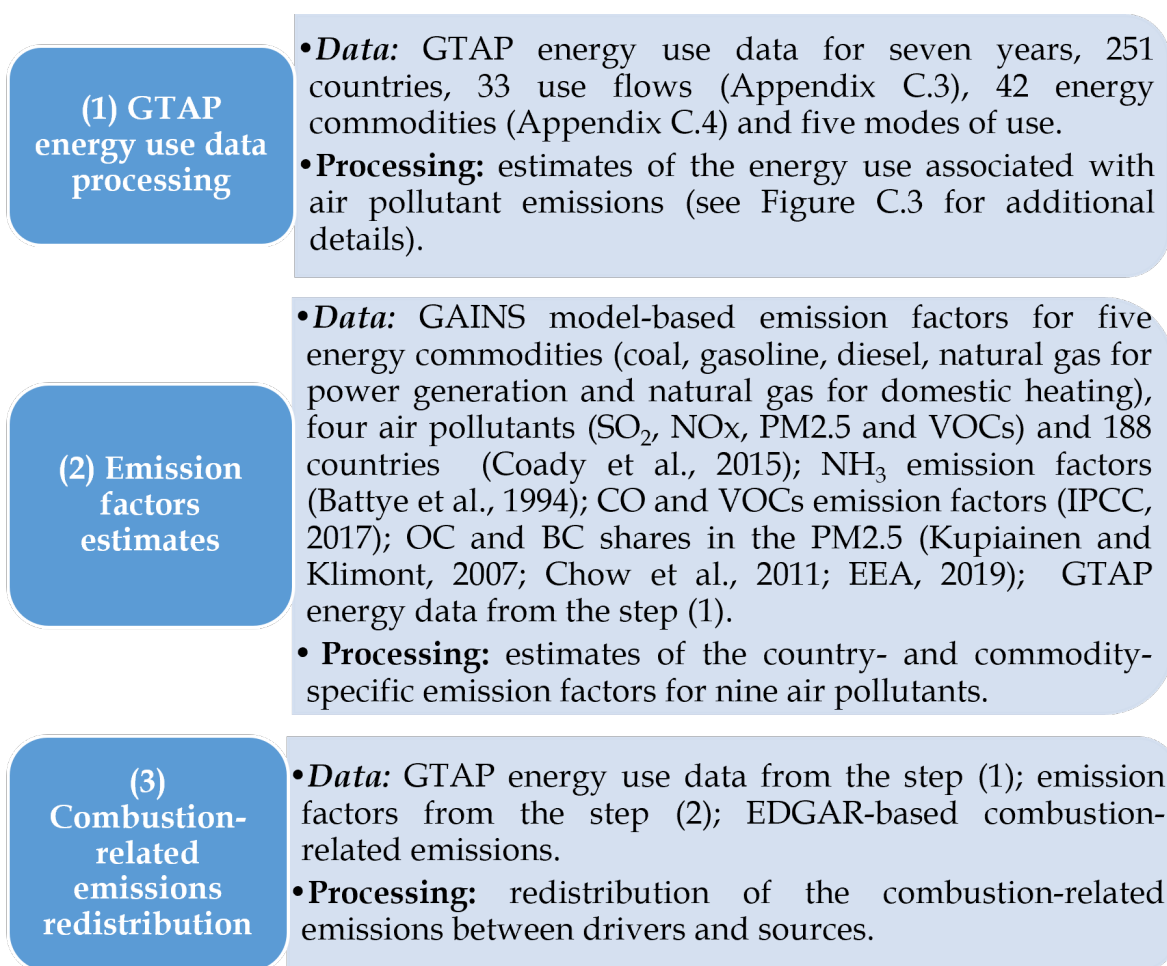
C.3.3.2 Fossil fuel combustion emissions: overall approach and energy flow estimates

A different treatment is applied to the IPCC categories associated with the combustion of fossil fuels (IPCC categories without the “#” sign in Appendix C.1). Figure C.2 provides an overview of the general approach to the fuel combustion-related emission redistribution.

In the case of combustion-related emissions, in the first step, we estimate energy use associated with air pollutant emissions. In the case of some IPCC pollution categories, we assume that all energy use is associated with the corresponding pollution, while in other cases a share of all energy use is considered. We consider only such energy use that is associated with energy combustion and exclude fuel feedstocks that are transformed or exported, which, for instance, is the case for petroleum industry with high volumes of oil transformation. Figure C.3 provides an overview of the energy data processing steps for the fuel combustion-related emissions treatment.

The GTAP 12 Data Base energy data is not as disaggregated as required for the development of the air pollutant emissions database, therefore we apply an additional disaggregation. This is the case for petroleum products, which are reported in aggregate in the GTAP 12 Data Base, while available emission factors are differentiated for gasoline and diesel. We also need energy use data at a country level (rather than by composite regions). To implement this, we use the GTAP 12 energy dataset (EDS) (Chapter 12) with the corresponding flows reported in the GTAP 12 Data

