MEIC-global-CO_2: a new global CO_2 emission inventory with highly-resolved source category and sub-country information

Ruochong Xu[1], Dan Tong[1], Qingyang Xiao[1], Xinying Qin[1], Cuihong Chen[1], Liu Yan[1], Jing Cheng[1], Can Cui[1], Hanwen Hu[2], Wenyu Liu[1], Xizhe Yan[1], Huaxuan Wang[2], Xiaodong Liu[2], Guannan Geng[2], Yu Lei[3], Dabo Guan[1], Kebin He[2,4], and Qiang Zhang[1,*]

[1]Department of Earth System Science, Ministry of Education Key Laboratory for Earth System Modeling, Institute for Global Change Studies, Tsinghua University, Beijing 100084, People's Republic of China
[2]State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, People's Republic of China
[3]Chinese Academy of Environmental Planning, Beijing, People's Republic of China
[4]Institute for Carbon Neutrality, Tsinghua University, Beijing 100084, People's Republic of China

*corresponding author: qiangzhang@tsinghua.edu.cn

Abstract

CO_2 emission inventory provides fundamental data for climate research and emission mitigation. Currently, most global CO_2 emission inventories were developed with energy statistics from International Energy Agency (IEA) and were available at country level with limited source categories. Here, as the first step toward a high-resolution and dynamic updated global CO_2 emission database, we developed a data-driven approach to construct seamless and highly-resolved energy consumption data cubes for 208 countries/territories, 797 sub-country administrative divisions in 29 countries, 42 fuel types, and 52 sectors, with the fusion of activity data from 24 international statistics and 65 regional/local statistics. Global CO_2 emissions from fossil fuel combustion and cement production in 1970-2021 were then estimated with highly-resolved source category (1,484 of total) and sub-country information (797 of total). Specifically, 72% of global CO_2 emissions in 2021 were estimated with sub-country information, providing considerably improved spatial resolution for global CO_2 emission accounting. With the support of detailed information, the dynamics of global CO_2 emissions across sectors and fuel types were presented, representing the evolution of global economy and progress of climate mitigation. Remarkable differences of sectoral contribution were found across sub-country administrative divisions within a given country, revealing the uneven distribution of energy and economic structure among different regions. Our estimates were generally consistent with existing databases at aggregated level for global total or large emitters, while large discrepancies were observed for middle and small emitters. Our database, named the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC) is publicly available through http://meicmodel.org.cn with highly-resolved information and timely update, which provides an independent carbon emission accounting data source for climate research.

Keywords

CO_2 emissions, data-driven approach, highly-resolved source category, sub-country information

1. Introduction

Anthropogenic carbon dioxide (CO_2) emissions have been firmly demonstrated as the main driver of modern climate change [1,2], which negatively affects ecosystems [3], settlements [4], infrastructure [5], and human lives [6]. As the fundamental database for climate research and emission mitigation, global past-to-present CO_2 emission inventories with bottom-up information support various relevant studies such as accumulative human impacts [1], assessment of carbon budgets [2], development of future scenarios [7,8], assessment of mitigation efforts [9,10], and targeted policymaking [11] etc.

Several global CO_2 emission inventories have been developed [2,12-19], providing global CO_2 emission trends starting from around 1960s-1970s with a few exceptions extended back to pre-industrial time [13,16], and are mostly updated annually to the year before last or the previous year. A few of those inventories are developed based on bottom-up estimates using International Energy Agency (IEA) or United Nation (UN) energy statistics as primary data source of activity rates [20,21], such as the Emissions Database for Global Atmospheric Research (EDGAR) [19], IEA database [12], and Carbon Dioxide Information Analysis Center (CDIAC) database [13]. In contrast, other inventories are built upon existing bottom-up inventories and used data integration approach to improve region- or source-specific accuracy. For example, the Global Carbon Project (GCP) database [2] integrates the CDIAC database [13], United Nations Framework Convention on Climate Change (UNFCCC) national inventory [15], BP statistics [14], and a bottom-up emission inventory for cement production [22]. Despite the differences of methodologies and underlying data, current emission inventories generally agree well on overall magnitudes and trends at global level [23].

However, current global CO_2 emission inventories are still subject to several important limitations in the following aspects. First, most inventories were developed based on the global energy statistics from IEA, which are generally of high quality for developed countries but less accurate for many developing countries and emerging economies. For example, energy consumption between IEA and local statistics can differ by 10% in specific years for China and India [24,25]. Second, while PKU-CO_2 emission inventory integrates sub-national statistics in 45 countries [18], all global CO_2 inventories are presented at country level and lack of sub-country information. Given remarkable emission heterogeneity within a country (especially for large emitters) [26-28], the coarse spatial resolution may further impact the accuracy of gridded emissions when using country totals as the start point. Last, most inventories (except CEDS which provides 27 sectors and 8 fuel types [16]) are available with highly aggregated information on sectors and fuel types, which hinders the comprehensive cross-validation of data and prevent the in-depth analysis of CO_2 emitting sources.

To provide an open-access consistent time series of global CO_2 emissions with detailed sector, fuel type, and sub-country information, here we develop a new global CO_2 emission database, the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC). MEIC model is a bottom-up emission model which was initially developed for estimating anthropogenic emissions in China [28], and it is upgraded to global scale in this work. As the first step toward a high-resolution and dynamic updated global CO_2 emission database, we developed a data-driven approach to harmonize activity data from 24 international statistics and 65 regional/local statistics

and construct seamless and highly-resolved activity data cubes for 208 countries/territories, 797 sub-country administrative divisions in 29 countries, 42 fuel types, and 52 sectors. Global CO_2 emissions from fossil fuel combustion and cement production in 1970-2021 were then estimated with highly-resolved source category (1,484 of total) and sub-country information (797 of total). Specifically, 72% of global CO_2 emissions in 2021 were calculated based on sub-country information, representing considerable improvements on spatial resolution. The new global CO_2 emission inventory, named MEIC-global-CO_2, is publicly available through http://meicmodel.org.cn with highly-resolved information and timely update, which can be used to support various climate research and emission mitigation assessments.

The details of methodology and data are described in Section 2. In Section 3, we present highly-resolved and multi-dimensional dynamics of global CO_2 emissions in 1970-2021, reveal the evolution of emissions driven by global economic growth and climate mitigation, and explore remarkable sub-country heterogeneity of CO_2 emissions in large emitters owing to uneven distribution of energy and economic structures. In Section 4, comprehensive comparisons with other global databases are presented, along with discussions on the uncertainties and limitations of MEIC-global-CO_2 database. Concluding remarks and insights on future work are presented in Section 5.

2. Methods and data

2.1 Methodological overview

The methodological framework of the MEIC-global-CO_2 database are presented in Fig.1. Emissions from fossil fuel combustion and cement production were classified into 1,484 source categories from the combination of 52 sectors and 42 fuel types. Activity rates of each country were collected from a series of international statistics or databases such as IEA energy statistics [12], BP energy statistics [14], and World Road Statistics [29] etc. Activity rates of China and 30 emerging economies were overridden by two existing regional emission databases, the Multi-resolution Emission Inventory for China (MEIC-China) [28] and the Carbon Emission Accounts and Datasets (CEADs) [25], respectively. Activity rates for sub-country administrative divisions in 29 countries are collected from MEIC-China, CEADs (20 emerging economies), and local statistics from eight countries (see SI for details).

A data-driven approach is developed to integrate all the data above into a unified framework and generate seamless and highly-resolved data cubes of activity rates for 208 countries/territories, 797 sub-country administrative divisions, 42 fuel types, and 52 sectors. We first develop a series of mapping procedures to harmonize the sector, fuel type, and country information from different data sources to a unified definition of source categories and countries. Activity data for each source category and country are then fulfilled by international statistics and then overridden by MEIC-China and CEADs for China and another 30 emerging economies. Sub-country data collected from MEIC-China, CEADs, and local statistics are then used to downscale activity rates of 29 countries from national total to sub-country administrative divisions. To fill the gap of temporal coverage in different statistics, a step-by-step approach is used to extrapolate the full time-series data for the period of 1970-2021. Finally, CO_2 emissions by source and country/sub-country administrative division are estimated by using CO_2 emission factors collected from international databases and

local literatures.

2.2 Source category

MEIC-global-CO_2 covers 1,484 anthropogenic sources of fossil fuel combustion and cement industry from the combination of 52 sectors and 42 fuel types. Definition of the source categories is presented in Table S1 and S2. The total number of source categories is smaller than the product of sector and fuel types because some sectors only consume selected type of fuels. The sector definition conforms to the category classification in the IPCC 2006 Guideline (IPCC GL) [30]. The major five sectors (i.e., energy production, manufacturing industries and construction, transport, commercial, residential, and other non-specified, and industrial process) are corresponding to IPCC GL category codes 1A1-1A5 and 2A1, as shown in Table S1. The detailed 52 sectors are also compatible with IPCC GL definitions with refined classification beyond the IPCC GL to improve the sectoral resolution. For instance, the transformation industries of energy production (IPCC GL 1A1b and 1A1c) are further divided into 15 detailed sectors; non-metallic mineral industry (IPCC GL 1A2f) is separated into cement industry and other non-metallic mineral industry; road transport (IPCC GL 1A3b) is distinguished by vehicle category based on a fleet-based model (see Section 2.4.1); residential sector (IPCC GL 1A4b) is separated into urban and rural. The 42 fuel types cover different types of coal, oil, natural gas, as well as other fossil fuels such as oil shale. Biofuels are not included here because their combustion emits short-cycle carbon that is generally reported under the Agriculture, Forestry and Land Use (AFOLU) sector [19].

2.3 Definition of countries and territories

MEIC-global-CO_2 include 208 countries/territories. The detailed list along with their mapping to the ISO-3166 country codes is presented in Table S3. Following the country definition in other global emission inventories [2,16,19], we define the countries/territories based on current global country patterns. For those countries that historically existed but have been disintegrated (e.g., the Former Soviet Union and Former Yugoslavia, see Table S4 for the complete list), we map the activity rates to their successor countries for the years they were still existed (see Section 2.5). A few small countries/territories, mainly remote islands, are not included in MEIC-global-CO_2 due to data availability (See Table S5).

2.4 Data sources of activity rates

2.4.1 Country-level activity rates

The country-level activity rates for fossil fuel combustion are primarily obtained from IEA energy statistics (2022 edition) [12], which cover 45 sectors and 42 fuel types from 1960 to 2020 for 38 Organization for Economic Co-operation and Development (OECD) countries and from 1971 to 2020 for 112 non-OECD countries/territories and 3 aggregated regions (i.e., Other Africa, Other non-OECD Americas, and Other non-OECD Asia). The BP Statistical Review of World Energy 2022 is used [14] to extrapolate activity rates to the year 2021, which includes energy consumption of coal, oil, and natural gas in 1965-2021 for 82 countries/territories and 12 aggregated regions. The

country-level activity rates of cement production are derived from the United States Geological Survey (USGS) Mineral Yearbooks [31]. The mapping table between 45 sectors in IEA statistics and 52 sectors in MEIC-global-CO_2 is provided in Table S6. Despite mostly directly-mapped sectors, fuel consumption of other non-metallic mineral industry is obtained by deducting the fuel consumption of cement industry (which is provided by a facility-level database as described in Section 2.5.5) from total non-metallic mineral industry in IEA statistics. Activity rates of road transport and residential sectors are derived as described below.

Activity rates for road transport in 1970-2021 are obtained from a fleet-based approach constrained by country-level fuel consumption in IEA statistics [20]. In MEIC-global-CO_2, on-road vehicles are classified into five categories: car, bus, light-duty truck, heavy-duty truck, and motorcycle. Vehicle population by category for each country are obtained from the World Road Statistics (WRS) [29] and statistics from the International Organization of Motor Vehicle Manufacturers (OICA) [32] and supplemented by local statistics for large economies [33-35]. Fuel consumption by each vehicle category and country is then estimated by using vehicle population, fuel shares, vehicle mileage traveled, and fuel economy [36], and is constraint by IEA statistics at country level.

Residential energy consumption in IEA statistics is divided into urban and rural consumption by using country-level urban-to-rural energy consumption ratios derived from multiple linear regression models. We first sample the coal, oil, and gas consumption in countries and years with urbanization rate higher than 85% and lower than 15% from IEA statistics to represent the residential energy consumption in urban and rural regions, respectively (i.e., dependent variables). Next, heating degree days (HDD), urbanization rates, and GDP per capita, which are widely used as predictors of residential energy consumption in previous studies [37], are included as independent variables to build the urban and rural multiple linear regression models, respectively. Then the fitted models are applied to each country and each year to predict the residential energy consumption in urban and rural regions, further deriving the urban-to-rural energy consumption ratios. More details about the urban-to-rural splitting are described in Text S1.

Remarkable discrepancies between energy consumption data in IEA statistics and national statistics were observed for many developing countries such as China [24], India [25], and Russia [27] etc. In this work, we use activity data in two regional CO_2 emission databases to override the data for some developing countries. Specifically, activity data in MEIC-China compiled from China Energy Statistical Yearbook [38] are used to derive energy consumption by sector and fuel type, and CEADs database is used to obtain activity data for 30 emerging economies as listed in Table S7 [25]. CEADs provides activity rates of fossil fuel combustion for 47 sectors and 8 fuel types for the period of 2010-2018, which were originally obtained from various energy statistics of regional research centers (e.g., African Energy Commission [39] and Economic Research Institute for ASEAN and East Asia [40]) and national statistics bureaus (see Table S7 for details). Detailed comparisons between CEADs and IEA statistics confirm the higher quality of local energy statistics in many emerging economies [25].

2.4.2 Sub-country information

MEIC-global-CO_2 integrates activity data of 797 sub-country administrative divisions in 29 countries as shown in Table S8. Sub-country data for China were obtained from MEIC-China, which

provides activity rates of 31 provinces in mainland China derived from province-level energy balances in China Energy Statistical Yearbook [38]. CEADs includes activity rates of about 600 sub-country administrative divisions in 20 emerging economies (i.e., Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Estonia, Ethiopia, Ghana, Guatemala, India, Indonesia, Kenya, Mongolia, Peru, Russia, South Africa, Tanzania, Turkey, and Uganda). In CEADs, sub-country activity rates are compiled from regional, national, and provincial/state-level statistics, or downscaled by relevant proxies, e.g., industrial production for energy consumption in industrial sectors [25]. Activity rates of ~150 sub-country administrative divisions in 8 large emitters are integrated from national statistics in the United States [41-43], Canada [44], Germany [45], the United Kingdom [46,47], France [48], Italy [49], Australia [50,51], and Saudi Arabia [52] (See Table S9 for details).

2.5 Data fusion for seamless data cubes of activity rates

Seamless data cubes of activity rates with source categories defined in this work are generated using a data-driven approach which fuses the data from 24 international statistics and 65 regional/local statistics as described above. The data fusion approach includes the following procedures: harmonization of country definition, integration of regional databases, downscaling of sub-country statistics, reconstruction of time series, and reconciliation with facility-level database. The generated data cubes cover activity rates of 52 sectors and 42 fuel types (plus cement production) for 208 countries/territories and 797 sub-country administrative divisions in 29 countries over the period of 1970-2021. The data cubes are then used to develop MEIC-global-CO_2 emission inventory with highly-resolved source category and sub-country information.

2.5.1 Harmonization of country definition

Since 1970, 27 new countries have been created as a result of dissolution and independence movements. For a given year in the IEA statistics, energy consumption data are presented by country that existed in that year. For example, energy data for the Former Soviet Union are presented as a whole before 1991 and then split to 15 countries after that. In the MEIC-global-CO_2 database, country definition is based on the countries that existed in the year of 2021. For the years when the country had not yet existed, activity rates are split or merged from the energy data of its predecessor using the sector- and fuel-specific shares in the year when the successor countries were created. Detailed mapping of current countries and their predecessors is presented in Table S4.

For 62 small countries in the MEIC-global-CO_2 database, energy data are provided as lumped regional totals in the IEA statistics. The lumped total data are then proportionally disaggregated to each country using sector-specific parameters that are closely related to energy consumption, such as industrial production [53], sectoral value added [54], industrial GDP [55], and population [56]. Table S10 provides the details of the parameters used for the dissaggreation.

2.5.2 Integration of regional databases

As discussed in Sect. 2.4.1, activity rates from MEIC-China and CEADs are used to override the IEA statistics for China and 30 emerging economies respectively, to better represent the actual energy consumption in developing countries. Given that the definition of sector/fuel type is quite different between IEA statistics and the two regional databases, the sectors and fuel types in MEIC-China and CEADs are mapped to the 45 sectors and 42 fuel types in IEA statistics, respectively. The

sector- and fuel-specific mapping tables between IEA and the two regional databases are presented in Table S11-S14. Following the mapping tables, activity rates for China and 30 emerging economies are overridden by MEIC-China and CEADs for the years when the two databases are available.

2.5.3 Downscaling of sub-country activity rates

Sub-country activity rates in MEIC-China and CEADs are then used to obtain the spatial variabilities of activity rates within the country, following the sector- and fuel-specific mapping procedures described above. In MEIC-China, the sums of sub-country activity rates by source are consistent with country-level data. While CEADs provides activity rates for both country total and sub-country level, the sums of sub-country data are not always consistent with the country total [25]. In this case, we downscale the activity rates of country total to sub-country administrative divisions using the normalized proportional shares of sub-country activity rates to the country total.

For the other 8 large emitters, we first map the collected local energy data to the sector and fuel type in IEA statistics, and then downscale the national total activity rates in IEA statistics to sub-country level using the proportional shares from local statistics. The detailed mapping procedures are provided in Table S15-S16. For the sectors and fuel types which are missing from local statistics, proxies at sub-country level that represent the relevant energy consumption (e.g., industrial production) are used for downscaling, and the mappings between the proxies and related activity rates are also summarized in Table S15-S16.

2.5.4 Reconstruction of time series

As the temporal coverage from different data sources are always incomplete for the whole period of 1970 to the present, time series reconstruction is necessary for deriving a seamless and consistent activity rates across countries, sub-country administrative divisions, and source categories. In this work, the following steps are implemented to obtain the full time series of data.

In IEA statistics, activity rates in non-OECD countries were available since 1971. The sector- and fuel-specific growth rates between 1971-1972 were used to extrapolate activity rates in 1970. IEA energy data in earlier years (1970-1977) was provided by aggregated fuel types. To be consistent with later years' data, fuel consumption by aggregated fuel types are disaggregated into detailed fuel types by using fuel consumption in 1978 when detailed fuel type data are available.

For China, activity rates during 1990-2020 are obtained from MEIC-China. For the years before 1990, we use the trend in IEA statistics but calibrate the 1990 data to MEIC-China to get a consistent time series. Similarly, activity rates of the 30 emerging economies are obtained from CEADs for the period of 2010-2018 and then extrapolated to 1970-2020 using the trend in IEA statistics. Sub-country activity rates for the 29 countries are also incomplete. The data for the whole period of 1970-2020 follow the trends of the full time series data at country level as constraints, assuming that the shares of sub-country activity rates in data-missing years keep consistent to the nearest year with data.

Finally, fuel-specific growth rate of fuel consumption in 2020-2021 are obtained from the BP Statistical Review of World Energy 2022 [14] and used to derive the activity rates in the year of 2021. The countries/territories and fuel types in the BP statistics are first mapped to those defined in this work before extrapolating. The mapping tables are presented in Table S17.

2.5.5 Reconciliation with facility-level database

As emerging efforts towards a high-resolution global emission inventory, in previous work, we developed a bottom-up facility-level emission database for global thermal power, iron and steel, and cement industries [57-59]. The facility-level database, which is named the Global Infrastructure Emission Database (GID, http://gidmodel.org.cn/), includes energy use and CO_2 emissions for 101,607 thermal power units, 3,234 iron and steel plants, and 4,196 cement plants globally. The detailed methodologies for developing global emissions at facility level are presented in previous studies [57-59]. Although the bottom-up information in GID is not included in MEIC-global-CO_2, it is worth noting here that the country-level and sub-country activity rates in MEIC-global-CO_2 are used to constrain the facility-level activity rates in GID for each country/sub-country administrative division, which ensures the data consistency between the two databases.