Figure C.2: Steps to redistribute the fuel combustion-related emissions

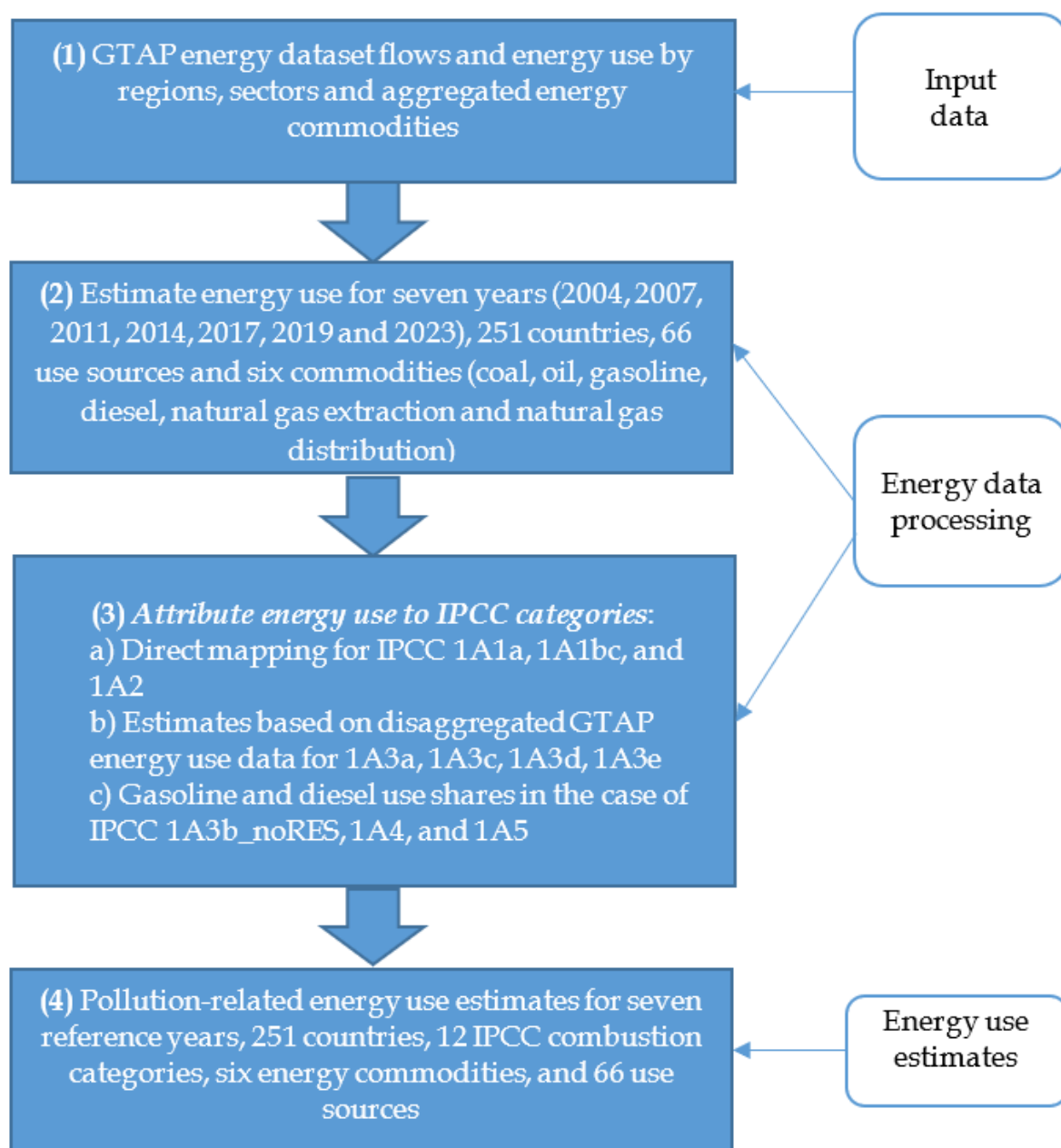


Source: Author.

Base energy module. The EDS data provides energy use by years, countries, 33 use flows, 42 energy commodities, and five modes of use. Using these two data sources we estimate energy use for seven reference years (2004, 2007, 2011, 2014, 2017, 2019 and 2023), 251 countries, 66 use sources (65 GTAP 12 Data Base sectors and households), and six commodities (coal, oil, gasoline, diesel, natural gas extraction, and natural gas distribution).

Using the mappings between IPCC emission sources, emission drivers and the GTAP use sources (Appendix C.1), we allocate estimated energy use flows to the IPCC categories. In the case of public electricity and heat production, other energy industries, manufacturing industries and construction, we assume that the EDGAR-based emissions are redistributed based on energy use volumes and a one-to-many or one-to-one mapping from the IPCC codes to the GTAP use categories is used. For instance, in the case of coal use in public electricity and heat production, we assume that the emissions are redistributed (in this case, only between drivers, as the public electricity and heat production is mapped to a single GTAP sector) based on the coal use data.

Figure C.3: GTAP energy data processing for the fuel combustion-related emission estimates



Source: Author.

In the case of transportation activities—domestic aviation, road transportation, rail transportation, inland navigation, other transportation, international aviation, and international navigation—there is no available one-to-many or one-to-one mapping from the IPCC to GTAP use categories. For instance, GTAP’s other transportation sector includes rail, road, and other transportation IPCC categories (Appendix C.1). Similarly, air transportation includes both domestic and international aviation. To estimate energy use flows for such categories, we use EDS data. A list of the corre-

sponding IPCC categories and mapping to the EDS commodities is provided in Appendix C.5.

Road transportation IPCC category is mapped to the other transportation activity and households (Appendix C.1). To provide a more consistent reallocation of the emission flows, we assume that all gasoline is associated with road transportation activities by households; however, not all diesel is used for road transportation. Therefore, we assume that in the case of household use, the share of diesel used for road transportation equals the share of diesel used for road transportation in total national diesel consumption. For instance, if country A consumes 100 tonnes of oil equivalent (toe) of diesel fuel of which 80 toe (or 80%) is consumed by road transportation, then we assume that in the case of households the share of diesel used for the road transportation equals 80%, while the remaining 20% is used for the other purposes (e.g., heating).

Finally, in the case of households under the residential and other sectors category, we assume that no emissions are associated with gasoline use (as the gasoline-related emissions are attributed to road transportation activities). The share of diesel associated with emissions by households within this category equals “1” less the share of diesel associated with road transportation use (this would be 0.2 in the case of the example above). This step finalizes the GTAP energy data processing for combustion-related emission estimates (Figure C.3).

C.3.3.3 Fossil fuel combustion emissions: estimates of emission factors and emissions redistribution

In general, energy use statistics alone could be enough to redistribute the air pollutants between drivers and sectors based on an assumption of uniform emission factors for different energy commodities and industrial processes. But, as the literature suggests (Coady et al. 2015; IPCC 2017), this is not the case, as emission factors vary significantly across commodities and activities. We combine multiple data sources (Battye et al. 1994; Coady et al. 2015; IPCC 2017; Kupiainen and Klimont 2007; Chow et al. 2011; EEA 2019) to derive country-, sector-, energy commodity- and pollutant-specific emission factors.

The International Monetary Fund (IMF) energy subsidies database (Coady et al. 2015) provides emission factors for 188 countries, five energy commodities (coal, gasoline, diesel, natural gas for power generation and natural gas for domestic heating), and four air pollutants (SO₂, NO_x, PM_{2.5} and VOCs) based on the IIASA GAINS model. We first estimate weighted average emission factors for seven aggregate regions,¹⁶ five energy commodities, and four air pollutants to gap-fill the country cases with unavailable data. For each country with unavailable emission factors, we further use emission factors from the corresponding aggregate region. As the weights for the aggregate region-average emission factors, we use the energy data flows estimated in Step 1 (Figure C.3). Emission factors for natural gas for domestic heating are applied to natural gas used by households. In the case of natural gas used by industrial users and commercial consumers, we apply the emission factors for natural gas used in power generation.

¹⁶The corresponding aggregate regions include East Asia and Pacific, Europe and Central Asia, Latin America and the Caribbean, Middle East and North Africa, North America, South America and Sub-Saharan Africa. The country mapping for each region is available at <https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups>.

We further map four air pollutants from Coady et al. 2015 to seven air pollutants reported in the EDGAR dataset. The corresponding mapping is provided in Appendix C.6. In the case of the BC and OC emissions, we further adjust the $PM_{2.5}$ emission factors based on the percentage shares of BC and OC in total $PM_{2.5}$ mass. The corresponding BC and OC mass shares are estimated for six energy commodities (coal, oil, gasoline, diesel, natural gas extraction, and natural gas distribution) and 66 emission sources based on Kupiainen and Klimont 2007; Chow et al. 2011; EEA 2019.

In the case of emission factors for ammonia (NH_3), we use data from Battye et al. 1994 and assume that these factors are uniform across countries. For the conversion of emission factors to uniform units (kt/PJ) we use data on the density of the corresponding fuels (Joint Research Centre (JRC), European Commission 2007; Unitrove 2017). The energy content of fuels is sourced from New Energy Research (NER) 2017. In the case of natural gas, we use the emission factors for utility and industrial boilers for all sectors except for households; for residential users we apply the emission factors of commercial boilers (Battye et al. 1994).

To derive the CO emission factors, we use the IPCC 2017 database. In the IPCC database, emission factors for combustion activities are provided for the 14 IPCC categories (Appendix C.7). Out of the 14 IPCC categories, only eight have available emission factors for CO, which we map to the GTAP use categories (Appendix C.7). In some cases, the IPCC database reports identical emission factors for several IPCC categories (e.g., 1A4A, 1A4B, 1A4C1).

In terms of the emission drivers, out of the 23 fuels reported in the IPCC emission factors database for CO, only 10 have non-zero values and we map them to the six energy commodities for further emissions redistribution (Appendix C.8). IPCC-based estimation of the CO emission factors finalizes Step 2 of the emissions redistribution process (Figure C.3). As Coady et al. 2015 do not provide VOCs emission factors for natural gas and coal combustion, we use the IPCC values to gap fill this dataset.

We do not map emission factors related to biomass combustion, as in the GTAP energy dataset, all energy flows associated with the biomass or biofuel use are discarded from the construction process (Chapter 12). We use corresponding value flows to redistribute the bio-based emissions (Appendix C.2). Once available within the GTAP Data Base accounting framework, a reliance on the biomass energy flows could improve the treatment of the bio-based emissions redistribution.

To assist with the combustion-related emissions allocation, we estimate emission weights multiplying combustion-related energy use by the corresponding emission factors to derive the $EFEmiReg$ values. With the processed energy use data and estimated emission factors, we move to Step 3 (Figure C.3) and redistribute combustion-related emissions ($ENCOMBEMI$):

$$ENCOMBEMI_{t,r,b,f,s,e} = \frac{EmiReg_{t,e,b,r} EFEmiReg_{t,r,b,f,s,e}}{\sum_{q,v} EFEmiReg_{t,r,b,q,v,e}}, \quad (13.6)$$

where b is the set of air pollutant emission categories in the IPCC emission factors database associated with fossil fuel combustion (Appendix C.7); f, q represent the set of six energy commodities (coal, oil, gasoline, diesel, natural gas extraction and natural gas distribution) associated with air pollutant emissions; s, v correspond to emission sources.

An example of the combustion-related emissions includes emissions from the other energy industries (excluding electricity and heat production). In the GTAP Data Base, the corresponding set of industries is represented by five sectors—mining of coal, oil and gas, production of petroleum products and distribution of gas. The EDGAR-sourced emissions for this category are redistributed between the corresponding five GTAP sectors and four fossil fuel commodities (coal, oil, gas and petroleum products) based on the sector- and commodity-specific emission weights, as discussed above.

International aviation and navigation emissions are redistributed between countries based on the value of exports reported in GTAP 12 Data Base for air transport and water transport, respectively, excluding exports of travelers' expenditures. These emissions are further mapped to drivers and users and added to the consumption-related emissions. Under such treatment, for example, air pollutant emissions associated with a ship leaving from Rotterdam are accounted in the country of the ship's destination.

After this step, we have redistributed over 99.9% of emissions reported in the EDGAR database. However, as was identified, there are some cases (less than 0.1% of the global air pollutant emissions) where EDGAR-reported emissions corresponding to the combustion-related drivers and users in the GTAP Data Base have no energy consumption. To deal with these cases, we map such instances to users with non-zero energy consumption. Appendix C.9 provides the mapping.

Finally, the redistributed emissions from the fossil fuel combustion (*ENCOMBEMI*) are mapped to the emissions associated with the consumption by households (*APQP*) and firms (*APQF*).

C.4 Land use emissions

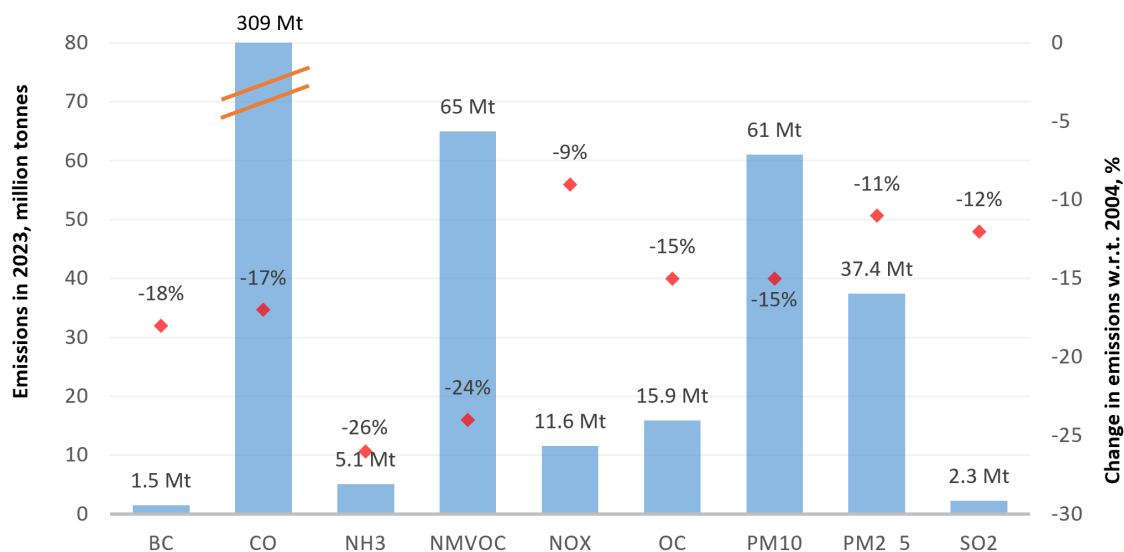
EDGAR v8.1 does not report emissions from large-scale biomass burning and activities of land use, land-use change, and forestry. To complement the air pollutant database with these emissions, we use the FAO-reported volumes of biomass burning by land cover type and emission factors compiled from several sources. Figure C.10.1 (Appendix C.10) provides an overview of the biomass burned (dry matter) by land cover types (FAO 2025). Volumes of the burned biomass declined by around 17% between 2004 and 2023, reaching 3,822 million tons. Compared to the air pollution estimates in the GTAP 11 Data Base, five additional categories of biomass burning activities have been introduced. These include burning of closed shrubland, open shrubland, grassland, savanna and woody savanna.

Table C.10.1 (Appendix C.10) provides a summary of assumptions regarding the value of emission factors by land cover type. These emission factors are primarily based on Akagi et al. 2011 and are complemented by estimates from Yokelson et al. 2013; Hu et al. 2018; California Air Resources Board 2025; Liu et al. 2024. As the literature suggests (e.g., Akagi et al. 2011), there is large uncertainty regarding estimated emission factors, so implied estimates of land use-related air pollutant emissions should be used with caution.

Estimates suggest that, in the case of all pollutants, over the analyzed time horizon, the

highest emission levels were observed in 2004. Emissions across all substances have been declining at a rate of around 1% to 2% per year during 2004–2023 (Figure C.4). Across all emission categories, in 2023, humid tropical forests were the largest contributor to emissions in the case of six (out of nine) air pollutants (Table C.10.2, Appendix C.10).

Figure C.4: Global air pollutant emissions from forests and organic soils burning



Notes: Columns represent the level of emissions in 2023 (primary vertical axis); diamonds report the change in the level of emissions w.r.t. 2004 (secondary vertical axis).