2.6 CO_2 emission estimates

CO_2 emissions for each source are estimated using the following equation:

$$Emis_{s,f,j,y} = A_{s,f,j,y} \times EF_{s,f,j,y} = \ A_{s,f,j,y} \times H_{s,f,j,y} \times CA_{s,fj} \times O_{s,f,j} \times \frac{44}{12} \quad (1)$$

Where s, f, j and y represent sector, fuel type, country/sub-country administrative division, and year, respectively; $Emis$ represents the CO_2 emissions; A represents the activity rates; EF represents the CO_2 emission factor (kt/kt for solid and liquid fuels, kt/m^3 for gaseous fuels); H represents the heating value (GJ kt^{-1} for solid and liquid fuels, GJ m^{-3} for gaseous fuels); CA represents the carbon content (ktC GJ^{-1}); O represents the carbon oxidation factor (unitless); 44/12 is the molecular weight ratio of CO_2 to carbon.

Country-specific heating values for each fuel type obtained from IEA World Conversion Factor database [20] are used as global defaut for *H*. Fuel-specific carbon contents (*CA*) are derived from the recommended values from IPCC GL [30]. The fuel-specific oxidation factor (*O*) followed the values in CDIAC database [13,60]. For process emissions in cement industry, CO_2 emission factors per unit clicker produced for different kilns are obtained from an emission inventory for cement production included in the GCP database [22,61]. More details on the parameters are presented in Supplementary Data.

For China, fuel-specific heating values and carbon contents are obtained from CEADs [62,63], which are based on the measurements of over 4,000 coal mine samples in China. The sector- and combustion-technology-specific oxidation factors are obtained from the Guidelines for Provincial Greenhouse Gas Inventory [64]. For the 30 emerging economies in CEADs, CO_2 emission factors are preferentially collected from local sources such as national submissions in UNFCCC [15], and recommended values in IPCC GL are used when local data are unavailable [30]. The detailed sources of CO_2 emission factors in CEADs are shown in Table S7.

3. Results

3.1 Dynamics of global CO_2 emissions across fuel types and sectors

Figure 2a and S1 present the evolution of global CO_2 emissions by fuel type and sector. Globally, anthropogenic CO_2 emissions increased from 14.0 Gt to 34.9 Gt from 1970 to 2021, with distinct contributions from different fuels and sectors. CO_2 emissions from coal combustion grew fast and surpassed oil as the largest contributor in early 2000s, but have remained stable in the recent decade (Fig. 2b). Contribution of power generation in coal emissions increased from 40% to 62% during 1970-2021, owing to the withdrawal of coal from end-use sectors and the booming of coal power plants in developing countries [57]. Iron and steel industry was the largest coal consumer and emitter among the manufacturing industries throughout the period, following by cement and chemical industries. In 2021, the top 5 contributors from manufacturing industries totally contributed 23% of CO_2 emissions from coal combustion. Emission contribution from residential sectors were continuously decreasing from 10% in 1970 to 3% in 2021, mainly driven by energy transition towards electricity and other clean fuels (e.g., natural gas and LPG) in developed countries (Fig. S2).

CO_2 emissions from oil combustion grew rapidly in 1970s and dominated total emissions before the 2000s, with dominant and increasing contributions from transport sectors (Fig. 2c and Fig. S3). Road transport by car is the largest contributor during the period, contributing 17% of total fuel emissions in 1970 and 26% in 2021. Other important and growing emission contributor include trucks, international navigation, and international aviation. For example, emission contribution from heavy-duty truck and light-duty truck increased from 4% and 3% in 1970 to 14% and 7% in 2021, respectively. In contrast, the shares of industrial sectors in oil combustion emissions were generally decreasing from 1970-2021.

The most striking growth was observed in the CO_2 emissions from natural gas combustion (i.e., 2.5% per year during 1970-2021, see Fig. 2d). Among different sectors, the share of power generation increased from 21% in 1970 to 42% in 2021 due to shift from coal-fired to gas-fired power plants in developed countries (Fig. S4). Other important emission contributors for natural gas combustion include urban residential, commercial/institutional, and oil and gas extraction, accounting for 14%, 7%, and 6% of CO_2 emissions in 2021, respectively.

Emission dynamics across fuel types and sectors can be further revealed in "sector-fuel" emission matrix (Fig. 3 and Fig. S5-S6). Despite remarkable increasing trends, emission hotspots were dynamically changed over the time. A few emission hotspots existed in 1970 and kept growing in the past 50 years, such as bituminous coal consumption for power generation, gasoline consumption by cars, and coke consumption in iron and steel industry. Meanwhile, emerging hotspots showed striking increases since 1970, such as natural gas combustion in energy production and manufacturing industries, bituminous coal in manufacturing industries, and liquefied petroleum gases (LPG) in commercial and residential sectors. In contrast, many emission hotspots existing in 1970 have been shrunk. For instance, emissions from fuel oil combustion decreased by 40-90% during 1970-2021 in most sectors. Driven by electrification progress, emissions from diesel combustion in residential sector and coal combustion for railways substantially declined. In

summary, the highly-resolved source category in MEIC-Global-CO_2 allows a more detailed analysis for global emission dynamics.

3.2 Evolution of country-level top emitters

Figure S7 shows the country-level CO_2 emissions in 2021 along with the historical emission trends of global top 15 emitting countries. The top 15 countries contributed 74% of global CO_2 emissions in 2021, indicating highly concentrated emissions among countries. Figure 4 presented the evolution of global top emitters over the time. The United States was the global leading emitter during 1970-2000, and 9 out of the 15 top emitters were developed countries in 2000, representing the dominant responsibility of developed countries for historical CO_2 emissions. Despite stable or declining trends in the past two decades, 6 developed countries still remain the 15 top emitters in 2021.

After 2000, boosted by rapid socio-economic development and infrastructure expansion [5], emissions from emerging economies have been increased remarkably. The annual average growth rates of China, India, Indonesia, Iran, and Saudi Arabia reached 3-6% during 2000-2021. Consequently, more developing economies appeared in the top 15 country list. In 2021, China was the largest emitter worldwide and 9 out of the top 15 emitters were developing countries. The 9 top emerging economies (i.e., China, India, Russia, Indonesia, Iran, Saudi Arabia, Brazil, Turkey, and Mexico) totally contribute 51% (17.9 Gt) of global emissions. Although the dissolution of Former Soviet Union caused the abrupt emission decrease in 1990s, resulting in Ukraine's withdrawal from the top list after 1990, Russia still ranked the fourth largest emitters with 1.64 Gt CO_2 emissions in 2021. Other hotspot countries with over 200 Mt annual CO_2 emissions in 2021 were mostly located in Southeast Asia (e.g., Vietnam, Thailand, and Malaysia), Central Asia (e.g., Kazakhstan), North Africa (e.g., Egypt), and the Middle East (e.g., the United Arab Emirates).

3.3 Sub-country emission patterns

The sub-country information incorporated in MEIC-global-CO_2 allows a "zoom-in" look of heterogenic emission patterns within a country. Figure 5 presents sub-country emission distribution of the year 2021 for 12 countries. Remarkable emission heterogeneity at sub-country level was generally observed, reflecting the disparities of socio-economic development within a country. For instance, emission hotspots in China were mostly located in eastern coastal provinces with developed economy, large population, and intensive industries, while the CO_2 emissions were much lower in inland provinces (Fig. 5a). However, Inner Mongolia and Xinjiang, the two provinces located in inland China, have large CO_2 emissions due to expansion of energy-intensive industries in the recent decade. In Indonesia (Fig. 5b), five provinces on Java Island, the most developed Indonesian region accounting for less than 7% of land area, disproportionately emitted 63% of national CO_2 emissions in 2021. In Turkey (Fig. 5c), Istanbul and Izmir, two hubs of economics accounting for ~2% of land area, contributed 41% of national CO_2 emissions. Similar heterogenic emission patterns could also be found in South Africa, Brazil, Argentina, and Russia (Fig. 5d-g).

In other countries, the heterogeneity of sub-country CO_2 emissions is less significant, especially for developed countries owing to balanced economic development. In the United States (Fig. 5h),

although Texas and California were eye-catching emission hotspots, there were 14 and 35 states emitting over 100 and 50 Mt CO_2 respectively in 2021, widely distributed in conterminous U.S. Similar patterns were also observed in Canada, Germany, and the United Kingdom (Fig. 65i-k). In India, although industry-intensive central states such as Maharashtra, Chhattisgarh, and Uttar Pradesh were leading emitters with over 200 Mt CO_2 emissions, there were totally 16 states that contributed more than 50 Mt CO_2 in 2021 (Fig. 5l). These states accounted for 86% of land area and contributed 95% of CO_2 emissions.

Sectoral contributions to sub-country CO_2 emissions also varied significantly, representing uneven distribution of economic and energy structure (Fig. S8). In emerging economies, provinces/states with large CO_2 emissions generally had higher contributions (70-90%) from energy-producing and manufacturing sectors because of coupled energy and industrial production system, such as Shandong in China, Maharashtra in India, Chelyabinsk in Russia, Rio de Janeiro in Brazil, and Istanbul in Turkey. In contrast, sub-country emitters with lower emissions tended to have higher contributions from transport and commercial/residential sectors. This occurred in some political hubs (e.g., Beijing and NCT of Delhi), but also occurred in many agriculture/forestry-dominant provinces (e.g., Santiago del Estero in Argentina).

In developed countries, large sub-country emitters usually had higher shares (60-90%) of power generation and transport sectors, such as California in the United States, Alberta in Canada, and South East England in the United Kingdom. Large contributions from manufacturing sectors were only observed in a few industry-intensive provinces/states, such as Indiana (largest steel producing state in the U.S.) and Sachsen-Anhalt (important chemical-manufacturing state in Germany). The dominance of transport and commercial/residential sectors in small sub-country emitters were not as significant as that in emerging economies, but is still observed in political centers like the District of Columbia and Greater London.

4. Discussions

4.1 Comparison with other databases

We compared the MEIC-global-CO_2 database with three global CO_2 databases, namely EDGAR, CEDS, and GCP at global, national, and sector levels [2,16,19]. Globally, the magnitudes and trends of CO_2 emissions in MEIC-global-CO_2 database are generally consistent with other databases (Fig. S9). The relative differences in 1970-2021 range from -6.5% to +8.2%, and lie within ±5% in most years (Table S18-S19). Specifically, the MEIC estimates are generally higher than CEDS but lower than GCP at global scale, and more consistent with EDGAR. The differences are more significant in specific countries and sectors, which could be not only attributed to the integration process of activity rates (e.g., data fusion, statistics disintegration, and reconstruction of time-series) but also to different sources of emission factors as discussed in detail below.

Figure 6 compares CO_2 emissions between MEIC and the ensembled average of EDGAR, CEDS, and GCP databases by country in ascending order of CO_2 emissions. In general, the discrepancies increased with decreased national emissions. For example, in 2019, the normalized mean error (NME) increases from 1.9% for large emitters (i.e., national annual emission >1,000 Mt) to 5.9%

for medium emitters (i.e., 100-1,000 Mt), and exceeds 23% for small emitters with national emissions less than 10 Mt (Table S20). This can be mainly explained by the discrepancies between international datasets used in EDGAR, CEDS, and GCP and local statistics used in this study. Another important reason is the ways of disaggregating lumped IEA statistics for small countries. In this work, we used sector-specific parameters to disaggregate regional total to individual countries (See Section 2.5.1), whereas in other databases, disaggregation was generally based on aggregated country-level production/consumption indicators [16,19].

It is observed that the differences between MEIC-global-CO_2 and other databases are diminished over the time. NME of all countries decreased from 6.1% in 1970 to 4.3% in 1990 and further to 3.8% in 2019 (Table S20). This may represent the narrowed gaps between international and local statistics following the improvement in statistical reporting systems. The process of reconstructing time-series also contributed to large differences in early years, for example, splitting statistical data of Former Soviet Union to 15 countries for the years before 1991.

The differences in sectoral emissions by country are more significant (Fig. S10), which could be largely attributed to the integration of regional databases in this work. Also, the differences of sectoral CO_2 emissions between MEIC-global-CO_2 and other databases increase as magnitudes of emissions decrease. The discrepancy could be partly explained by the sector-specific disaggregation of statistics. On the other hand, the differences of process emissions in cement industry are more likely to be explained by emission factors. In MEIC-global-CO_2, emission factors are determined by kiln type from a facility-level database [59], while country-level average emission factors are used in other databases.

4.2 Uncertainties and limitations

CO_2 emission estimates in MEIC-global-CO_2 database are subject to several uncertainties. First, harmonization of country definition can introduce uncertainties for newly established countries whose activity rates are split or merged from its predecessor or successor countries or for small countries whose activity rates are disaggregated from regional totals in IEA statistics. Second, integration of regional databases (i.e., CEADs and MEIC-China) also involves uncertainties although we believe it can significantly improve data quality for emerging economies. For instance, cross-mapping between the source categories of MEIC-global-CO_2 and CEADs can introduce additional uncertainties. Third, downscaling of sub-country information may lead to uncertainties for sub-country emission estimates in addition to country totals. Fourth, reconstruction of time-series may result in large uncertainties for the years when the data is missing, especially for early years.

Our study also bears several limitations, which could be improved in future work. First, current estimates don't include a few minor emitting sources such as gas flaring and process emissions in chemical industry, which will be included in future updates. Second, our estimates begin from the year 1970. To support climate modeling, a full time-series extended to pre-industrial time should be developed in the future. Third, the UNFCCC GHG database provides well-compiled activity rates and emission factors reported by Annex I countries, which could be integrated into MEIC-global-CO_2 in future versions.

5. Concluding remarks

In this study, we develop a new global CO_2 emission database, named the MEIC-global-CO_2 database, to provide highly-resolved source category information and sub-country estimates. A data-driven approach is developed to construct seamless data cubes of activity rates for the period of 1970-2021 for 208 countries/territories, 797 sub-country administrative divisions in 29 countries, 42 fuel types, and 52 sectors, with the fusion of energy consumption from 24 international statistics and 65 regional/local statistics. We then use the seamless data cube of activity rates to estimate global CO_2 emissions from fossil fuel combustion and cement production in 1970-2021 with detailed information described above.

Based on the MEIC-global-CO_2 database, dynamics of global CO_2 emissions across fuel types and sectors are tracked, revealing distinct and dynamically changing contributions from different emitting sources. Some sources maintained large contribution since 1970, while some others grew as new hotspots or significantly shrunk as global economy evolved, industrial patterns changed, and climate governance proceeded. Among global top emitters, developed countries played important roles throughout the period, while emissions from emerging economies have been increasing remarkably after 2000. Moreover, sub-country emission heterogeneity was remarkable in large emitters with more significant differences in sectoral contributions, reflecting uneven layouts of energy, industrial, transport, and residential infrastructures within a country.

The MEIC-global-CO_2 database is publicly available through http://meicmodel.org.cn with highly-resolved information and timely update. More data products, such as monthly emissions and high-resolution emission grids, will also be developed in the future to extend the applicability of MEIC-global-CO_2 database. With future efforts on expanding the methodological framework and collecting more reliable data, we expect that MEIC-global-CO_2 will serve as a high-quality, timely-updated, and open-access emission database for climate research and climate governance.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (41921005), the New Cornerstone Science Foundation through the XPLORER PRIZE, and Tsinghua University Initiative Scientific Research Program (20223080041).

Author contributions

Q.Z. and D.T. designed the study. R.X. performed data set construction and emission estimates with support from Q.X., X.Q., C.C., and L.Y. on global sectoral emission estimates, from J.C. and H.H. on emission estimates in China, from D.G. and C.C. on emission estimates in emerging economies from CEADs, from W.L., X.Y., and H.W. on data compilation, and from X.L. on accounting system. R.X. and Q.Z. interpreted the data. R.X. and Q.Z. wrote the paper with input from all co-authors.

References

[1] V. Masson-Delmotte, P. Zhai, A. Pirani, et al., Climate Change 2021: The Physical Science Basis (2021). https://www.ipcc.ch/report/ar6/wg1/

[2] P. Friedlingstein, M.W. Jones, M. O'sullivan, et al., Global Carbon Budget 2021, Earth Syst. Sci. Data 14 (4) (2022) 1917-2005.

[3] M. Scholze, W. Knorr, N.W. Arnell, et al., A climate-change risk analysis for world ecosystems, Proc. Natl. Acad. Sci. U.S.A. 103 (35) (2006) 13116-13120.

[4] G. Mcgranahan, D. Balk, B. Anderson, The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones, Environ. Urban. 19 (1) (2007) 17-37.

[5] D. Tong, Q. Zhang, Y. Zheng, et al., Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target, Nature 572 (7769) (2019) 373-377.

[6] H.P. Jones, D.G. Hole, E.S. Zavaleta, Harnessing nature to help people adapt to climate change, Nat. Clim. Change 2 (7) (2012) 504-509.

[7] J. Deangelo, I. Azevedo, J. Bistline, et al., Energy systems in scenarios at net-zero CO_2 emissions, Nat. Commun. 12 (1) (2021) 6096.

[8] G. Luderer, Z. Vrontisi, C. Bertram, et al., Residual fossil CO_2 emissions in 1.5–2 °C pathways, Nat. Clim. Change 8 (7) (2018) 626-633.

[9] N. Höhne, M. Den Elzen, J. Rogelj, et al. Emissions: world has four times the work or one-third of the time, Nature 579 (2020) 25-28.

[10] J. Rogelj, O. Geden, A. Cowie, et al., Three ways to improve net-zero emissions targets, Nature 591 (2021) 365-368.

[11] D. Tong, Q. Zhang, S.J. Davis, et al., Targeted emission reductions from global super-polluting power plant units, Nat. Sustain. 1 (1) (2018) 59-68

[12] International Energy Agency (IEA), Greenhouse Gas Emissions from Energy 2021 Edition, (2022). https://origin.iea.org/data-and-statistics/data-product/greenhouse-gas-emissions-from-energy

[13] R.J. Andres, T.A. Boden, F.M. Bréon, et al., A synthesis of carbon dioxide emissions from fossil-fuel combustion, Biogeosciences 9 (5) (2012) 1845-1871.

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

[15] United Nations Framework Convention on Climate Change (UNFCCC), National Inventory Submissions, (2022). https://di.unfccc.int/flex_annex1

[16] R.M. Hoesly, S.J. Smith, L. Feng, et al., Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS), Geosci. Model Dev. 11 (1) (2018) 369-408.

[17] Z. Liu, P. Ciais, Z. Deng, et al., Carbon Monitor, a near-real-time daily dataset of global CO_2 emission from fossil fuel and cement production, Sci. Data 7 (1) (2020) 392.

[18] R. Wang, S. Tao, P. Ciais, et al., High-resolution mapping of combustion processes and implications for CO_2 emissions, Atmos. Chem. Phys. 13 (10) (2013) 5189-5203.

[19] G. Janssens-Maenhout, M. Crippa, D. Guizzardi, et al., EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012, Earth Syst. Sci. Data 11 (3) (2019) 959-1002.

[20] International Energy Agency (IEA), World Energy Statistics and Balances 2022, (2022). https://www.iea.org/data-and-statistics/data-product/world-energy-balances

[21] United Nation Statistics Division, Energy Statistics, (2022). https://unstats.un.org/unsd/energystats/

[22] R.M. Andrew, Global CO_2 emissions from cement production, 1928–2018, Earth Syst. Sci. Data 11 (4) (2019) 1675-1710.