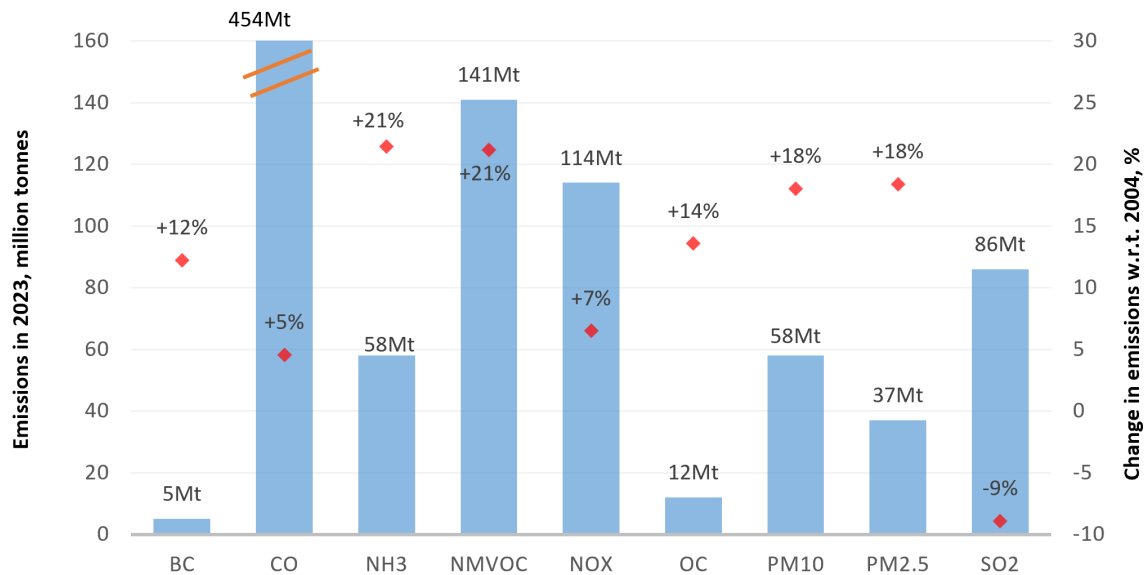
Source: Estimated by the author based on FAO 2025; Akagi et al. 2011; Yokelson et al. 2013; Hu et al. 2018; Liu et al. 2024; California Air Resources Board 2025.

C.5 Overview of the air pollutant emissions database

In this section, we provide an overview of the air pollutant emissions linked to the GTAP emission drivers, i.e., emissions that are not associated with the forests and organic soils burning. Over the 2004–2023 period, global air pollutant emissions have been increasing steadily for almost all pollutants, with the only exception being SO₂, which observed around 9% decline in emissions over the analyzed period (Figure C.5). The highest growth rates were observed for NH₃ and NMVOC (on average 1% per year), followed by PM₁₀ and PM_{2.5} (0.9% per year) (Figure C.5).

At the global level, consumption is the most common driver of pollution (Figure C.6). In the case of all 9 air pollutants, intermediate and final consumption accounts for at least 60% of all emissions. Output is the second most important pollution driver for all substances. Only in the case of NH₃ emissions, the endowment driver provides a relatively substantial contribution (21.6%) to the total volume of emissions, with the corresponding emission flows being associated with land and capital inputs.

Figure C.5: Global emissions in 2023 by air pollutants

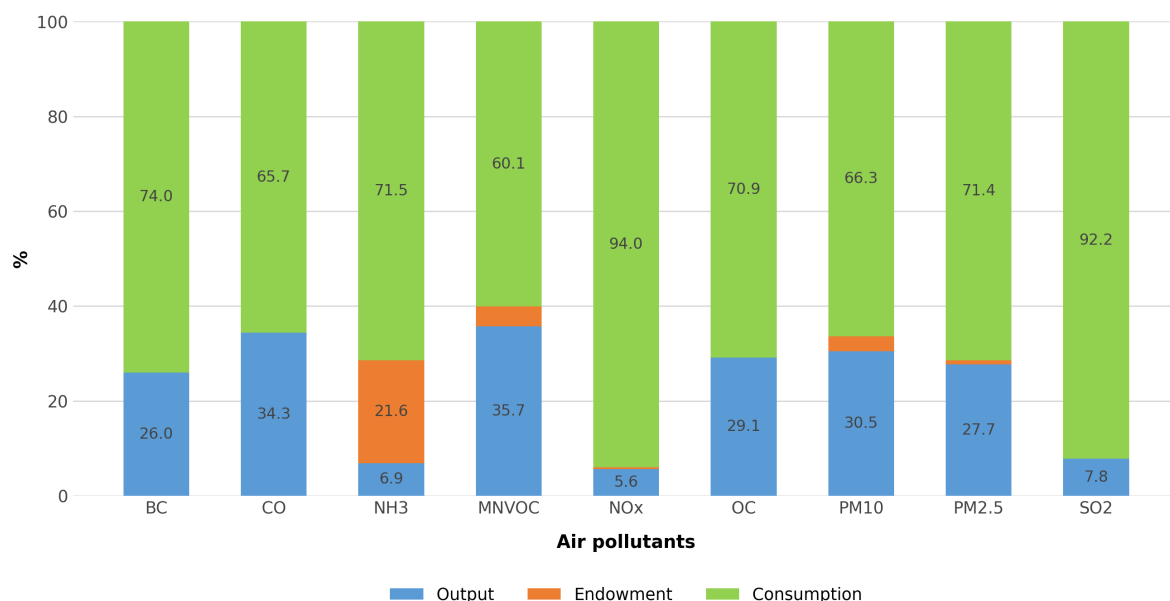


Notes: Emissions from forests and organic soils are not reported on this figure. The red diamond represents the percent changes in emissions in 2023 relative to the 2004 levels.

Source: Estimated by the author based on the EDGAR v8.1 database (Joint Research Centre, European Commission 2024) and the GTAP 12 air pollutant emissions database.

At the sectoral level, key emitters largely vary by air pollutants. Based on the 2023 data, in the case of six pollution categories (BC, CO, NMVOC, OC, PM₁₀ and PM_{2.5}), households are the key contributors, accounting for at least 21% of all emissions (Figure C.7). Electricity generation activity is the largest contributor in the case of SO₂, reaching almost 40%. At the global level, the contribution of the top five key emitting sectors ranges from around 50% (for NMVOC) to 73% (for SO₂ and NO_x) (Figure C.7).

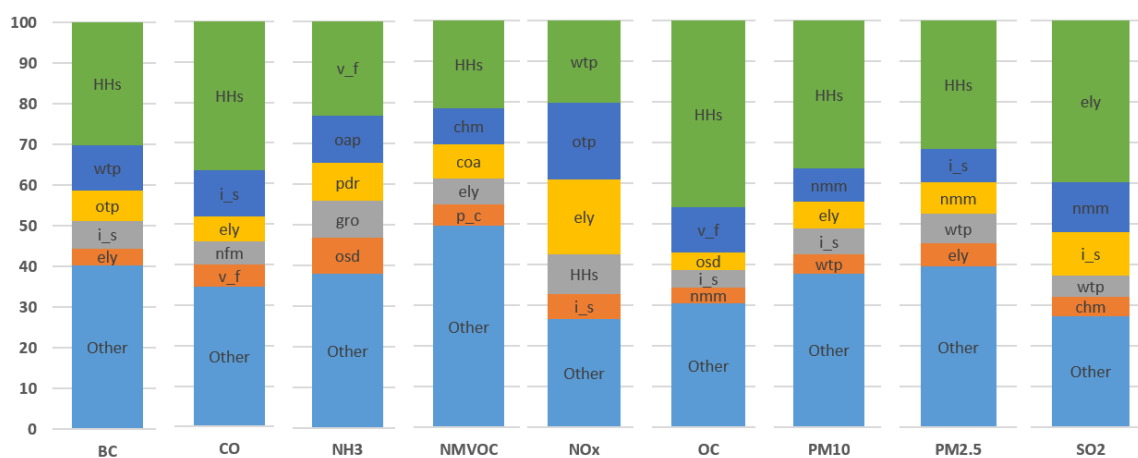
Figure C.6: Global average distribution of air pollutants by source (2004, 2007, 2011, 2014, 2017, 2019 and 2023 weighted average)



Source: Author's estimates based on EDGAR v8.1 database (Joint Research Centre, European Commission 2024) and GTAP 12 air pollutant emissions database.

Note: Emissions from forests and organic soils are not reported in this figure.

Figure C.7: Distribution of global emissions by users in 2023, %



Notes: The top five contributors are explicitly identified for each pollutant; the rest of the users are labeled “Other”. Sectoral labels follow definitions provided at

https://www.gtap.agecon.purdue.edu/databases/v12/v12_sectors.aspx. “HHs” stands for households. Emissions from forests and organic soils are not reported in this figure.

Source: Author's estimates based on the GTAP 12 air pollutant emissions database.

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Appendix

Table C.1: Mapping between EDGAR fossil-based air pollutant emission sources, emission drivers and GTAP sectors

No.	IPCC code	Air pollutant emissions source description	Emission driver	ISIC Rev. 3 code	Comments on sectoral mapping	GTAP 12 use sources mapping	Source for emissions distribution
1	1A1a	Main Activity Electricity and Heat Production	Consumption (coa, oil, gas, gdt, p_c)	40	Mapped to the electricity sector, as heat production in GTAP is part of the electricity sector	ely	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
2	1A1bc	Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries	Consumption (coa, oil, gas, gdt, p_c)	10, 11, 23, 27 (40)	ISIC 40 is excluded as a non-primary source for this category. ISIC 27 emissions are attributed to 1A2 only.	coa, oil, gas, p_c, gdt	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
3	1A2	Manufacturing Industries and Construction	Consumption (coa, oil, gas, gdt, p_c)	15-22, 24-37, 45 (10-14, 23)	ISIC 10-11 and 23 are excluded as non-primary sources, and to avoid overlapping with 1A1bc. ISIC 12-14 are included to complement the sectoral coverage of 1A1a and 1A1bc.	oxt, cmt, omt, vol, mil, pcr, sgr, ofd, b_t, tex, wap, lea, lum, ppp, chm, bph, rpp, nmm, i_s, nfm, fmp, mvh, otn, ele, eeq, ome, omf, cns	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
4	1A3a	Civil Aviation	Consumption (coa, oil, gas, gdt, p_c)	62	1-to-1 correspondence with the GTAP sector	atp	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017) – for domestic aviation; For international aviation, the distribution by regions is based on the value of exports

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No.	IPCC code	Air pollutant emissions source description	Emission driver	ISIC Rev. 3 code	Comments on sectoral mapping	GTAP 12 use sources mapping	Source for emissions distribution
5	1A3b_N ^o	Road transportation (no resuspension)	Consumption (coa, oil, gas, gdt, p_c)	01-99, Household transport	Emissions are attributed to other transportation and households	otp, HHs	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
6	1A3b_RES#	Road transportation (resuspension)	Output		Emissions are linked to road transportation only	otp	
7	1A3c	Railways	Consumption (coa, oil, gas, gdt, p_c)	60	1-to-1 correspondence with the GTAP sector	otp	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
8	1A3d	Water-borne navigation	Consumption (coa, oil, gas, gdt, p_c)	61, 05	While Eurostat (2015) maps ISIC 05 into the 1A3d category, IPCC guidelines (Houghton et al, 1997) exclude fishing from the 1A3d category.	wtp	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017) – for domestic navigation; For international navigation, the distribution by regions is based on the value of exports
9	1A3e	Other transportation	Consumption (coa, oil, gas, gdt, p_c)	60	1-to-1 correspondence with the GTAP sector. Mainly pipeline transport and non-specified transportation.	otp	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
10	1A4	Residential and other sectors	Consumption (coa, oil, gas, gdt, p_c)	01-05, 50-99 (40), Households	ISIC 40 is excluded as a non-primary source. Transport sectors are excluded as non-primary contributors. ISIC 41 is added for water distribution activities coverage	pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk, wol, frs, fsh, wtr, trd, afs, whs, cmn, ofi, ins, obs, rsa, ros, osg, edu, hht, dwe, HHs	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)

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No.	IPCC code	Air pollutant emissions source description	Emission driver	ISIC Rev. 3 code	Comments on sectoral mapping	GTAP 12 use sources mapping	Source for emissions distribution
11	1A5	Non-specified	Consumption (coa, oil, gas, gdt, p_c)	50-99, (40)	ISIC 40 is excluded as a non-primary source. Transport sectors are excluded as non-primary contributors. ISIC 41 is added for water distribution activities coverage	wtr, trd, afs, whs, cmn, ofi, ins, obs, rsa, ros, osg, edu, hht, dwe	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
12	1B1#	Fugitive emissions from solid fuels	Output	10, 23, 27 (24, 26, 40)	Mainly associated with coal, mapped only to ISIC 10 (in line with Irfanoglu and van der Mensbrugghe, 2015)	coa	Direct attribution
13	1B2#	Fugitive emissions from oil and gas	Output	11, 23, 40, 50, (60, 63)	Emission is associated only with ISIC 11, 23 and 40. Due to the highly aggregated trade sector ("trd") in GTAP Data Base, we exclude ISIC 50 code from mapping.	gas, oil, gdt, p_c	Distribute proportionally to output
14	2A1#	Cement production	Output	26		nmn	Direct attribution
15	2A2#	Lime production	Output	26		nmn	Direct attribution
16	2A3#	Glass Production	Output	26			Direct attribution
17	2A4#	Production of other minerals	Output	26		nmn	Direct attribution
18	2B#	Chemical Industry	Output	24	Taking into account GTAP sectoral splits, all emissions are attributed to ISIC 24.1, 24.2	chm	Direct attribution
19	2C#	Metal industry	Output	27		i_s, nfm	Distributed proportionally to output values

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No.	IPCC code	Air pollutant emissions source description	Emission driver	ISIC Rev. 3 code	Comments on sectoral mapping	GTAP 12 use sources mapping	Source for emissions distribution
20	2D#	Non-Energy Products from Fuels and Solvent Use	Consumption of chemical products ("chm")			b_t, lum, ppp, chm, bph, rpp, nmm, i_s, nfm, fmp, ele, eeq, ome, mvh, otn, omf, cns, trd, afs, ros, osg, edu, hht, HHs	Distributed proportionally to the use of chemical products
21	2G#	Other Product Manufacture and Use	Consumption of chemical ("chm") and pharmaceutical ("bph") products			chm, ele, eeq, osg, hht	Distributed proportionally to the use of chemical and pharmaceutical products
22	2H#	Other	Output			ofd, b_t, ppp, omf	Distributed proportionally to output values
23	3A2#	Manure management	Output	01		ctl, oap, rmk	Distributed proportionally to output
24	3C1#	Emissions from biomass burning	Output	01		pdr, wht, gro, v_f, osd, c_b, pfb, ocr	Distributed proportionally to output values
25	3C2#	Liming	Consumption of non-metallic minerals ("nmm")	01		pdr, wht, gro, v_f, osd, c_b, pfb, ocr	Distributed proportionally to the use of non-metallic minerals
26	3C4#	Direct N ₂ O Emissions from managed soils	Consumption of chemical products ("chm")	01		pdr, wht, gro, v_f, osd, c_b, pfb, ocr	Distributed proportionally to chemical products consumption
27	3C7#	Rice cultivation	Output	01		pdr	Direct mapping
28	4A#	Solid waste disposal	Output	75, 90		wtr	Direct mapping
29	4B#	Biological Treatment of Solid Waste	Output	10-45, 90	ISIC 90 is assumed to be key contributor, others are ignored	wtr	Direct mapping