[23] R.M. Andrew, A comparison of estimates of global carbon dioxide emissions from fossil carbon sources, Earth Syst. Sci. Data 12 (2) (2020) 1437-1465.

[24] C. Hong, Q. Zhang, K. He, et al., Variations of China's emission estimates: response to uncertainties in energy statistics, Atmos. Chem. Phys. 17 (2) (2017) 1227-1239.

[25] C. Cui, S. Li, W. Zhao, et al., Energy-related CO_2 emission accounts and datasets for 40 emerging economies in 2010–2019, Earth Syst. Sci. Data 15 (3) (2023) 1317-1328.

[26] H. Xiao, W. Zhao, Y. Shan, et al., CO_2 emission accounts of Russia's constituent entities 2005–2019, Sci. Data 8 (1) (2021) 172.

[27] Q. Huang, H. Zheng, J. Li, et al., Heterogeneity of consumption-based carbon emissions and driving forces in Indian states, Adv. Appl. Energy 4 (2021) 100039.

[28] B. Zheng, D. Tong, M. Li, et al., Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions, Atmos. Chem. Phys. 18 (19) (2018) 14095-14111.

[29] International Road Federation (IRF), the World Road Statistics 2019 Millennium Data: 2000-2017, (2021). https://worldroadstatistics.org/get-data/

[30] Intergovernmental Panel on Climate Change (IPCC), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, (2006). https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

[31] United States Geological Survey (USGS), Cement Statistics and Information, (2022). https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information

[32] Organisation Internationale des Constructeurs d'Auto (OICA), World vehicle in use, (2021). https://www.oica.net/category/vehicles-in-use/

[33] Oak Ridge National Laboratory, Transportation Energy Data Book, (2020). https://tedb.ornl.gov/data/

[34] CEIC, CEIC Global Database, (2020). https://www.ceicdata.com/en

[35] European Commission, Directorate-General for Mobility and Transport 2019, (2020). https://commission.europa.eu/statistics_en

[36] International Energy Agency (IEA), Energy Efficiency Statistics 2019 Edition, (2019). https://www.iea.org/data-and-statistics/data-product/energy-efficiency-indicators

[37] H. Chen, Y. Huang, H. Shen, et al., Modeling temporal variations in global residential energy consumption and pollutant emissions, Appl. Energy 184 (2016) 820-829.

[38] National Bureau of Statistics, China Energy Statistical Yearbooks 1997-2020: Provincial Energy Balances. https://data.cnki.net/yearbook/Single/N2022060061

[39] African Energy Commission (AFREC), Africa Energy Database. https://au-afrec.org/

[40] Economic Research Institute for ASEAN and East Asia (ERIA), Energy Balance Tables. https://www.eria.org/RPR_FY2015_No.8_Chapter_2.pdf

[41] U.S. Energy Information Adminstrative (EIA). https://www.eia.gov/

[42] U.S. Department of Agriculture. https://www.usda.gov/

[43] Bureau of Economic Analysis. https://www.bea.gov/

[44] Statistics Canada. https://www.statcan.gc.ca/

[45] Statistisches Bundesamt. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Bevoelkerungsstand/Publikationen/Downloads-Bevoelkerungsstand/bevoelkerungsfortschreibung-2010130207005.html

[46] Department for Business, Energy & Industrial Strategy. https://www.gov.uk/search/research-and-statistics?parent=%2Fenvironment%2Fclimate-change-energy&topic=62e08e6f-9161-42c6-b9dd-0cf8fcab2c69

[47] Office for National Statistic. https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/populationestimatesforukenglandandwalesscotlandandnorthernireland

[48] Institut national de la statistique et des études économiques (INSEE). https://www.insee.fr/fr/statistiques/1893198

[49] Istituto nazionale di statistica (Istat). http://dati.istat.it/Index.aspx

[50] Department of Industry, Science, Energy and Resources. https://www.dcceew.gov.au/

[51] Australian Bureau of Statistics. https://www.abs.gov.au/

[52] Saudi Arabian Bureau of Statistics. https://www.stats.gov.sa/

[53] World Steel Assoiciation, Steel Statistical Yearbooks 1978-2020, (2021). https://worldsteel.org/steel-topics/statistics/steel-statistical-yearbook/

[54] United Nation Statistics Division, UN Statistical Yearbooks 1970-2020 (2021). https://unstats.un.org/UNSDWebsite/Publications/StatisticalYearbook/

[55] World Bank, Indicators, (2022). https://data.worldbank.org.cn/indicator

[56] United Nations, Department of Economic and Social Affairs, Population Division, World Population Prospects 2019, (2019). https://population.un.org/wpp/Download/Standard/Population/

[57] X. Qin, D. Tong, F. Liu, et al., Global and regional drivers of power plant CO_2 emissions over the last three decades, Earth's Future 10 (10) (2022) e2022EF002657.

[58] R. Xu, D. Tong, S.J. Davis, et al. Plant-by-plant decarbonization strategies for global steel industry, Nat. Clim. Change (2023). Accepted.

[59] C. Chen, R. Xu, D. Tong, et al., A striking growth of CO_2 emissions from the global cement industry driven by new facilities in emerging countries, Environ. Res. Lett. 17 (4) (2022) 044007.

[60] T. Boden, G. Marland, R. Andres. Estimates of global, regional, and national CO_2 emissions from fossil-fuel burning, cement production, and gas flaring: 1950–1992. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, (1995). https://www.osti.gov/biblio/207068

[61] R.M. Andrew, Global CO_2 emissions from cement production, 1928–2017, Earth Syst. Sci. Data 10 (4) (2018) 2213-2239.

[62] Y. Shan, D. Guan, H. Zheng, et al., China CO_2 emission accounts 1997–2015, Sci. Data 5 (1) (2018) 170201.

[63] Y. Shan, Q. Huang, D. Guan, et al., China CO_2 emission accounts 2016–2017, Sci. Data 7 (1) (2020) 54.

[64] Department of Climate Change of National Development and Reform Commission, Department of Climate Change of National Development and Reform Commission, Guidelines for Provincial Greenhouse Gas Inventory, (2011).

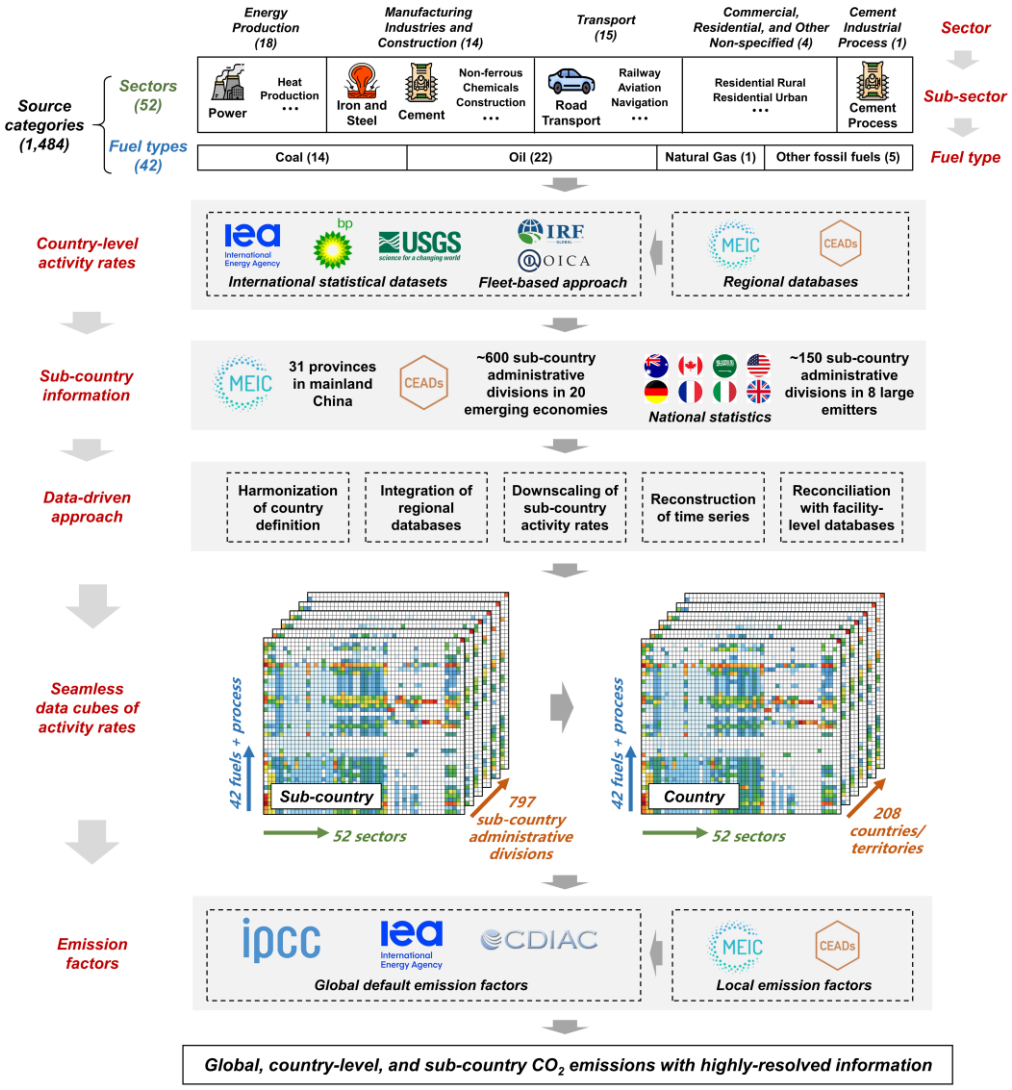

Figure 1. The overall methodological framework of MEIC-global-CO_2.

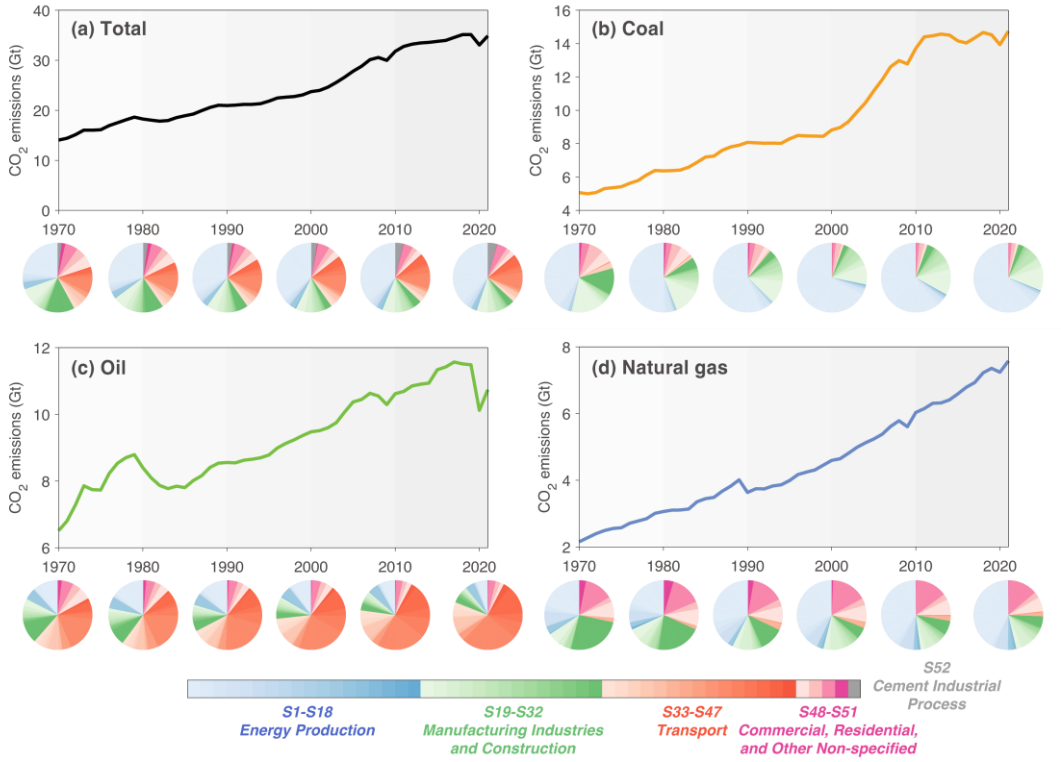

Figure 2. The CO_2 emissions (solid lines) and sectoral shares (pie charts) of (a) all anthropogenic sources, (b) coal combustion, (c) oil combustion, and (d) natural gas combustion. The mapping of 42 fuel types to coal, oil, and natural gas is presented in Table S2.

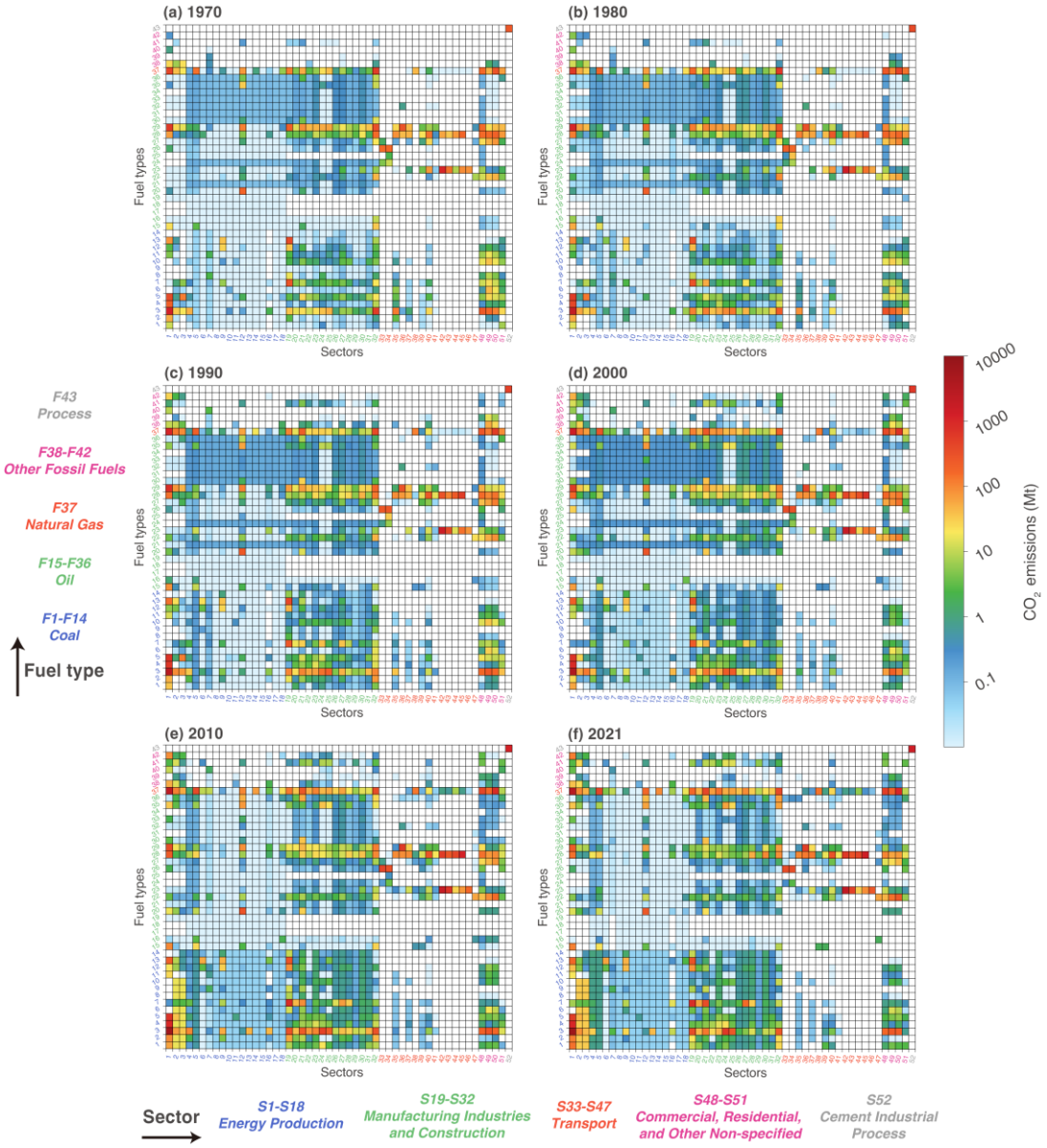

Figure 3. The "sector-fuel" matrices of CO_2 emissions in (a) 1970, (b) 1980, (c) 1990, (d) 2000, (e) 2010, and (f) 2021. The x axis represents 52 sectors, and the y axis represents 42 fuel types and process emissions in cement industry.

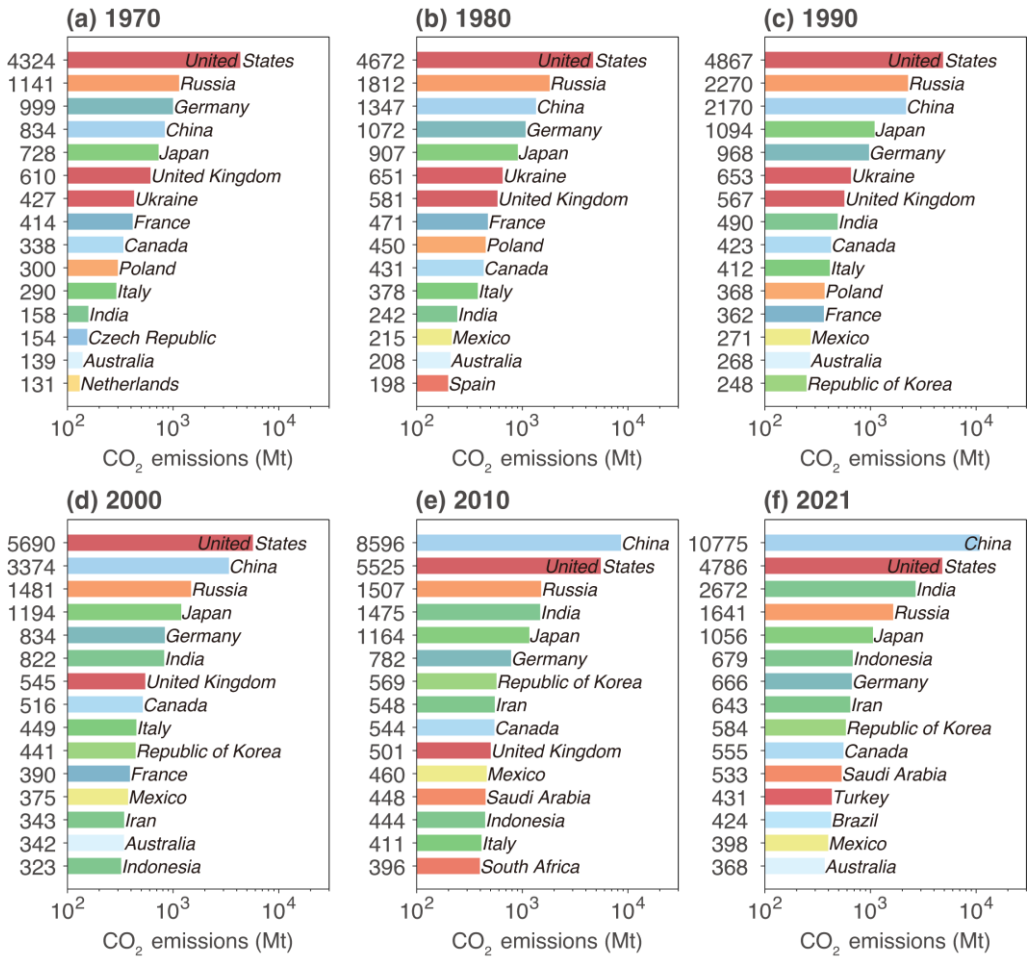

Figure 4. The top 15 countries of CO_2 emissions in (a) 1970, (b) 1980, (c) 1990, (d) 2000, (e) 2010, and (f) 2021.