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No.	IPCC code	Air pollutant emissions source description	Emission driver	ISIC Rev. 3 code	Comments on sectoral mapping	GTAP 12 use sources mapping	Source for emissions distribution
30	4C#	Incineration and Open Burning of Waste	Output	01, 10-37, 75, 90, 93	Agricultural sectors are excluded and it is assumed that all agricultural waste burning is associated with 4F	coa, oil, gas, oxt, cmt, omt, vol, mil, pcr, sgr, ofd, b_t, tex, wap, lea, lum, ppp, p_c, chm, bph, rpp, nmm, i_s, nfm, fmp, mvh, otn, ele, eeq, ome, omf, wtr	Distributed proportionally to sectoral output
31	4D#	Wastewater handling	Output	10-45, 90	ISIC 90 is assumed to be the key contributor, others are ignored	wtr	Direct mapping
32	5B#	Fossil fuel fires	Output		Fossil-fuel fires are assumed to be mainly associated with coal mining and oil extraction	coa, oil	Distributed proportionally to sectoral output

Notes: *Authors' assumptions on coding; # indicates IPCC categories with emission distribution based on GTAP value data. The sector correspondence is based on ISIC Rev. 3.1 definitions. Categories shown in square brackets are the corresponding GTAP sector codes. The household category 1A3b is assigned only to petroleum products (p_c), while household emissions under 1A4 are allocated among coal (coa), petroleum products (p_c), natural gas (gas), and gas manufacture and distribution (gdt). For category 1B1 in Africa, emissions are redistributed across the mapped sectors using GTAP value data.

Source: Developed by authors.

Table C.2: Mapping between EDGAR bio-based air pollutant emission sources, emission drivers and GTAP sectors

No.	IPCC code	Air pollutant emissions source description	Emission driver	Comments on sectoral mapping (ISIC 3.1 codes are reported)	GTAP 12 use sources mapping	Source for emissions distribution
1	1A1a	Main Activity Electricity and Heat Production	Consumption (frs, lum)	Mapped to the electricity sector as heat production in GTAP is part of the electricity sector	ely	Distributed proportionally to intermediate consumption
2	1A1bc	Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries	Consumption (frs, lum)	ISIC 40 is excluded as a non-primary source for this category. ISIC 27 emissions are attributed to 1A2 only.	coa, oil, gas, p_c, gdt	Distributed proportionally to intermediate consumption
3	1A2	Manufacturing Industries and Construction	Consumption (frs)	ISIC 10-11 and 23 are excluded as non-primary sources and to avoid overlapping with 1A1bc. ISIC 12-14 are included to complement sectoral coverage of 1A1a and 1A1bc. Output is used as the main driver to avoid instances of non-energy intermediate use in specific sectors (e.g. “frs” and “lum” use in construction industry)	oxt, cmt, omt, vol, mil, pcr, sgr, ofd, b_t, tex, wap, lea, lum, ppp, chm, bph, rpp, nmm, i_s, nfm, fmp, mvh, otn, ele, eeq, ome, omf, cns	Distributed proportionally to intermediate consumption
4	1A3b_NORES	Road transportation (no resuspension)	Consumption (p_c)	Emissions are attributed to Other transportation	otp	Direct attribution
5	1A3b_RE	Road transportation (resuspension)	Output	Emissions are linked to road transportation only	otp	Direct attribution
6	1A3c	Railways	Consumption (p_c)	60	otp	Direct attribution
7	1A3d	Water-borne Navigation	Consumption (p_c)	61, 05; While Eurostat (2015) maps ISIC 05 into 1A3d category, IPCC guidelines (Houghton et al, 1997) exclude fishing from the 1A3d category.	wtp	Direct attribution for domestic transport. For international navigation, the distribution by regions is based on the value of exports

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No.	IPCC code	Air pollutant emissions source description	Emission driver	Comments on sectoral mapping (ISIC 3.1 codes are reported)	GTAP 12 use sources mapping	Source for emissions distribution
8	1A3e	Other transportation	Consumption (p_c)	60; 1-to-1 correspondence with GTAP sector. Mainly pipeline transport and non-specified transportation.	otp	Direct attribution
9	1A4	Residential and other sectors	Consumption (frs)	Literature suggests that in the case of residential and other non-agricultural sectors, the main source of PM _{2.5} bio emissions in the major emitting countries – China, India and Nigeria – is the households' consumption of the solid biomass for cooking and heating purposes (Zhang and Cao, 2015; Nagar et al., 2017; Chowdhury et al., 2019). Therefore, 1A4 emissions are mapped to households' consumption of the solid biomass ('frs') in the GTAP framework.	HHs	Direct attribution
10	1A5	Non-specified	Consumption (frs)	ISIC 40 is excluded as a non-primary source. Transport sectors are excluded as non-primary contributors.	trd, afs, whs, cmn, ofi, ins, obs, rsa, ros, osg, edu, hht, dwe	Distributed proportionally to consumption
11	1B1	Fugitive emissions from solid fuels	Output	Following IPCC (2019), four sources of fugitive emissions for biomass are identified, these include emissions arising during the production of charcoal and biochar, emissions during the production of wood pellets and emissions from the transformation of biomass into syngas, and, then into liquid hydrocarbons fuels.	chm, lum, gdt	Proportionally to output

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No.	IPCC code	Air pollutant emissions source description	Emission driver	Comments on sectoral mapping (ISIC 3.1 codes are reported)	GTAP 12 use sources mapping	Source for emissions distribution
12	1B2	Fugitive emissions from oil and gas	Output	11, 23, 40, 50, (60, 63). Emissions are associated only with ISIC 11, 23 and 40. Due to the highly aggregated trade sector (“trd”) in GTAP Data Base, we exclude ISIC 50 code from mapping.	gas, oil, gdt, p_c	Proportionally to output
13	2C	Production of metals	Output		i_s, nfm	Proportionally to output
14	3C1	Emissions from biomass burning	Output	Allocated to crop sectors	pdr, wht, gro, v_f, osd, c_b, pfb, ocr	Distributed proportionally to sectoral output
15	4C	Incineration and Open Burning of Waste	Output	Agricultural sectors are excluded. It is assumed that all agricultural waste burning is associated with 4F	coa, oil, gas, oxt, cmt, omt, vol, mil, pcr, sgr, ofd, b_t, tex, wap, lea, lum, ppp, p_c, chm, bph, rpp, nmm, i_s, nfm, fmp, mvh, otn, ele, eeq, ome, omf, wtr	Distributed proportionally to sectoral output

Notes: *Authors’ assumptions on coding. Only categories with non-zero emissions for bio-based products are reported.

Source: Developed by authors.