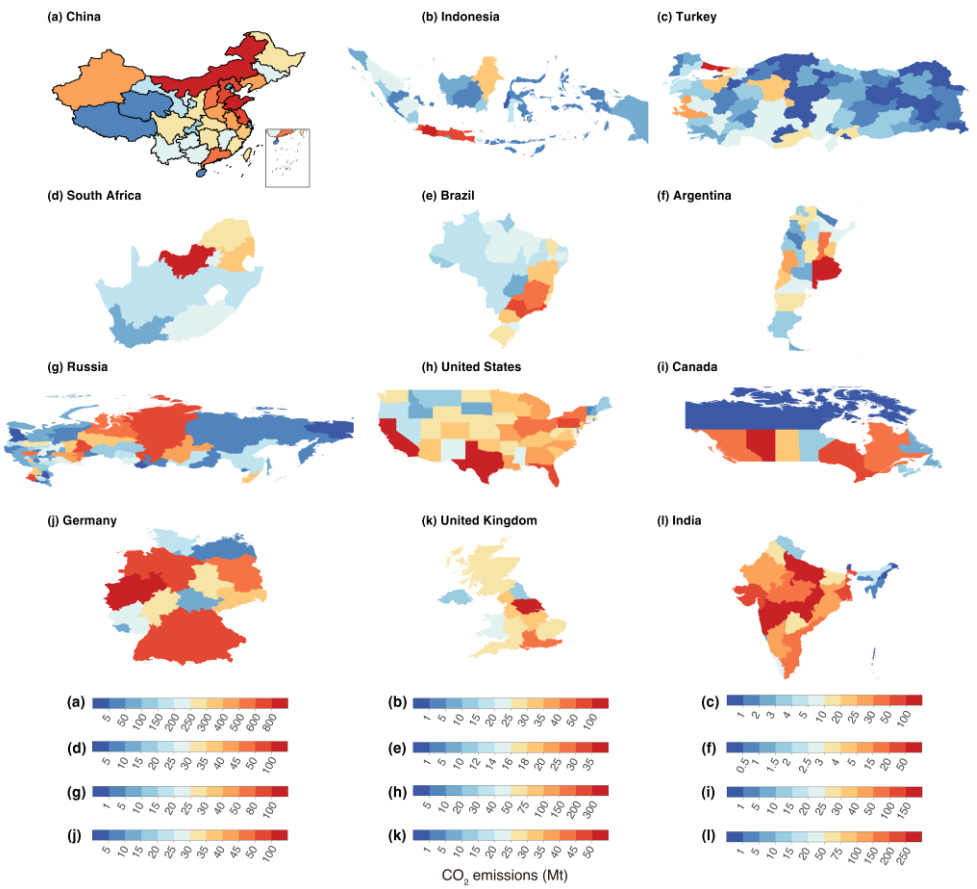

Figure 5. Sub-country CO_2 emissions in (a) China, (b) Indonesia, (c) Turkey, (d) South Africa, (e) Brazil, (f) Argentina, (g) Russia, (h) the United States, (i) Canada, (j) Germany, (k) the United Kingdom, and (l) India in 2021.

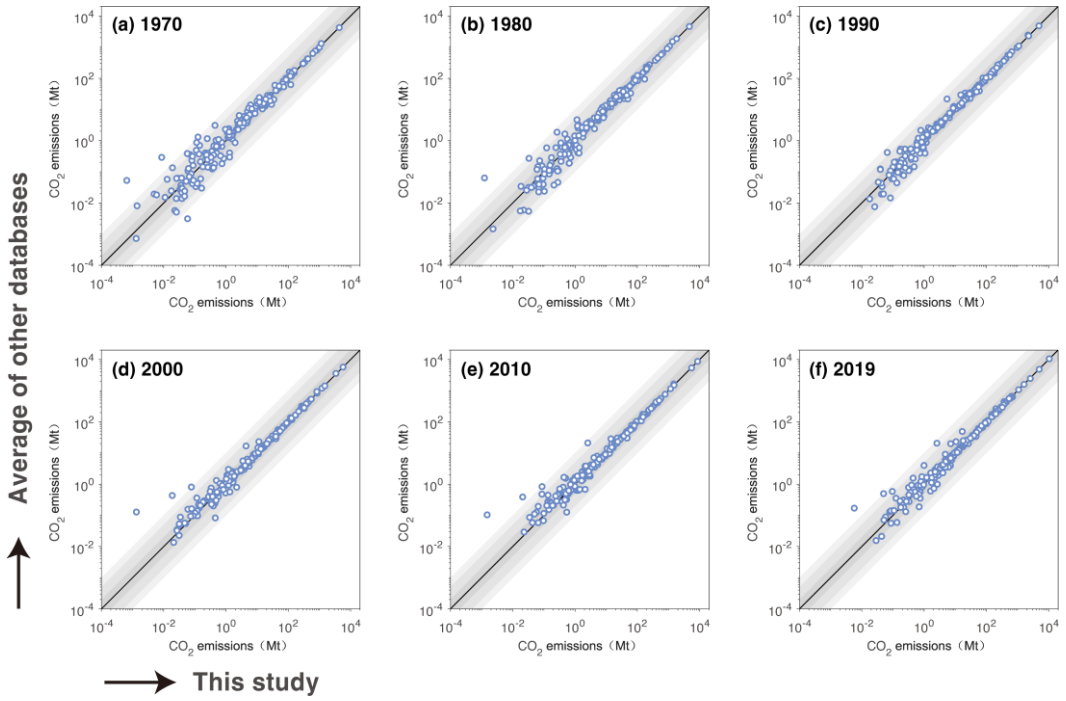

Figure 6. Comparison of country-based CO_2 emissions between the average of EDGAR, CEDS, and GCP databases (y axis) and MEIC database (x axis) in (a) 1970, (b) 1980, (c) 1990, (d) 2000, (e) 2010, and (f) 2019. The solid black line represents the 1:1 line, and the grey shades represent the 1:2 (2:1), 1:5 (5:1), and 1:10 (10:1) ranges, respectively. Here 2019 is used as the latest year because some databases haven't been updated.

Data availability

Global CO_2 emission data generated from this study are publicly available at: http://meicmodel.org.cn/.

Code availability

The code used to manipulate the data and generate the results is available from the corresponding author upon reasonable request.

Supplementary Information of

MEIC-global-CO_2: a new global CO_2 emission inventory with highly-resolved source category and sub-country information

Ruochong Xu[1], Dan Tong[1], Qingyang Xiao[1], Xinying Qin[1], Cuihong Chen[1], Liu Yan[1], Jing Cheng[1], Can Cui[1], Hanwen Hu[2], Wenyu Liu[1], Xizhe Yan[1], Huaxuan Wang[2], Xiaodong Liu[2], Guannan Geng[2], Yu Lei[3], Dabo Guan[1], Kebin He[2,4], and Qiang Zhang[1,*]

[1]Department of Earth System Science, Ministry of Education Key Laboratory for Earth System Modeling, Institute for Global Change Studies, Tsinghua University, Beijing 100084, People's Republic of China
[2]State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, People's Republic of China
[3]Chinese Academy of Environmental Planning, Beijing, People's Republic of China
[4]Institute for Carbon Neutrality, Tsinghua University, Beijing 100084, People's Republic of China

*corresponding author: qiangzhang@tsinghua.edu.cn

Text S1. The method to divide rural and urban residential consumption.

The annual urban-to-rural ratios on residential energy consumption of each country were estimated by linear regressions. Previous studies reported that the residential energy consumption is closely related to heating degree days (HDD), urbanization rate, and people income [1]. In this study, we first calculated the national average HDD from daily average temperature extracted from MERRA-2 dataset [2]. HDD is defined as the number of degrees that a day's average temperature is below 15°C and 5°C, for developed countries and developing countries, respectively [3,4]. The average of national HDD during 1980-2020 was included as a predictor. Urbanization rate and per capita GDP were obtained from databases developed by the United Nation and World Bank [5-7]. Due to the lack of data on urban and rural residential energy consumption, we selected the total residential energy consumption in countries and years with urbanization rate higher than 85% as the urban group and lower than 15% as the rural group to fit the linear regressions. Linear regressions were fitted with coal, oil, gas, and biomass consumption as dependent variables and HDD, urbanization rate, per capita GDP as independent variables for the urban group data and rural group data, respectively. Next, we interpolated the urban residential energy consumption by setting the urbanization rate in the urban group regression as 1 and interpolated the rural residential energy consumption by setting the urbanization rate in the rural group regression as 0. National annual urban-to-rural ratios of energy consumption were then estimated as the urban consumption interpolation divided by the rural consumption interpolation. Countries/territories with missing data were filled by the group average estimates of other countries in the same income group (high income, upper middle income, lower middle income, and low income as shown in Table S22). Ratios during 1970-1979 were calculated as the linear extrapolation of data during 1980-1984, and ratios in 2021 were set as the same values in 2020. Finally, 10-year moving average was performed to remove random variations.

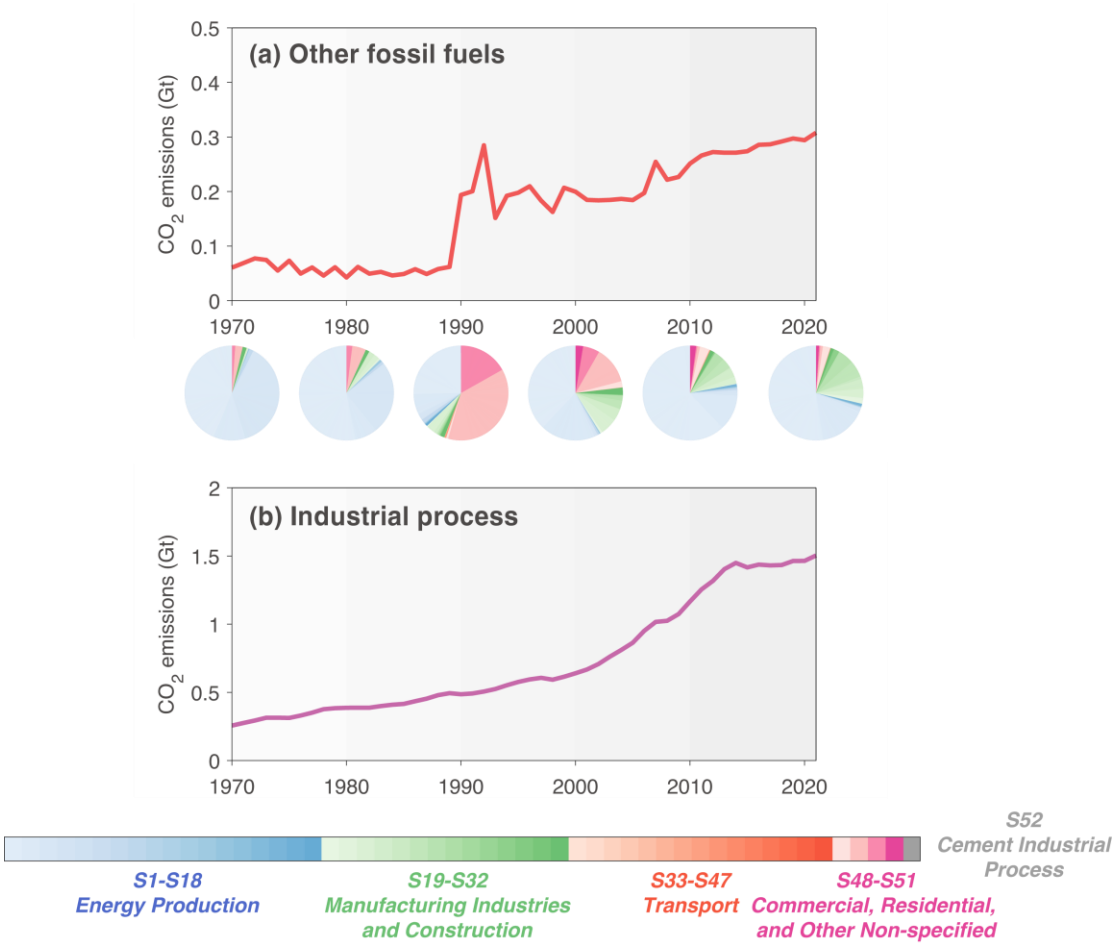

Figure S1. The same as Fig. 2 but for (a) other fossil fuel combustion and (b) industrial process. Industrial process emissions are only contributed by cement industry and thus the pie charts are not shown here. The mapping of fuel types to other fossil fuels is presented in Table S2.

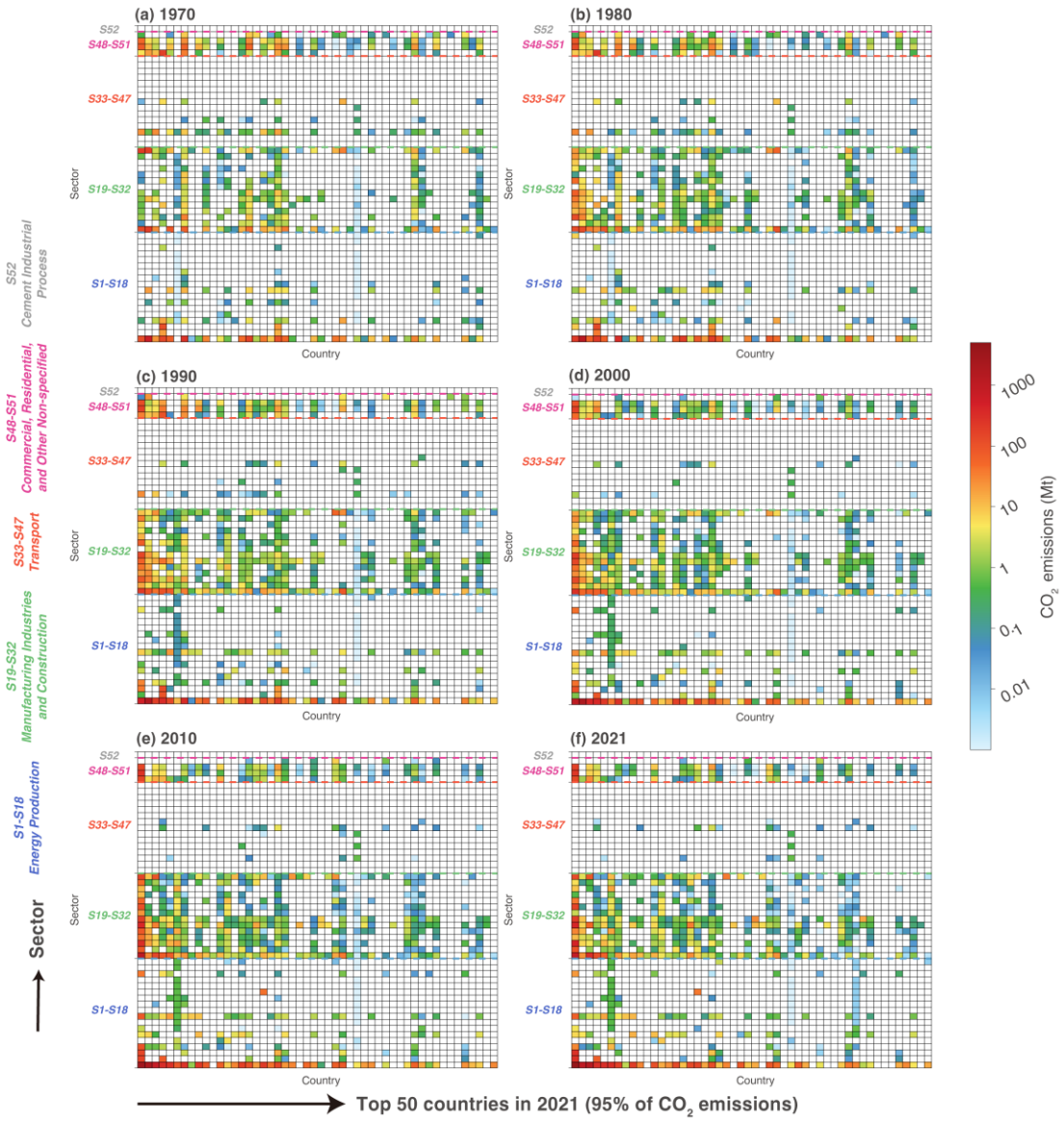

Figure S2. The "country-sector" matrices of CO_2 emissions for coal combustion in (a) 1970, (b) 1980, (c) 1990, (d) 2000, (e) 2010, and (f) 2021. The x axis represents the top 50 emitters in 2021 among the 208 countries/territories, which accounts for 95% of CO_2 emissions in 2021; the y axis represents 52 sectors.

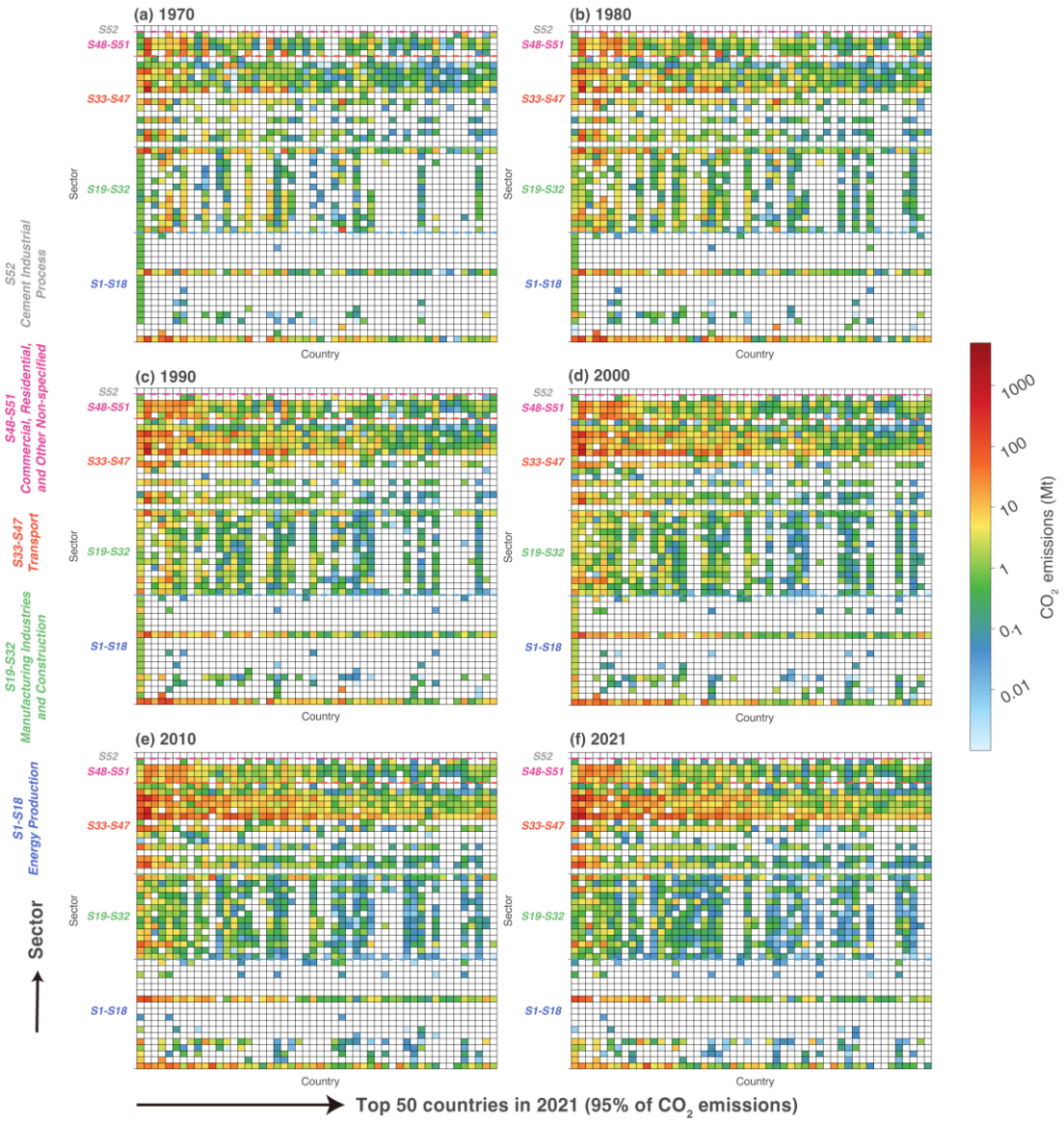

Figure S3. The same as Fig. S2 but for CO_2 emissions from oil combustion.