Table C.3: Concordance between GTAP energy dataset industries and GTAP sectors

No.	GTAP energy dataset (EDS) use flows	Use flow names
1	Exp	Export
2	IntlMarBnkr	International marine bunkers
3	IntlAvBnkr	International aviation bunkers
4	Elect_Gen	Electricity generation
5	P_C_Transfm	Petroleum and coal transformation
6	Gas_Transfm	Gas transformation
7	Coal	Coal mines
8	CrudeOils	Crude oil
9	NatGas	Natural gas
10	IronXSteel	Iron and steel
11	ChemXPetro	Chemical and petrochemical
12	FidStok4CRP	Petrochemical feed-stocks
13	NonFeroMetal	Non-ferrous metals
14	NonMetalMinr	Non-metallic minerals
15	TranspEqpmt	Transport equipment
16	MachineryMf	Machinery
17	MiningXQuary	Mining and quarrying
18	FoodXTabaco	Food and tobacco
19	PapXPulpXPrn	Paper, pulp and printing
20	WoodXWudProd	Wood and wood products
21	ConstctnInd	Construction
22	TextlXLether	Textile and leather
23	NonSpecfInd	Non-specified industry
24	DomAviaTrnsp	Domestic air transport
25	RoadTransp	Road transport
26	RailTransp	Rail transport
27	PipelnTransp	Pipeline transport
28	HomeOwnShips	Internal navigation
29	NonSpecTrnsp	Non-specified transport
30	AgriForFish	Agriculture, forestry and fishery
31	ComXPubServ	Commercial and public services
32	HouseHolds	Households
33	MilitaryUse	Military use

Source: Based on IEA 2017; Chepeliev 2026.

Table C.4: Concordance between disaggregated GTAP energy dataset (EDS) commodities and aggregated energy commodities reported in the standard GTAP Data Base

No.	GTAP EDS commodity code	GTAP EDS commodity description	Corresponding aggregated GTAP energy commodity
1	AntCoal	Anthracite	coa
2	CokCoal	Coking coal	coa
3	BitCoal	Other bituminous coal	coa
4	SubCoal	Sub-bituminous coal	coa
5	Lignite	Lignite	coa
6	PatFuel	Patent fuel	coa
7	OvenCoke	Coke oven coke	p_c
8	GasCoke	Gas coke	p_c
9	CoalTar	Coal tar	p_c
10	BKB	Brown coal briquettes	coa
11	GasWksGs	Gas works gas	gas
12	CokeOvGs	Coke oven gas	p_c
13	BlFurGs	Blast furnace gas	p_c
14	OGases	Other recovered gases	p_c
15	Peat	Peat	coa
16	PeatProd	Peat products	coa
17	OilShale	Oil shale and oil stands	oil
18	NatGas	Natural gas	gas
19	CrudeOil	Crude oil	oil
20	NGL	Natural gas liquids	gas
21	RefFeeds	Refinery feedstocks	p_c
22	Additive	Additives/blending components	crp
23	NonCrude	Other hydrocarbons	crp
24	RefinGas	Refinery gas	p_c
25	Ethane	Ethane	p_c
26	LPG	Liquefied petroleum gases	p_c
27	NonBioGaso	Motor gasoline excluding bio	p_c
28	AvGas	Aviation gasoline	p_c
29	JetGas	Gasoline type jet fuel	p_c
30	NonBioJetK	Kerosene type jet fuel excl. bio	p_c
31	OthKero	Other Kerosene	p_c
32	NonBioDies	Gas/diesel oil excluding bio	p_c
33	ResFuel	Fuel oil	p_c
34	Naphtha	Naphtha	p_c
35	WhiteSp	White spirit and industrial spirit (SPB)	p_c
36	Lubric	Lubricants	p_c
37	Bitumen	Bitumen	p_c
38	ParWax	Paraffin waxes	p_c
39	PetCoke	Petroleum coke	p_c
40	ONonSpec	Non-specified oil products	p_c
41	Electr	Electricity	ely
42	Heat	Heat	ely

Source: Based on IEA 2017; Chepeliev 2026.

Table C.5: Correspondence between IPCC categories and GTAP energy dataset commodities

IPCC category code	IPCC category description	GTAP EDS use flow code	GTAP EDS use flow description
1A3a	Civil aviation (country dimension)	DomAviaTrnsp	Domestic air transport
1A3a	Civil aviation (international bunkers)	IntlAvBnkr	International aviation bunkers
1A3c	Rail transportation	RailTransp	Rail transport
1A3d	Water-borne navigation (by country)	HomeOwnShips	Internal navigation
1A3d	Water-borne navigation (international bunkers)	IntlMarBnkr	International marine bunkers
1A3e	Other transportation	PipelnTransp	Pipeline transport
		NonSpecTrnsp	Non-specified transport

Source: Author.

Table C.6: Correspondence between air pollutants with available emission factors and EDGAR dataset air pollutants

No.	EDGAR database pollutants	EDGAR database pollutant name	Air pollutants with available emission factors	Emission factors source
1	BC	Black carbon	PM _{2.5} + estimates of the BC share	Klimont (2007), Chow et al. (2011) and EEA (2019), Coady et al. (2015)
2	CO	Carbon monoxide	CO	IPCC (2017)
3	NH ₃	Ammonia	NH ₃	Battye et al. (1994)
4	NMVOC	Non-methane volatile organic compounds	Volatile organic compounds (VOCs)	Coady et al. (2015)
5	NO _x	Nitrogen oxides	NO _x	Coady et al. (2015)
6	OC	Organic carbon	PM _{2.5} + estimates of the OC share	Klimont (2007), Chow et al. (2011) and EEA (2019), Coady et al. (2015)
7	PM ₁₀	Particulate matter 10	PM _{2.5}	Coady et al. (2015)
8	PM _{2.5}	Particulate matter 2.5	PM _{2.5}	Coady et al. (2015)
9	SO ₂	Sulfur dioxide	SO ₂	Coady et al. (2015)

Source: Author.

Table C.7: Correspondence between IPCC combustion-related categories in the IPCC emission factor database and GTAP sectors

No.	IPCC category code	IPCC category description	Fossil fuel combustion emission factors data availability for CO	GTAP use categories
1	1A	Fuel combustion activities	-	-
2	1A1	Energy industries	+	coa, oil, gas, p_c, ely, gdt
3	1A2	Manufacturing industries and construction	+	oxl, cmt, omt, vol, mil, pcr, sgr, ofd, b.t, tex, wap, lea, lum, ppp, chm, bph, rpp, nmm, i.s, nfm, fmp, mvh, otn, ele, eeq, ome, omf, cns
4	1A3A	Civil aviation	+	atp
5	1A3A1	International aviation (international bunkers)	-	-
6	1A3A2	Domestic aviation	-	-
7	1A3B_NORES	Road transportation (no resuspension)	+	otp
8	1A3C	Railways	+	otp
9	1A3D	Navigation	+	wtp
10	1A4A	Commercial/institutional	+ (database provides identical emission factors for all three IPCC categories)	wtr, trd, afs, whs, cmn, ofi, ins, obs, rsa, ros, osg, edu, hht, dwe
11	1A4B	Residential		HHs
12	1A4C1	Stationary emission in agriculture/forestry/fishing		pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk, wol, frs, fsh
13	1A4C2	Off-road vehicles and other machinery emissions in agriculture/-forestry/fishing	-	-
14	1A5B	Other mobile emissions	+	-

Source: Based on IPCC 2017.

Table C.8: Correspondence between IPCC database fuels and six energy commodities for air pollutant emission estimates

No	IPCC database fuel code	IPCC fuel code description	Air pollutant emissions database fuels
1	111	Wood/wood waste	-
2	112	Charcoal	-
3	205	Diesel oil	Diesel (“dsl”)
4	208	Motor gasoline	Gasoline (“gsl”)
5	301	Natural gas*	Gas extraction and distribution (“gas”, “gdt”)
6	302	Natural gas liquids*	-
7	318	Other bituminous coal*	-
8	322	Other oils	Oil (“oil”)
9	329	Other solid biomass	-
10	S01	Undifferentiated coal*	Coal (“coa”)

Notes: *Natural gas (301) and Natural gas liquids (302), as well as Other bituminous coal (318) and Undifferentiated coal (S01) have identical emission factors. Therefore, for the mapping purposes only one representative product from each pair is used.