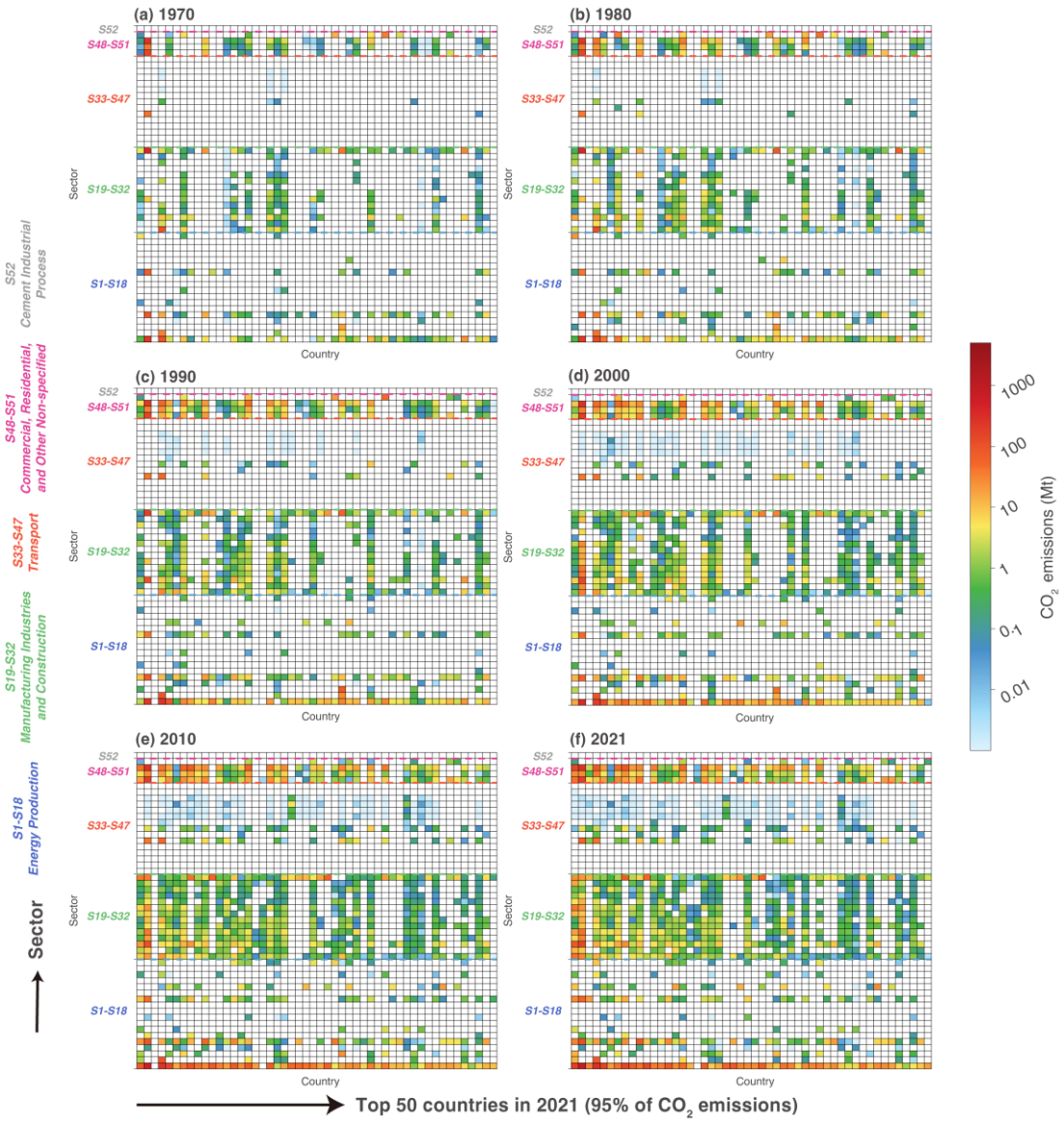

Figure S4. The same as Fig. S2 but for CO_2 emissions from natural gas combustion.

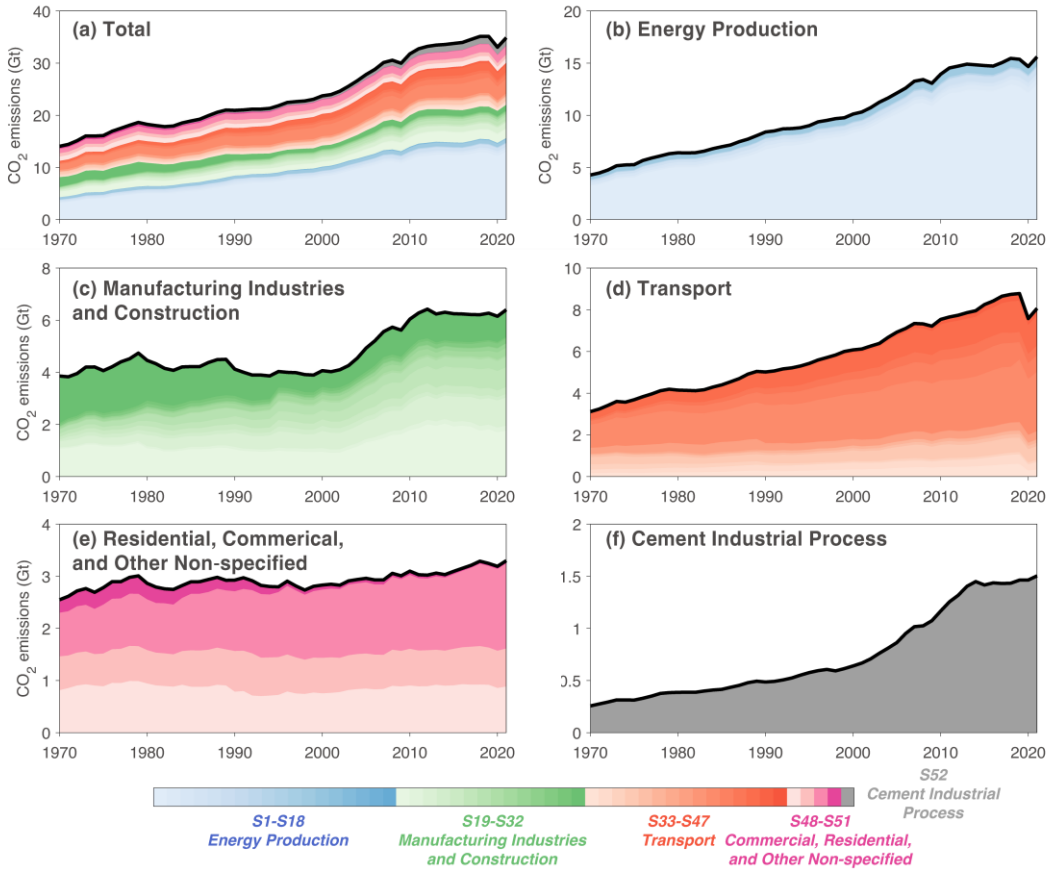

Figure S5. The sectoral CO_2 emissions of (a) total emissions, (b) energy production, (c) manufacturing industries and construction, (d) transport, (e) residential, commercial, and other non-specified, and (f) process emissions of cement industry. The mapping of 52 detailed sectors to five major sectors is presented in Table S1.

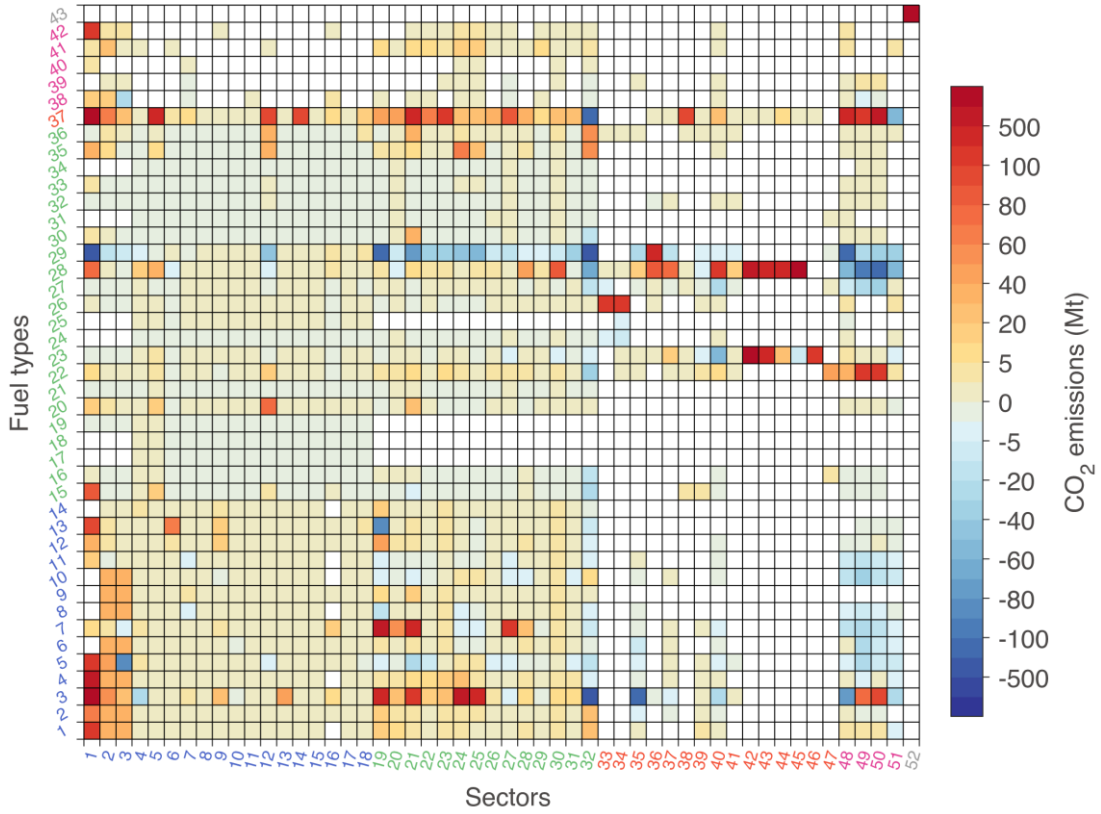

Figure S6. The "sector-fuel" matrices of CO_2 emission differences between 1970 and 2021. The x axis represents 52 sectors, and the y axis represents 42 fuel types and process emissions in cement industry.

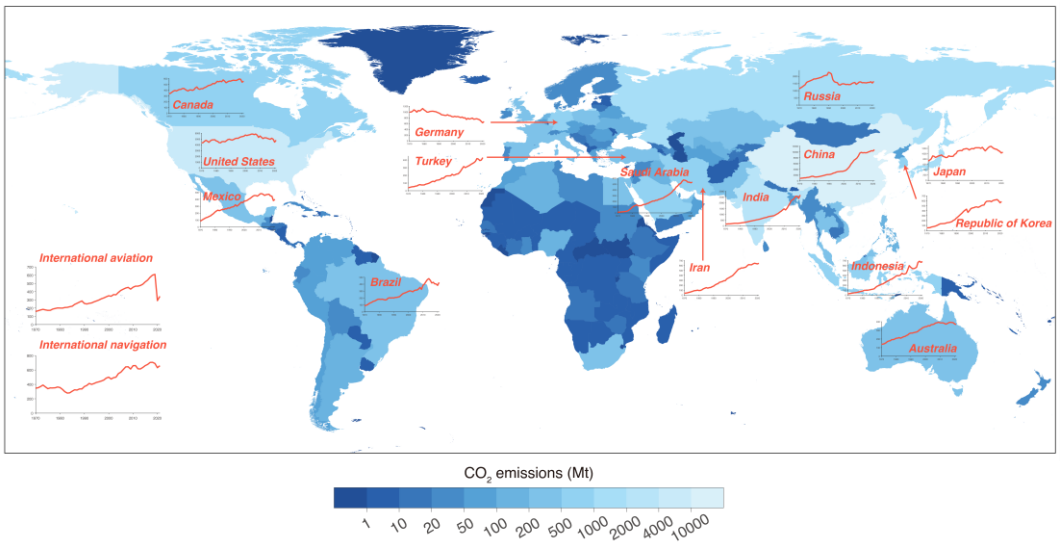

Figure S7. The map of country-level CO_2 emissions in 2021. The time series (solid lines) represent the 1970-2021 CO_2 emissions for top 15 emitters in 2021 as well as international aviation and navigation.

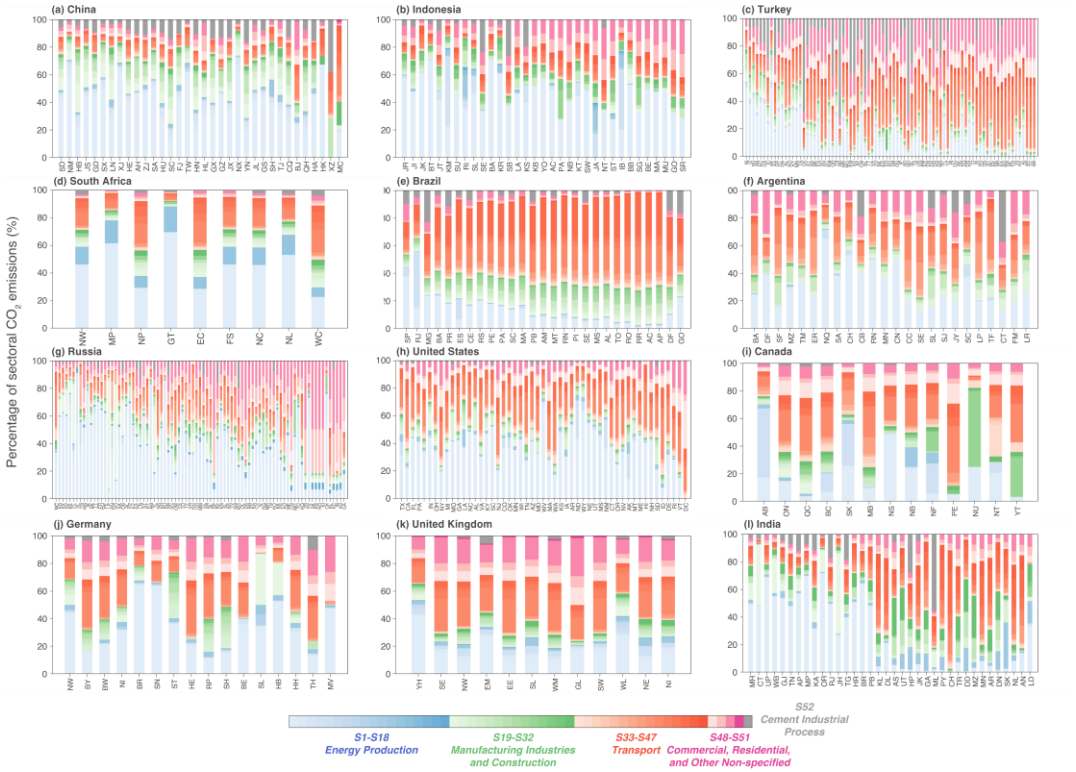

Figure S8. The sectoral shares of sub-country CO_2 emissions in (a) China, (b) Indonesia, (c) Turkey, (d) South Africa, (e) Brazil, (f) Argentina, (g) Russia, (h) the United States, (i) Canada, (j) Germany, (k) the United Kingdom, and (l) India in 2021. Full names and abbreviations of the sub-countries are shown in Table S8.

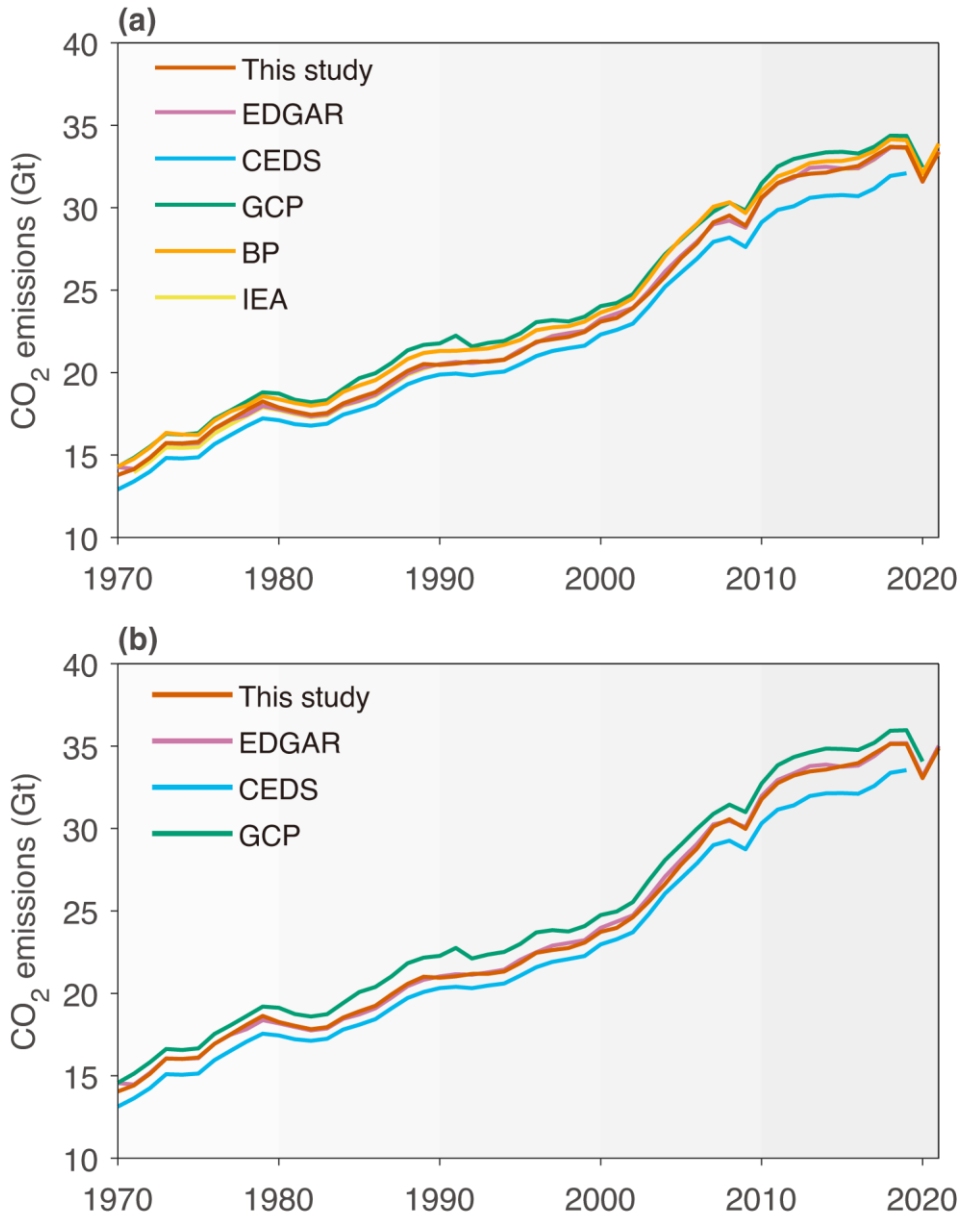

Figure S9. The comparisons of global CO_2 emissions from (a) fossil fuel combustion and (b) all anthropogenic sources between MEIC and other existing databases CO_2 emissions in 1970-2021. Note that not all the databases have been updated to 2021.

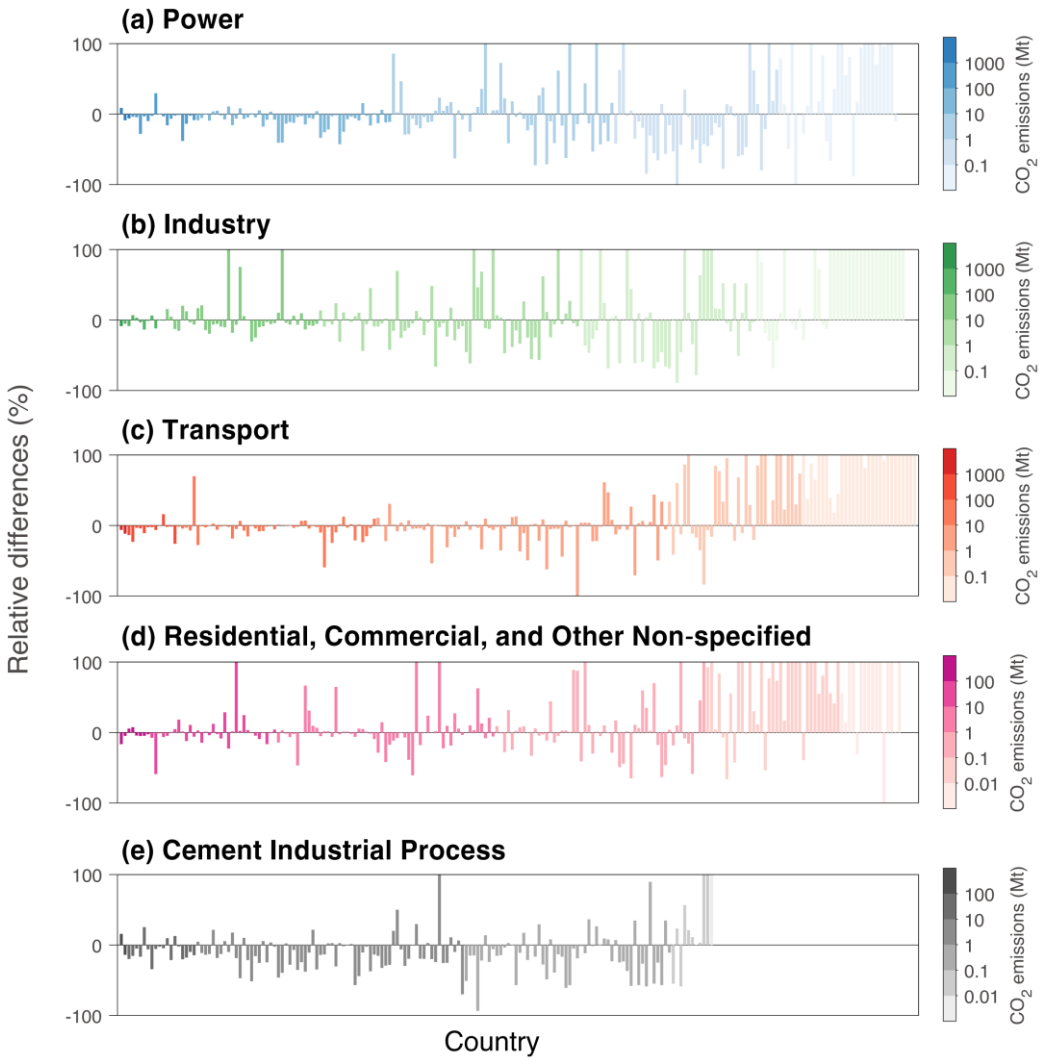

Figure S10. Relative differences of sectoral CO_2 emissions in each country between the ensembled average of EDGAR and CEDS and MEIC database in 2019. The panels show (a) power, (b) industry, (c) transport, (d) residential, commercial and other non-specified, and (e) cement industrial process emission sectors. The countries are ranked by sectoral emissions in each panel and the bar colors represent emission magnitudes. The sectors are combined to the five aggregated sectors as shown in Table S21 to allow comparison across the databases with different sectoral data products.

Table S1. The major and detailed sectors of source categories and their IPCC GL code categories.

Major	Detailed No.	Detailed	IPCC GL Code Category
Energy production	1	Power generation	1A1a
	2	Heat (auto producer)	1A1a
	3	Heat (public)	1A1a
	4	Coal mines	1A1b and 1A1c
	5	Oil and gas extraction	1A1b and 1A1c
	6	Blast furnaces	1A1b and 1A1c
	7	Gas works	1A1b and 1A1c
	8	Gasification plants for biogases	1A1b and 1A1c
	9	Coke ovens	1A1b and 1A1c
	10	Patent fuel plants	1A1b and 1A1c
	11	BKB/peat briquette plants	1A1b and 1A1c
	12	Oil refineries	1A1b and 1A1c
	13	Coal liquefaction plants	1A1b and 1A1c
	14	Liquefaction (LNG) / regasification plants	1A1b and 1A1c
	15	Gas-to-liquids (GTL) plants	1A1b and 1A1c
	16	Own use in electricity, CHP and heat plants	1A1b and 1A1c
	17	Charcoal production plants	1A1b and 1A1c
	18	Non-specified transformation industries	1A1b and 1A1c
Manufacturing industries and construction	19	Iron and steel	1A2a
	20	Non-ferrous metals	1A2b
	21	Chemicals	1A2c
	22	Pulp and paper	1A2d
	23	Food and tobacco	1A2e
	24	Cement	1A2f
	25	Other non-metallic minerals	1A2f
	26	Transport equipment	1A2g
	27	Machinery	1A2h
	28	Mining and quarrying	1A2i
	29	Wood products	1A2j
	30	Construction	1A2k
	31	Textile and leather	1A2l
	32	Other non-specified industries	1A2m
Transport	33	International aviation	1A3a
	34	Domestic aviation	1A3a
	35	Rail	1A3c
	36	International navigation	1A3d
	37	Domestic navigation	1A3d
	38	Pipeline transport	1A3e

	39	Other non-specified transport	1A3e
	40	Agriculture and forestry	1A4c
	41	Fishing	1A4c
	42	Cars	1A3b
	43	Light duty trucks	1A3b
	44	Buses	1A3b
	45	Heavy duty trucks	1A3b
	46	Motorcycles	1A3b
	47	Other fleet totals	1A3b
Residential, commercial, and other non-specified	48	Commercial and institutional	1A4a
	49	Residential (rural)	1A4b
	50	Residential (urban)	1A4b
	51	Non-specified sectors	1A5
Industrial process	52	Process emissions in cement industry	2A1

Table S2. The fuel types of source categories.

	No.	Fuel type
Coal	1	Anthracite
	2	Coking coal
	3	Other bituminous coal
	4	Sub-bituminous coal
	5	Lignite
	6	Patent fuel
	7	Coke oven coke
	8	Gas coke
	9	Coal tar
	10	BKB
	11	Gas works gas
	12	Coke oven gas
	13	Blast furnace gas
	14	Other recovered gases
Oil	15	Crude oil
	16	Natural gas liquids
	17	Refinery feedstocks
	18	Additives/blending components
	19	Other hydrocarbons
	20	Refinery gas
	21	Ethane
	22	Liquefied petroleum gases (LPG)
	23	Motor gasoline excluding biofuels
	24	Aviation gasoline
	25	Gasoline type jet fuel
	26	Kerosene type jet fuel excluding biofuels
	27	Other kerosene
	28	Gas/diesel oil excluding biofuels
	29	Fuel oil
	30	Naphtha
	31	White spirit and SBP
	32	Lubricants
	33	Bitumen
	34	Paraffin waxes
	35	Petroleum coke
	36	Other oil products
Natural gas	37	Natural gas
Other fossil fuels	38	Peat
	39	Peat products
	40	Oil shale and oil sands

	41	Industrial waste
	42	Non-renewable municipal waste

Table S3. The countries/territories and their ISO-3166 codes.

Country/territory	ISO-3166 code	Country/territory	ISO-3166 code
Afghanistan	AFG	Kyrgyzstan	KGZ
Albania	ALB	Laos	LAO
Algeria	DZA	Latvia	LVA
Angola	AGO	Lebanon	LBN
Anguilla	AIA	Lesotho	LSO
Antigua and Barbuda	ATG	Liberia	LBR
Argentina	ARG	Libya	LBY
Armenia	ARM	Lithuania	LTU
Aruba	ABW	Luxembourg	LUX
Australia	AUS	Madagascar	MDG
Austria	AUT	Malawi	MWI
Azerbaijan	AZE	Malaysia	MYS
Bahamas	BHS	Maldives	MDV
Bahrain	BHR	Mali	MLI
Bangladesh	BGD	Malta	MLT
Barbados	BRB	Martinique	MTQ
Belarus	BLR	Mauritania	MRT
Belgium	BEL	Mauritius	MUS
Belize	BLZ	Mexico	MEX
Benin	BEN	Moldova	MDA
Bermuda	BMU	Mongolia	MNG
Bhutan	BTN	Montenegro	MNE
Bolivia	BOL	Montserrat	MSR
Bonaire, Sint Eustatius and Saba	BES	Morocco	MAR
Bosnia and Herzegovina	BIH	Mozambique	MOZ
Botswana	BWA	Myanmar	MMR
Brazil	BRA	Namibia	NAM
Brunei Darussalam	BRN	Nepal	NPL
Bulgaria	BGR	Netherlands	NLD
Burkina Faso	BFA	New Caledonia	NCL
Burundi	BDI	New Zealand	NZL
Cape Verde	CPV	Nicaragua	NIC
Cambodia	KHM	Niger	NER
Cameroon	CMR	Nigeria	NGA
Canada	CAN	North Macedonia	MKD
Cayman Islands	CYM	Norway	NOR
Central African Republic	CAF	Oman	OMN

Chad	TCD	Pakistan	PAK
Chile	CHL	Palau	PLW
China (including Hong Kong, Macao, and Taiwan)	CHN	Palestine	PSE
Colombia	COL	Panama	PAN
Comoros	COM	Papua New Guinea	PNG
Democratic Republic of Congo	COD	Paraguay	PRY
Congo	COG	Peru	PER
Cook Islands	COK	Philippines	PHL
Costa Rica	CRI	Poland	POL
Croatia	HRV	Portugal	PRT
Cuba	CUB	Puerto Rico	PRI
Curacao	CUW	Qatar	QAT
Cyprus	CYP	Romania	ROU
Czech Republic	CZE	Russia	RUS
Cote d'Ivoire	CIV	Rwanda	RWA
Denmark	DNK	Reunion	REU
Djibouti	DJI	Saint Kitts and Nevis	KNA
Dominica	DMA	Saint Lucia	LCA
Dominican Republic	DOM	Saint Pierre and Miquelon	SPM
Ecuador	ECU	Saint Vincent And Grenadines	VCT
Egypt	EGY	Samoa	WSM
El Salvador	SLV	Sao Tome and Principe	STP
Equatorial Guinea	GNQ	Saudi Arabia	SAU
Eritrea	ERI	Senegal	SEN
Estonia	EST	Serbia	SRB
Swaziland	SWZ	Seychelles	SYC
Ethiopia	ETH	Sierra Leone	SLE
Falkland Islands	FLK	Singapore	SGP
Fiji	FJI	Sint Maarten	SXM
Finland	FIN	Slovakia	SVK
France	FRA	Slovenia	SVN
French Guiana	GUF	Solomon Islands	SLB
French Polynesia	PYF	Somalia	SOM
Gabon	GAB	South Africa	ZAF
Gambia	GMB	South Sudan	SSD
Georgia	GEO	Spain	ESP
Germany	DEU	Sri Lanka	LKA

Ghana	GHA	Sudan	SDN
Gibraltar	GIB	Suriname	SUR
Greece	GRC	Sweden	SWE
Greenland	GRL	Switzerland	CHE
Grenada	GRD	Syria	SYR
Guadeloupe	GLP	Tajikistan	TJK
Guatemala	GTM	Tanzania	TZA
Guinea	GIN	Thailand	THA
Guinea-Bissau	GNB	Timor-Leste	TLS
Guyana	GUY	Togo	TGO
Haiti	HTI	Tonga	TON
Honduras	HND	Trinidad and Tobago	TTO
Hungary	HUN	Tunisia	TUN
Iceland	ISL	Turkey	TUR
India	IND	Turkmenistan	TKM
Indonesia	IDN	Turks and Caicos Islands	TCA
Islamic Republic of Iran	IRN	Uganda	UGA
Iraq	IRQ	Ukraine	UKR
Ireland	IRL	United Arab Emirates	ARE
Israel	ISR	United Kingdom	GBR
Italy	ITA	United States	USA
Jamaica	JAM	Uruguay	URY
Japan	JPN	Uzbekistan	UZB
Jordan	JOR	Vanuatu	VUT
Kazakhstan	KAZ	Venezuela	VEN
Kenya	KEN	Vietnam	VNM
Kiribati	KIR	British Virgin Islands	VGB
Democratic People's Republic of Korea	PRK	Yemen	YEM
Republic of Korea	KOR	Zambia	ZMB
Kuwait	KWT	Zimbabwe	ZWE

Table S4. The list of countries that once existed but have been disintegrated.

Country before dissolution	Countries after dissolution	Dissolution year
Former Soviet Union	Armenia	1990
	Azerbaijan	
	Belarus	
	Estonia	
	Georgia	
	Kazakhstan	
	Kyrgyzstan	
	Latvia	
	Lithuania	
	Moldova	
	Russia	
	Tajikistan	
	Turkmenistan	
	Ukraine	
	Uzbekistan	
Former Yugoslavia	Bosnia and Herzegovina	1990
	Croatia	
	North Macedonia	
	Montenegro	
	Slovenia	
	Serbia	
Ethiopia	Ethiopia	1992
	Eritrea	
Sudan	Sudan	2012
	South Sudan	
Serbia	Serbia	2005
	Montenegro	

Table S5. Small countries/territories that are not included.

Country/territory	ISO-3166 code	Country/territory	ISO-3166 code
American Samoa	ASM	Niue	NIU
Faeroe Islands	FRO	Norfolk Island	NFK
Guam	GUM	Northern Mariana Islands	MNP
Isle of Man	IMN	Pitcairn	PCN
Jersey	JEY	Saint Helena	SHN
Liechtenstein	LIE	Tokelau	TKL
Marshall Islands	MHL	Tuvalu	TUV
Mayotte	MYT	United States Virgin Islands	VIR
Federated States of Micronesia	FSM	Wallis and Futuna Islands	WLF
Nauru	NRU	Western Sahara	ESH

Table S6. The mapping table between the sectors in IEA statistics and MEIC.

IEA	MEIC
Main activity producer electricity plants	Power generation
Autoproducer electricity plants	
Main activity producer CHP plants	
Autoproducer CHP plants	
Main activity producer heat plants	Heat (auto producer)
Autoproducer heat plants	Heat (public)
Coal mines	Coal mines
Oil and gas extraction	Oil and gas extraction
Blast furnaces	Blast furnaces
Gas works	Gas works
Gasification plants for biogases	Gasification plants for biogases
Coke ovens	Coke ovens
Patent fuel plants	Patent fuel plants
BKB/peat briquette plants	BKB/peat briquette plants
Oil refineries	Oil refineries
Coal liquefaction plants	Coal liquefaction plants
Liquefaction (LNG) / regasification plants	Liquefaction (LNG) / regasification plants
Gas-to-liquids (GTL) plants	Gas-to-liquids (GTL) plants
Own use in electricity, CHP and heat plants	Own use in electricity, CHP and heat plants
Charcoal production plants	Charcoal production plants
Non-specified (energy)	Non-specified transformation industries
Iron and steel	Iron and steel
Non-ferrous metals	Non-ferrous metals
Chemical and petrochemical	Chemicals
Paper, pulp, and printing	Pulp and paper
Food and tobacco	Food and tobacco
Non-metallic minerals	Cement
	Other non-metallic minerals
Transport equipment	Transport equipment
Machinery	Machinery
Mining and quarrying	Mining and quarrying
Wood and wood products	Wood products
Construction	Construction
Textile and leather	Textile and leather
Industry not elsewhere specified	Other non-specified industries
International aviation bunkers	International aviation
Domestic aviation	Domestic aviation
Rail	Rail

International marine bunkers	International navigation
Domestic navigation	Domestic navigation
Pipeline transport	Pipeline transport
Transport not elsewhere specified	Other non-specified transport
Agriculture/forestry	Agriculture and forestry
Fishing	Fishing
Road	Cars
	Light duty trucks
	Buses
	Heavy duty trucks
	Motorcycles
	Other fleet totals
Commercial and public services	Commercial and institutional
Residential	Residential (rural)
	Residential (urban)
Final consumption not elsewhere specified	Non-specified sectors
Not included*	Process emissions in cement industry

*IEA only provides energy consumption statistics without data on process.

Table S7. The list of emerging economies and their data sources in CEADs.

Emerging economies	ISO-3166 code	Activity rate source [8]	Emission factor source [8]
Argentina	ARG	The National Institute of Statistics and Censuses, Argentina [9]	IEA Global Engagement [10]
Bolivia	BOL	Ministerio de Hidrocarburos y Energías, Bolivia [11]; Instituto Nacional de Estadística [12]	IPCC [13]
Brazil	BRA	Energy Research Office, Brazil [14]; Instituto Brasileiro de Geografia e Estatística [15]	IEA Global Engagement [10]
Chile	CHL	Energía Abierta - Comisión Nacional de Energía, Chile [16]; Instituto Nacional de Estadísticas [17]	IPCC [13]
Colombia	COL	Unidad de Planeación Minero Energética, Columbia [18]	IPCC [13]
Ecuador	ECU	Ministerio de Energía y Minas, Ecuador [19]; Instituto Nacional de Estadística y Censos [20]	IPCC [13]
Estonia	EST	Statistics Estonia [21]	UNFCCC National Inventory Submissions [22]
Ethiopia	ETH	Central Statistical Agency, Ethiopia [23]	IPCC [13]
Ghana	GHA	Energy Commission, Ghana [24]; Ghana Statistical Services [25]	IPCC [13]
Guatemala	GTM	Ministerio de Energía y Minas, Guatemala [26]; Instituto Nacional de Estadística Guatemala [27]	IPCC [13]
India	IND	Ministry of Statistics and Programme Implementation, India [28]; GHG Platform India [29]	IPCC [13]
Indonesia	IDN	Badan Pusat Statistik, Indonesia [30]; CEIC Database [31]	IPCC [13]
Kenya	KEN	UN stats [32];	IPCC [13]

		Kenya National Bureau of Statistics [33]	
Mongolia	MNG	Mongolian Statistical Information Service [34]	IPCC [13]
Peru	PER	Sistema Nacional de Información Ambiental, Peru [35]; Instituto Nacional de Estadística e Informática [36]	IPCC [13]
Russia	RUS	ЕМИСС Government Statistics [37]	ЕМИСС Government Statistics [37]
South Africa	ZAF	Department of Energy, South Africa [38]	IEA Global Engagement [10]
Tanzania	TZA	African Energy Commission (AFREC) [39]; Tanzania National Bureau of Statistics [40]	IPCC [13]
Turkey	TUR	World Energy Council Turkish National Committee [41]; Turkish Statistical Institute [42]	UNFCCC National Inventory Submissions [22]
Uganda	UGA	African Energy Commission (AFREC) [39]; Uganda Bureau of Statistics [43]	IPCC [13]
Cambodia	KHM	Economic Research Institute for ASEAN and East Asia (ERIA) [44]; Asian Development Bank [45]	IPCC [13]
Djibouti	DJI	African Energy Commission (AFREC) [39]; National Institute of Statistics of Djibouti [46]	IPCC [13]
Jamaica	JAM	Ministry of Science, Energy & Technology, Jamaica [47]; Statistical Institute of Jamaica [48]	IEA Global Engagement [10]
Jordan	JOR	Minister of Energy and Mineral Resources, Jordan [49]; Department of Statistics, Jordan [50]	IPCC [13]
Laos	LAO	Economic Research Institute for ASEAN and East Asia (ERIA) [44]; Laos Statistical Information	IPCC [13]

		Service [51]	
Moldova	MDA	Statistical databank, Moldova [52]	IPCC [13]
Myanmar	MMR	Economic Research Institute for ASEAN and East Asia (ERIA) [44]; Asian Development Bank [45]	IPCC [13]
Paraguay	PRY	Instituto Nacional de Estadística, Paraguay [53]	IPCC [13]
Thailand	THA	Department of Alternative Energy Development and Efficiency, Thailand [54]; Asian Development Bank [45]	IPCC [13]
Uruguay	URY	Instituto Nacional de Estadística, Uruguay [55]	IPCC [13]

Table S8. The sub-country administrative divisions included.