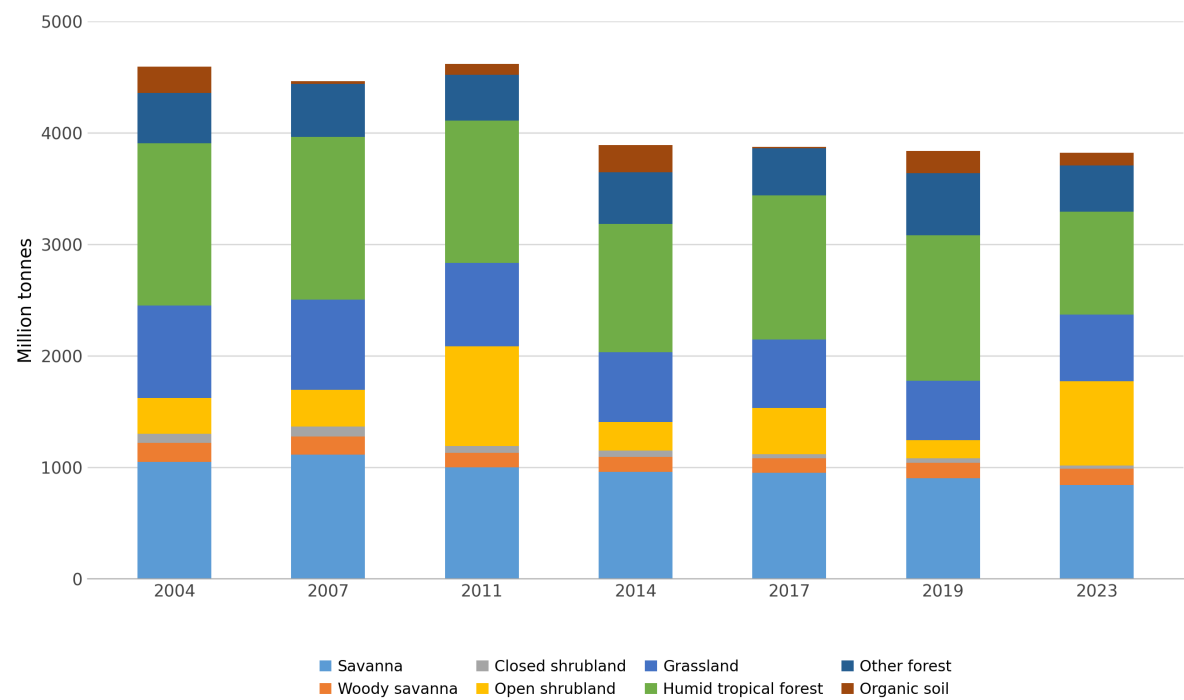
Source: Based on IPCC 2017.

Table C.9: IPCC correspondence for additional air pollutants redistribution between GTAP users and drivers

No.	IPCC pollution categories with cases of zero-energy use data in the GTAP Data Base and non-zero emissions in the EDGAR database		IPCC pollution categories used for emissions redistribution	
1	X1A3a	Domestic aviation	X1A4	Residential and other sectors
2	X1A1a	Main Activity Electricity and Heat Production	X1A4	Residential and other sectors
3	X1A3d	Inland navigation	X1A4	Residential and other sectors
4	X1A1bc	Other energy industries	X1A2	Manufacturing Industries and Construction
5	X1A3c	Rail transportation	X1A3b_NORES	Road transportation (no resuspension)
6	X1A3e	Other transportation	X1A3b_NORE	Road transportation (no resuspension)

Source: Author.

Figure C.10.1: Biomass burned (dry matter) by land cover types and years, million tonnes



Source: FAO 2025.

Table C.10.1: Emission factors for biomass burning (dry matter), g kg⁻¹

No.	Pollutant	Pollutant name	Organic soils	Humid tropical forest	Other forest	Closed shrubland	Grassland	Open shrubland	Savanna	Woody savanna
1	BC	Black carbon	0.20	0.52	0.56	0.2	0.37	0.2	0.37	0.37
2	CO	Carbon monoxide	182.00	93.00	122.00	67	63	67	63	63
3	NH ₃	Ammonia	10.80	1.33	2.46	1.03	0.52	1.03	0.52	0.52
4	NM VOC	Non-methane volatile organic compounds	48.70	26.00	27.00	6	12.4	6	12.4	12.4
5	NOx	Nitrogen oxides	0.80	2.55	1.12	3.26	3.9	3.26	3.9	3.9
6	OC	Organic carbon	6.23	4.71	9.15	3.7	2.62	3.7	2.62	2.62
7	PM ₁₀	Particulate matter 10	44.00*	18.50	30.49*	18.3*	7.2	18.3	7.2	11.4
8	PM _{2.5}	Particulate matter 2.5	19.17*	9.10	15.00	11.9	7.17	11.9	7.17	7.17
9	SO ₂	Sulfur dioxide	1.76*	0.40	1.06*	0.68	0.48	0.68	0.48	0.48

Notes: Emission factors (EFs) not marked by “*” are sourced from Akagi et al. 2011. For the Other forest category, the Extratropical forest EFs are used; these represent a weighted average of boreal and temperate forest EFs. SO₂ EFs for Organic soils and Other forest are from Yokelson et al. 2013. PM₁₀ and PM_{2.5} EFs for Organic soils are from Hu et al. 2018, using estimates for boreal and temperate peat. The PM₁₀ EF for Other forest is derived from the PM_{2.5} EF using the same particulate composition as Humid tropical forest. The Savanna EF is applied to Savanna, Woody savanna, and Grassland; the Shrubland EF is based on Chaparral. The PM₁₀ EF for Shrubland is from California Air Resources Board 2025, while the corresponding values for Savanna, Woody savanna, and Grassland are from Liu et al. 2024.

Source: Based on Akagi et al. 2011; Yokelson et al. 2013; Hu et al. 2018; California Air Resources Board 2025; Liu et al. 2024.

Table C.10.2: Emissions from biomass burning in 2023, million metric tons

No.	Pollutant	Humid tropical forest	Other forest	Organic soil	Closed shrubland	Grassland	Open shrubland	Savanna	Woody savanna
1	BC	479.2	228.7	23.2	5.9	221.5	150.7	311.2	53.9
2	CO	85701.4	49819	21116.2	1966.1	37706.6	50496.9	52995.2	9177.3
3	NH ₃	1225.6	1004.5	1253	30.2	311.2	776.3	437.4	75.7
4	NM VOC	23959.5	11025.5	5650.3	176.1	7421.6	4522.1	10430.8	1806.3
5	NO _x	2349.9	457.4	92.8	95.7	2334.2	2457	3280.7	568.1
6	OC	4340.4	3736.4	722.8	108.6	1568.1	2788.6	2203.9	381.7
7	PM ₁₀	17048.1	12450.7	5105	537	4309.3	13792.4	6056.6	1660.7
8	PM _{2.5}	8385.8	6125.3	2224.2	349.2	4291.4	8968.8	6031.4	1044.5
9	SO ₂	368.6	432.9	204.2	20	287.3	512.5	403.8	69.9

Source: Estimated by author.