Country	Sub-country administrative divisions	Abbreviation
Argentina	Buenos Aires	BA
	Catamarca	CT
	Chaco	CC
	Chubut	CH
	Ciudad de Buenos Aires	DF
	Córdoba	CB
	Corrientes	CN
	Entre Ríos	ER
	Formosa	FM
	Jujuy	JY
	La Pampa	LP
	La Rioja	LR
	Mendoza	MZ
	Misiones	MN
	Neuquén	NQ
	Río Negro	RN
	Salta	SA
	San Juan	SJ
	San Luis	SL
	Santa Cruz	SC
	Santa Fe	SF
	Santiago del Estero	SE
	Tierra del Fuego	TF
	Tucumán	TM
Australia	Ashmore and Cartier Islands	AS
	Australian Capital Territory	AC
	Coral Sea Islands Territory	CR
	Jervis Bay Territory	JB
	New South Wales	NS
	Northern Territory	NT
	Queensland	QL
	South Australia	SA
	Tasmania	TS
	Victoria	VI
	Western Australia	WA
Bolivia	Chuquisaca	CQ
	Cochabamba	CB
	El Beni	EB
	La Paz	LP
	Oruro	OR

	Pando	PA
	Potosí	PO
	Santa Cruz	SC
	Tarija	TR
Brazil	Acre	AC
	Alagoas	AL
	Amapá	AP
	Amazonas	AM
	Bahia	BA
	Ceará	CE
	Distrito Federal	DF
	Espírito Santo	ES
	Goiás	GO
	Maranhão	MA
	Mato Grosso	MT
	Mato Grosso do Sul	MS
	Minas Gerais	MG
	Pará	PA
	Paraíba	PB
	Paraná	PR
	Pernambuco	PE
	Piauí	PI
	Rio de Janeiro	RJ
	Rio Grande do Norte	RN
	Rio Grande do Sul	RS
	Rondônia	RO
	Roraima	RR
	Santa Catarina	SC
	São Paulo	SP
	Sergipe	SE
	Tocantins	TO
Canada	Alberta	AB
	British Columbia	BC
	Manitoba	MB
	New Brunswick	NB
	Newfoundland and Labrador	NF
	Northwest Territories	NT
	Nova Scotia	NS
	Nunavut	NU
	Ontario	ON
	Prince Edward Island	PE
	Quebec	QC
	Saskatchewan	SK

	Yukon	YT
Chile	Aysén del General Carlos Ibáñez del Campo	AI
	Antofagasta	AN
	Araucanía	AR
	Arica and Parinacota	AP
	Atacama	AT
	Biobío	BI
	Coquimbo	CO
	Libertador General Bernardo O'Higgins	LI
	Los Lagos	LL
	Los Ríos	LR
	Magallanes y de la Antártica Chilena	MA
	Maule	ML
	Ñuble	NB
	Región Metropolitana de Santiago	RM
	Tarapacá	TA
	Valparaíso	VS
China	Anhui	AH
	Beijing	BJ
	Chongqing	CQ
	Fujian	FJ
	Gansu	GS
	Guangdong	GD
	Guangxi	GX
	Guizhou	GZ
	Hainan	HA
	Hebei	HB
	Heilongjiang	HL
	Henan	HE
	Hubei	HU
	Hunan	HN
	Jiangsu	JS
	Jiangxi	JX
	Jilin	JL
	Liaoning	LN
	Nei Mongol	NM
	Ningxia Hui	NX
	Qinghai	QH
	Shaanxi	SA
	Shandong	SD
	Shanghai	SH
	Shanxi	SX
	Sichuan	SC

	Tianjin	TJ
	Xinjiang Uygur	XJ
	Xizang	XZ
	Yunnan	YN
	Zhejiang	ZJ
	Hong Kong	HK
	Macao	MC
	Taiwan	TW
Colombia	Amazonas	AM
	Antioquia	AN
	Arauca	AR
	Atlántico	AT
	Bolívar	BL
	Boyacá	BY
	Caldas	CL
	Caquetá	CQ
	Casanare	CS
	Cauca	CA
	Cesar	CE
	Chocó	CH
	Córdoba	CO
	Cundinamarca	CU
	Guainía	GN
	Guaviare	GV
	Huila	HU
	La Guajira	LG
	Magdalena	MA
	Meta	ME
	Nariño	NA
	Norte de Santander	NS
	Putumayo	PU
	Quindío	QD
	Risaralda	RI
	San Andrés y Providencia	SA
	Santander	ST
	Sucre	SU
	Tolima	TO
	Valle del Cauca	VC
	Vaupés	VP
	Vichada	VD
Ecuador	Azuay	AZ
	Bolivar	BO
	Cañar	CN

	Carchi	CR
	Chimborazo	CB
	Cotopaxi	CT
	El Oro	EO
	Esmeraldas	ES
	Galápagos	GA
	Guayas	GU
	Imbabura	IM
	Loja	LJ
	Los Rios	LR
	Manabí	MN
	Morona Santiago	MS
	Napo	NA
	Orellana	OR
	Pastaza	PA
	Pichincha	PI
	Santa Elena	SE
	Santo Domingo de los Tsáchilas	SD
	Sucumbíos	SU
	Tungurahua	TU
	Zamora Chinchipe	ZC
Estonia	Harju	HA
	Hiiu	HI
	Ida-Viru	IV
	Jõgeva	JR
	Järva	JN
	Lääne	LN
	Lääne-Viru	LV
	Pärnu	PR
	Peipsi	PP
	Põlva	PL
	Rapla	RA
	Saare	SA
	Tartu	TA
	Valga	VG
	Viljandi	VD
	Võru	VR
Ethiopia	Addis Abeba	AA
	Afar	AF
	Amhara	AM
	Benshangul-Gumaz	BE
	Dire Dawa	DD
	Gambela Peoples	GA

	Harari People	HA
	Oromia	OR
	Somali	SO
	Southern Nations, Nationalities and Peoples	SN
	Tigray	TI
Ghana	Ashanti	AH
	Brong Ahafo	BA
	Central	CP
	Eastern	EP
	Greater Accra	AA
	Northern	NP
	Upper East	UE
	Upper West	UW
	Volta	TV
	Western	WP
Guatemala	Alta Verapaz	AV
	Baja Verapaz	BV
	Chimaltenango	CM
	Chiquimula	CQ
	El Progreso	PR
	Escuintla	ES
	Guatemala	GU
	Huehuetenango	HU
	Izabal	IZ
	Jalapa	JA
	Jutiapa	JU
	Petén	PE
	Quetzaltenango	QZ
	Quiché	QC
	Retalhuleu	RE
	Sacatepéquez	SA
	San Marcos	SM
	Santa Rosa	SR
	Sololá	SO
	Suchitepéquez	SU
	Totonicapán	TO
	Zacapa	ZA
Indonesia	Aceh	AC
	Bali	BA
	Bangka Belitung	BB
	Banten	BT
	Bengkulu	BE
	Gorontalo	GO

	Jakarta Raya	JK
	Jambi	JA
	Jawa Barat	JR
	Jawa Tengah	JT
	Jawa Timur	JI
	Kalimantan Barat	KB
	Kalimantan Selatan	KS
	Kalimantan Tengah	KT
	Kalimantan Timur	KM
	Kepulauan Riau	KR
	Lampung	LA
	Maluku	MA
	Maluku Utara	MU
	Nusa Tenggara Barat	NB
	Nusa Tenggara Timur	NT
	Papua	PA
	Papua Barat	IB
	Riau	RI
	Sulawesi Barat	SR
	Sulawesi Selatan	SE
	Sulawesi Tengah	ST
	Sulawesi Tenggara	SG
	Sulawesi Utara	SW
	Sumatera Barat	SB
	Sumatera Selatan	SL
	Sumatera Utara	SU
	Yogyakarta	YO
India	Andaman and Nicobar	AN
	Andhra Pradesh	AP
	Arunachal Pradesh	AR
	Assam	AS
	Bihar	BR
	Chandigarh	CH
	Chhattisgarh	CT
	Dadra and Nagar Haveli	DN
	Daman and Diu	DD
	Goa	GA
	Gujarat	GJ
	Haryana	HR
	Himachal Pradesh	HP
	Jammu and Kashmir	JK
	Jharkhand	JH
	Karnataka	KA

	Kerala	KL
	Lakshadweep	LD
	Madhya Pradesh	MP
	Maharashtra	MH
	Manipur	MN
	Meghalaya	ML
	Mizoram	MZ
	Nagaland	NL
	NCT of Delhi	DL
	Odisha	OR
	Puducherry	PY
	Punjab	PB
	Rajasthan	RJ
	Sikkim	SK
	Tamil Nadu	TN
	Telangana	TG
	Tripura	TR
	Uttar Pradesh	UP
	Uttarakhand	UT
	West Bengal	WB
Kenya	Baringo	BA
	Bomet	BO
	Bungoma	BN
	Busia	BS
	Elgeyo-Marakwet	EM
	Embu	EB
	Garissa	GA
	Homa Bay	HB
	Isiolo	IS
	Kajiado	KJ
	Kakamega	KK
	Kericho	KR
	Kiambu	KB
	Kilifi	KF
	Kirinyaga	KY
	Kisii	KI
	Kisumu	KU
	Kitui	KT
	Kwale	KW
	Laikipia	LK
	Lamu	LM
	Machakos	MC
	Makueni	MK

	Mandera	MD
	Marsabit	MB
	Meru	ME
	Migori	MG
	Mombasa	MM
	Murang'a	MU
	Nairobi	NB
	Nakuru	NK
	Nandi	ND
	Narok	NR
	Nyamira	NM
	Nyandarua	NN
	Nyeri	NI
	Samburu	SA
	Siaya	SI
	Taita Taveta	TT
	Tana River	TR
	Tharaka-Nithi	NT
	Trans Nzoia	TN
	Turkana	TU
	Uasin Gishu	UG
	Vihiga	VI
	Wajir	WJ
	West Pokot	WP
Mongolia	Arhangay	AR
	Bayan-Ölgii	BO
	Bayanhongor	BH
	Bulgan	BU
	Darhan-Uul	DA
	Dornod	DD
	Dornogovi	DG
	Dundgovi	DU
	Dzavhan	DZ
	Govi-Altay	GA
	Govisümber	GS
	Hentiy	HN
	Hovd	HD
	Khövsgöl	HG
	Ömnögovi	OG
	Orhon	ER
	Övörkhangai	OH
	Selenge	SL
	Sükhbaatar	SB

	Töv	TO
	Ulaanbaatar	UB
	Uvs	UV
Peru	Amazonas	AM
	Ancash	AN
	Apurímac	AP
	Arequipa	AR
	Ayacucho	AY
	Cajamarca	CJ
	Callao	CL
	Cusco	CS
	Huancavelica	HV
	Huánuco	HC
	Ica	IC
	Junín	JU
	La Libertad	LL
	Lambayeque	LB
	Lima	LR
	Lima Province	LP
	Loreto	LO
	Madre de Dios	MD
	Moquegua	MQ
	Pasco	PA
	Piura	PI
	Puno	PU
	San Martín	SM
	Tacna	TA
	Tumbes	TU
	Ucayali	UC
Russia	Adygea	AD
	Altay	AL
	Amur	AM
	Arkhangelsk	AR
	Astrakhan'	AS
	Bashkortostan	BK
	Belgorod	BL
	Bryansk	BR
	Buryat	BU
	Chechnya	CN
	Chelyabinsk	CL
	Chukotka	CK
	Chuvash	CV
	City of St. Petersburg	SP

Dagestan	DA
Gorno-Altay	GA
Ingush	IN
Irkutsk	IK
Ivanovo	IV
Kabardino-Balkaria	KB
Kaliningrad	KN
Kalmyk	KL
Kaluga	KG
Kamchatka	KQ
Karachay-Cherkess	KC
Karelia	KI
Kemerovo	KE
Khabarovsk	KH
Khakass	KK
Khanty-Mansiy	KM
Kirov	KV
Komi	KO
Kostroma	KT
Krasnodar	KD
Krasnoyarsk	KX
Kurgan	KU
Kursk	KS
Leningrad	LN
Lipetsk	LP
Maga Buryatdan	MG
Mariy-El	ME
Mordovia	MR
Moscow City	
Moskva	MS
Murmansk	MM
Nenets	NN
Nizhegorod	NZ
North Ossetia	NO
Novgorod	NG
Novosibirsk	NS
Omsk	OM
Orel	OL
Orenburg	OB
Penza	PZ
Perm'	PE
Primorye	PR
Pskov	PS

	Rostov	RO
	Ryazan'	RZ
	Sakha	SK
	Sakhalin	SL
	Samara	SA
	Saratov	SR
	Smolensk	SM
	Stavropol	ST
	Sverdlovsk	SV
	Tambov	TB
	Tatarstan	TT
	Tomsk	TO
	Tula	TL
	Tuva	TU
	Tver	TV
	Tyumen'	TY
	Udmurt	UD
	Ulyanovsk	UL
	Vladimir	VL
	Volgograd	VG
	Vologda	VO
	Voronezh	VR
	Yamal-Nenets	YN
	Yaroslavl	YS
	Yevrey	YV
	Zabaykal'ye	ZB
Saudi Arabia	`Asir	AS
	Al Bahah	BA
	Al Hudud ash Shamaliyah	HS
	Al Jawf	JF
	Al Madinah	MD
	Al Quassim	QS
	Ar Riyad	RI
	Ash Sharqiyah	SH
	Ha'il	HA
	Jizan	JZ
	Makkah	MK
	Najran	NJ
	Tabuk	TB
Turkey	Adana	AA
	Adiyaman	AD
	Afyon	AF
	Agri	AG

Aksaray	AK
Amasya	AM
Ankara	AN
Antalya	AL
Ardahan	AR
Artvin	AV
Aydin	AY
Balikesir	BK
Bartın	BR
Batman	BM
Bayburt	BB
Bilecik	BC
Bingöl	BG
Bitlis	BT
Bolu	BL
Burdur	BD
Bursa	BU
Çanakkale	CK
Çankırı	CI
Çorum	CM
Denizli	DN
Diyarbakir	DY
Düzce	DU
Edirne	ED
Elazığ	EG
Erzincan	EN
Erzurum	EM
Eskisehir	ES
Gaziantep	GA
Giresun	GI
Gümüşhane	GU
Hakkari	HK
Hatay	HT
Iğdır	IG
Isparta	IP
Istanbul	IB
Izmir	IZ
K. Maras	KM
Karabük	KB
Karaman	KR
Kars	KA
Kastamonu	KS
Kayseri	KY

	Kilis	KI
	Kinkkale	KK
	Kirklareli	KL
	Kirsehir	KH
	Kocaeli	KC
	Konya	KO
	Kütahya	KU
	Malatya	ML
	Manisa	MN
	Mardin	MR
	Mersin	IC
	Mugla	MG
	Mus	MS
	Nevsehir	NV
	Nigde	NG
	Ordu	OR
	Osmaniye	OS
	Rize	RI
	Sakarya	SK
	Samsun	SS
	Sanliurfa	SU
	Siirt	SI
	Sinop	SP
	Sirnak	SR
	Sivas	SV
	Tekirdag	TG
	Tokat	TT
	Trabzon	TB
	Tunceli	TC
	Usak	US
	Van	VA
	Yalova	YL
	Yozgat	YZ
	Zinguldak	ZO
Tanzania	Arusha	AS
	Dar es Salaam	DS
	Dodoma	DO
	Geita	GE
	Iringa	IG
	Kagera	KG
	Katavi	KA
	Kigoma	KM
	Kilimanjaro	KL

	Lindi	LI
	Manyara	MY
	Mara	MA
	Mbeya	MB
	Morogoro	MO
	Mtwara	MT
	Mwanza	MZ
	Njombe	NJ
	Pemba North	PN
	Pemba South	PS
	Pwani	PW
	Rukwa	RU
	Ruvuma	RV
	Shinyanga	SY
	Simiyu	SI
	Singida	SD
	Tabora	TB
	Tanga	TN
	Zanzibar North	ZN
	Zanzibar South and Central	ZS
	Zanzibar West	ZW
Uganda	Adjumani	AD
	Apac	AC
	Arua	AW
	Bugiri	BG
	Bundibugyo	BN
	Bushenyi	BS
	Busia	BU
	Gulu	GL
	Hoima	HO
	Iganga	IN
	Jinja	JI
	Kabale	KA
	Kabarole	BR
	Kaberamaido	KD
	Kalangala	KN
	Kampala	KM
	Kamuli	KX
	Kamwenge	KE
	Kanungu	UU
	Kapchorwa	KP
	Kasese	KS
	Katakwi	KK

	Kayunga	KY
	Kibale	KI
	Kiboga	KG
	Kisoro	KR
	Kitgum	TG
	Kotido	KF
	Kumi	KU
	Kyenjojo	KJ
	Lake Albert	LL
	Lake Victoria	LV
	Lira	LA
	Luwero	LW
	Masaka	MA
	Masindi	MC
	Mayuge	MG
	Mbale	ME
	Mbarara	RR
	Moroto	MT
	Moyo	MY
	Mpigi	MI
	Mubende	MD
	Mukono	MN
	Nakapiripirit	NP
	Nakasongola	NA
	Nebbi	NE
	Ntungamo	NT
	Pader	PD
	Pallisa	PL
	Rakai	RA
	Rukungiri	RK
	Sembabule	SE
	Sironko	SI
	Soroti	SR
	Tororo	TR
	Wakiso	WA
	Yumbe	YU
United States	Alabama	AL
	Alaska	AK
	Arizona	AZ
	Arkansas	AR
	California	CA
	Colorado	CO
	Connecticut	CT

Delaware	DE
District of Columbia	DC
Florida	FL
Georgia	GA
Hawaii	HI
Idaho	ID
Illinois	IL
Indiana	IN
Iowa	IA
Kansas	KS
Kentucky	KY
Louisiana	LA
Maine	ME
Maryland	MD
Massachusetts	MA
Michigan	MI
Minnesota	MN
Mississippi	MS
Missouri	MO
Montana	MT
Nebraska	NE
Nevada	NV
New Hampshire	NH
New Jersey	NJ
New Mexico	NM
New York	NY
North Carolina	NC
North Dakota	ND
Ohio	OH
Oklahoma	OK
Oregon	OR
Pennsylvania	PA
Rhode Island	RI
South Carolina	SC
South Dakota	SD
Tennessee	TN
Texas	TX
Utah	UT
Vermont	VT
Virginia	VA
Washington	WA
West Virginia	WV
Wisconsin	WI

	Wyoming	WY
South Africa	Eastern Cape	EC
	Free State	FS
	Gauteng	GT
	KwaZulu-Natal	NL
	Limpopo	NP
	Mpumalanga	MP
	North West	NW
	Northern Cape	NC
	Western Cape	WC
Germany	Baden-Württemberg	BW
	Saarland	SL
	Berlin	BE
	Brandenburg	BR
	Bremen	HB
	Hamburg	HH
	Mecklenburg-Vorpommern	MV
	Niedersachsen	NI
	Sachsen-Anhalt	ST
	Schleswig-Holstein	SH
	Bayern	BY
	Hessen	HE
	Nordrhein-Westfalen	NW
	Rheinland-Pfalz	RP
	Sachsen	SN
	Thüringen	TH
United Kingdom	North East	NE
	North West	NW
	Yorkshire and the Humber	YH
	East Midlands	EM
	West Midlands	WM
	East of England	EE
	Greater London	GL
	South East	SE
	South West	SW
	Northern Ireland	NI
	Wales	WL
	Scotland	SL
Italy	Abruzzo	AB
	Apulia	AP
	Basilicata	BS
	Calabria	CL
	Campania	CP

	Emilia-Romagna	ER
	Friuli-Venezia Giulia	FV
	Lazio	LZ
	Liguria	LG
	Lombardia	LB
	Marche	MC
	Molise	ML
	Piemonte	PM
	Sardegna	SD
	Sicily	SC
	Toscana	TC
	Trentino-Alto Adige	TA
	Umbria	UB
	Valle d'Aosta	VD
	Veneto	VN
France	Bretagne	BT
	Auvergne-Rhône-Alpes	AR
	Bourgogne-Franche-Comté	BF
	Centre-Val de Loire	CN
	Corse	CE
	Grand Est	AO
	Île-de-France	IF
	Provence-Alpes-Côte d'Azur	PR
	Normandie	ND
	Nouvelle-Aquitaine	AC
	Occitanie	LP
	Pays de la Loire	PL
	Hauts-de-France	NC
	Monaco	MN

Table S9. The sources of sub-country energy data and proxy in Australia, Canada, Saudi Arabia, the United States, Germany, France, Italy, and the United Kingdom.

Country	Source
Australia	Australian Bureau of Statistics [56]
	Department of Industry, Science, Energy and Resources [57]
Canada	Statistics Canada [58]
France	INSEE [59]
Germany	Statistisches Bundesamt [60]
Italy	Istat [61]
Saudi Arabia	Saudi Arabian Bureau of Statistics [62]

	United States Geological Survey [63]
United States	U.S. Energy Information Administration [64]
	Bureau of Economic Analysis [65]
	U.S. Department of Agriculture [66]
	Office for National Statistic [67]
United Kingdom	Department for Business, Energy & Industrial Strategy [68]

Table S10. Country-based and sector-specific parameters for disaggregation of lumped IEA regional statistics.

Parameter	Source	Detailed sector
Power generation	GPED [69]	Power generation
		Heat (auto producer)
		Heat (public)
Cement production	USGS [70]	Cement
		Other non-metallic minerals
Pig iron production	World Steel Association [71]	Blast furnaces
		Coke ovens
Crude steel production	World Steel Association [71]	Iron and steel
GDP	World Bank [6]; UN data [72]	Cars
		Light duty trucks
		Buses
		Heavy duty trucks
		Motorcycles
		Other fleet totals
		Pipeline transport
		Other non-specified transport
		Commercial and institutional
		Non-specified sectors
Industry GDP	World Bank [6]	Coal mines
		Oil and gas extraction
		Gas works
		Gasification plants for biogases
		Patent fuel plants
		BKB/peat briquette plants
		Oil refineries
		Coal liquefaction plants
		Liquefaction (LNG) / regasification plants
		Gas-to-liquids (GTL) plants
		Own use in electricity, CHP and heat plants
		Charcoal production plants
		Non-specified transformation industries
		Mining and quarrying
		Other non-specified industries
Population	WPP [7]	Residential (rural)
		Residential (urban)
Value added by	UN Statistical Yearbook	Construction

construction	[73]	
Value added by manufacture	UN Statistical Yearbook [73]	Non-ferrous metals
		Chemicals
		Pulp and paper
		Food and tobacco
		Transport equipment
		Machinery
		Wood products
		Textile and leather
		Other non-specified industries
Value added by agriculture, hunting, forestry and fishing	UN Statistical Yearbook [73]	Agriculture and forestry
Aviation fuel consumption	OAG [74]	International aviation
		Domestic aviation
Merchant fleet (navigation)	UN Statistical Yearbook [73]	International navigation
		Domestic navigation
Net ton-kilometer (rail)	UN Statistical Yearbook [73]	Rail
Fish catches	UN Statistical Yearbook [73]	Fishing

Table S11. The mapping of sectors in this study and MEIC-China.

MEIC-China	This study
Power	Power generation
Heating (industrial)	Heat (auto producer)
	Heat (public)
Industrial boilers	Coal mines
	Oil and gas extraction
	Blast furnaces
	Gas works
	Gasification plants for biogases
	Coke ovens
	Patent fuel plants
	BKB/peat briquette plants
	Oil refineries
	Coal liquefaction plants
	Liquefaction (LNG) / regasification plants
	Gas-to-liquids (GTL) plants
	Own use in electricity, CHP and heat plants
	Charcoal production plants
	Non-specified transformation industries
	Iron and steel
	Non-ferrous metals
	Chemicals
	Pulp and paper
	Food and tobacco
	Cement
	Other non-metallic minerals
	Transport equipment
	Machinery
	Mining and quarrying
	Wood products
	Construction
	Textile and leather
	Other non-specified industries
Mobile source (off-road)	Domestic aviation
	Rail
	Domestic navigation
	Pipeline transport
	Other non-specified transport
	Agriculture and forestry
	Fishing
Mobile source (on-road)	Cars

	Light duty trucks
	Buses
	Heavy duty trucks
	Motorcycles
	Other fleet totals
Heating (residential)	Commercial and institutional
Residential (rural)	Residential (rural)
Residential (urban)	Residential (urban)
Cement process	Process emissions in cement industry

Table S12. The mapping of fuel types in this study and MEIC-China.

MEIC-China	This study
Raw coal Clean coal Other washed coal Briquettes Other coking products	Anthracite
	Coking coal
	Other bituminous coal
	Sub-bituminous coal
	Lignite
	Patent fuel
	Gas coke
	Coal tar
	BKB
Coke	Coke oven coke
Coke oven gas	Coke oven gas
Other gas	Gas works gas
	Blast furnace gas
	Other recovered gases
Crude oil	Crude oil
	Natural gas liquids
	Refinery feedstocks
	Additives/blending components
	Other hydrocarbons
Refinery gas	Refinery gas
Gasoline	Motor gasoline excluding biofuels
	Gasoline type jet fuel
Diesel oil	Gas/diesel oil excluding biofuels
Fuel oil	Fuel oil
LPG	Liquefied petroleum gases (LPG)
Kerosene	Kerosene type jet fuel excluding biofuels
	Other kerosene
Other petroleum products	Ethane
	Aviation gasoline
	Naphtha
	White spirit and SBP
	Lubricants
	Bitumen
	Paraffin waxes
	Petroleum coke
	Other oil products
Natural gas	Natural gas

Table S13. The mapping of sectors in this study and CEADs.

CEADs	This study
Production and Supply of Electric Power, Steam and Hot Water	Power generation
	Heat (auto producer)
	Heat (public)
	Own use in electricity, CHP and heat plants
Coal Mining and Dressing	Coal mines
Petroleum and Natural Gas Extraction	Oil and gas extraction
Production and Supply of Gas	Gas works
Petroleum Processing and Coking	Gasification plants for biogases
	Coke ovens
	Patent fuel plants
	BKB/peat briquette plants
	Oil refineries
	Coal liquefaction plants
	Liquefaction (LNG) / regasification plants
	Gas-to-liquids (GTL) plants
	Charcoal production plants
	Non-specified transformation industries
Smelting and Pressing of Ferrous Metals	Iron and steel
	Blast furnaces
Smelting and Pressing of Nonferrous Metals	Non-ferrous metals
Chemical Fiber Medical and Pharmaceutical Products Raw Chemical Materials and Chemical Products	Chemicals
Papermaking and Paper Products Printing and Record Medium Reproduction	Pulp and paper
Beverage Production Food Processing Food Production Tobacco Processing	Food and tobacco
Nonmetal Mineral Products	Cement
	Other non-metallic minerals
Transportation Equipment	Transport equipment
Electric Equipment and Machinery Electronic and Telecommunications Equipment Equipment for Special Purposes Instruments, Meters, Cultural and Office Machinery Metal Products Ordinary Machinery	Machinery
Ferrous Metals Mining and Dressing Nonferrous Metals Mining and Dressing	Mining and quarrying

Nonmetal Minerals Mining and Dressing Other Minerals Mining and Dressing	
Logging and Transport of Wood and Bamboo Timber Processing, Bamboo, Cane, Palm Fiber & Straw Products	Wood products
Construction	Construction
Garments and Other Fiber Products Leather, Furs, Down and Related Products Textile Industry	Textile and leather
Cultural, Educational and Sports Articles Furniture Manufacturing Other Manufacturing Industry Plastic Products Rubber Products	Other non-specified industries
Transportation, Storage, Post and Telecommunication Services	Domestic aviation
	Rail
	Domestic navigation
	Pipeline transport
	Other non-specified transport
	Cars
	Light duty trucks
	Buses
	Heavy duty trucks
	Motorcycles
	Other fleet totals
Agriculture, forestry, hunting, fishing and husbandry	Agriculture and forestry
	Fishing
Other Services Production and Supply of Tap Water Scrap and waste Wholesale, Retail Trade and Catering Services	Commercial and institutional
Rural	Residential (rural)
Urban	Residential (urban)

Table S14. The mapping of fuel types in this study and CEADs.

CEADs	This study
Coal	Anthracite
	Coking coal
	Other bituminous coal
	Sub-bituminous coal
	Lignite
	Patent fuel
	Gas coke
	Coal tar
	BKB
	Coke oven coke
	Coke oven gas
	Gas works gas
	Blast furnace gas
	Other recovered gases
Crude, NGL, Ref Feeds.	Crude oil
	Natural gas liquids
	Refinery feedstocks
	Additives/blending components
	Other hydrocarbons
Oil products	Refinery gas
	Motor gasoline excluding biofuels
	Gasoline type jet fuel
	Gas/diesel oil excluding biofuels
	Fuel oil
	Liquefied petroleum gases (LPG)
	Kerosene type jet fuel excluding biofuels
	Other kerosene
	Ethane
	Aviation gasoline
	Naphtha
	White spirit and SBP
	Lubricants
	Bitumen
	Paraffin waxes
	Petroleum coke
	Other oil products
Natural gas	Natural gas
Peat & Peat products	Peat
	Peat products
Oil shale & oil sands	Oil shale and oil sands

Table S15. Sub-country mapping of sector in energy data or proxy used to downscale activity rates in 8 large emitters. Proxy is marked by asterisk (*).

S15.1 Australia

MEIC Sector	Sector or proxy
Power generation	Sub-country energy consumption from GPED
Heat (auto producer)	Consumption of energy, Electricity supply
Heat (public)	
Coal mines	Consumption of energy, Mining
Oil and gas extraction	Production of crude oil and NGL*
Blast furnaces	Sub-country energy consumption from GISD
Gas works	Gross state product*
Gasification plants for biogases	
Coke ovens	Sub-country energy consumption from GISD
Patent fuel plants	Gross state product*
BKB/peat briquette plants	
Oil refineries	Production of crude oil and NGL*
Coal liquefaction plants	Gross state product*
Liquefaction (LNG) / regasification plants	
Gas-to-liquids (GTL) plants	
Own use in electricity, CHP and heat plants	Consumption of energy, Electricity supply
Charcoal production plants	Gross state product*
Non-specified transformation industries	
Iron and steel	Sub-country energy consumption from GISD
Non-ferrous metals	Consumption of energy, Manufacturing
Chemicals	Consumption of energy, Basic Chemical and Chemical, Polymer and Rubber Product
Pulp and paper	Consumption of energy, Pulp, paper and printing
Food and tobacco	Consumption of energy, Food, beverages and tobacco
Cement	Sub-country energy consumption from GCED
Other non-metallic minerals	Consumption of energy, Non-metallic mineral products
Transport equipment	Consumption of energy, Machinery and equipment
Machinery	
Mining and quarrying	Consumption of energy, Mining
Wood products	Consumption of energy, Wood and wood products
Construction	Consumption of energy, Construction
Textile and leather	Consumption of energy, Textile, clothing, footwear and leather
Other non-specified industries	Consumption of energy, Furniture and other manufacturing

International aviation	-
Domestic aviation	Consumption of energy, Air transport
Rail	Railway length*
International navigation	-
Domestic navigation	Consumption of energy, Of which coastal bunkers
Pipeline transport	Consumption of energy, Other transport, services and storage
Other non-specified transport	
Agriculture and forestry	Consumption of energy, Agriculture, forestry and fishing
Fishing	
Cars	Consumption of energy, Road transport
Light duty trucks	
Buses	
Heavy duty trucks	
Motorcycles	
Other fleet totals	
Commercial and institutional	Consumption of energy, Commercial and services
Residential (rural)	Consumption of energy, Residential
Residential (urban)	
Non-specified sectors	Population*
Process emissions in cement industry	Sub-country energy consumption from GCED

S15.2 Canada

MEIC Sector	Sector or proxy
Power generation	Sub-country energy consumption from GPED
Heat (auto producer)	Generation: Utilities*
Heat (public)	
Coal mines	Physical flow account for greenhouse gas emissions: Coal mining*
Oil and gas extraction	Physical flow account for greenhouse gas emissions: Oil and gas extraction*
Blast furnaces	Sub-country energy consumption from GISD
Gas works	Physical flow account for greenhouse gas emissions: Petroleum and coal product manufacturing*
Gasification plants for biogases	
Coke ovens	Sub-country energy consumption from GISD
Patent fuel plants	Physical flow account for greenhouse gas emissions: Petroleum and coal product manufacturing*
BKB/peat briquette plants	
Oil refineries	
Coal liquefaction plants	
Liquefaction (LNG) / regasification plants	
Gas-to-liquids (GTL) plants	
Own use in electricity, CHP and	Generation: Utilities*

heat plants	
Charcoal production plants	Physical flow account for greenhouse gas emissions: Petroleum and coal product manufacturing*
Non-specified transformation industries	
Iron and steel	Sub-country energy consumption from GISD
Non-ferrous metals	Physical flow account for greenhouse gas emissions: Primary metal manufacturing*
Chemicals	Physical flow account for greenhouse gas emissions: Basic chemical manufacturing*
Pulp and paper	Physical flow account for greenhouse gas emissions: Pulp, paper and paperboard mills*
Food and tobacco	Physical flow account for greenhouse gas emissions: Animal food manufacturing*
Cement	Sub-country energy consumption from GCED
Other non-metallic minerals	Physical flow account for greenhouse gas emissions: Non-metallic mineral product manufacturing (except cement and concrete products)*
Transport equipment	Physical flow account for greenhouse gas emissions: Other transportation equipment manufacturing*
Machinery	Physical flow account for greenhouse gas emissions: Machinery manufacturing*
Mining and quarrying	Physical flow account for greenhouse gas emissions: Metal ore mining*
Wood products	Physical flow account for greenhouse gas emissions: Wood product manufacturing*
Construction	Physical flow account for greenhouse gas emissions: Residential building construction*
Textile and leather	Physical flow account for greenhouse gas emissions: Textile and textile product mills*
Other non-specified industries	GDP*
International aviation	-
Domestic aviation	Physical flow account for greenhouse gas emissions: Air transportation*
Rail	Railway length*
International navigation	-
Domestic navigation	Physical flow account for greenhouse gas emissions: Water transportation*
Pipeline transport	Physical flow account for greenhouse gas emissions: Pipeline transportation*
Other non-specified transport	GDP*
Agriculture and forestry	Physical flow account for greenhouse gas emissions: Crop and animal production*
Fishing	Physical flow account for greenhouse gas emissions:

	Fishing, hunting and trapping*
Cars	Total road motor vehicle registrations*
Light duty trucks	
Buses	
Heavy duty trucks	
Motorcycles	
Other fleet totals	
Commercial and institutional	Population*
Residential (rural)	
Residential (urban)	
Non-specified sectors	
Process emissions in cement industry	Sub-country energy consumption from GCED

S15.3 Saudi Arabia

MEIC Sector	Sector or proxy
Power generation	Sub-country energy consumption from GPED
Heat (auto producer)	Total consumption for electricity; Population*
Heat (public)	
Coal mines	GDP*
Oil and gas extraction	
Blast furnaces	Sub-country energy consumption from GISD
Gas works	GDP*
Gasification plants for biogases	
Coke ovens	Sub-country energy consumption from GISD
Patent fuel plants	GDP*
BKB/peat briquette plants	
Oil refineries	
Coal liquefaction plants	
Liquefaction (LNG) / regasification plants	
Gas-to-liquids (GTL) plants	
Own use in electricity, CHP and heat plants	Total consumption for electricity; Population*
Charcoal production plants	GDP*
Non-specified transformation industries	
Iron and steel	Sub-country energy consumption from GISD
Non-ferrous metals	GDP*
Chemicals	
Pulp and paper	
Food and tobacco	
Cement	Sub-country energy consumption from GCED

Other non-metallic minerals	GDP*
Transport equipment	
Machinery	
Mining and quarrying	
Wood products	
Construction	
Textile and leather	
Other non-specified industries	
International aviation	-
Domestic aviation	GDP*
Rail	Railway length*
International navigation	-
Domestic navigation	GDP*
Pipeline transport	
Other non-specified transport	
Agriculture and forestry	Production of all cereals*
Fishing	
Cars	Numbers of car plates issued*
Light duty trucks	
Buses	
Heavy duty trucks	
Motorcycles	
Other fleet totals	GDP*
Commercial and institutional	
Residential (rural)	Population*
Residential (urban)	
Non-specified sectors	
Process emissions in cement industry	Sub-country energy consumption from GCED

S15.4 United States

MEIC Sector	Sector or proxy
Power generation	Sub-country energy consumption from GPED
Heat (auto producer)	Generation of electric generators, independent power producers*; Population*
Heat (public)	Generation of electric generators, electric utilities*; Population*
Coal mines	Coal production*
Oil and gas extraction	Crude oil production*
Blast furnaces	Sub-country energy consumption from GISD
Gas works	Carbon emission industrial*
Gasification plants for biogases	
Coke ovens	Sub-country energy consumption from GISD

Patent fuel plants	Carbon emission industrial*
BKB/peat briquette plants	
Oil refineries	
Coal liquefaction plants	
Liquefaction (LNG) / regasification plants	
Gas-to-liquids (GTL) plants	
Own use in electricity, CHP and heat plants	Generation of total electric power industry*
Charcoal production plants	Carbon emission industrial*
Non-specified transformation industries	
Iron and steel	Sub-country energy consumption from GISD
Non-ferrous metals	Aggregates used for chemical and metallurgical*
Chemicals	
Pulp and paper	Carbon emission industrial*
Food and tobacco	
Cement	Sub-country energy consumption from GCED
Other non-metallic minerals	Carbon emission industrial*
Transport equipment	
Machinery	
Mining and quarrying	
Wood products	
Construction	Aggregates used for construction*
Textile and leather	Carbon emission industrial*
Other non-specified industries	
International aviation	-
Domestic aviation	Carbon emission transportation*
Rail	Railway length*
International navigation	-
Domestic navigation	Carbon emission transportation*
Pipeline transport	
Other non-specified transport	
Agriculture and forestry	Aggregates used for agriculture*
Fishing	
Cars	Carbon emission transportation*
Light duty trucks	
Buses	
Heavy duty trucks	
Motorcycles	
Other fleet totals	
Commercial and institutional	Carbon emission commercial*
Residential (rural)	Carbon emission residential*

Residential (urban)	
Non-specified sectors	Population*
Process emissions in cement industry	Sub-country energy consumption from GCED

S15.5 Germany

MEIC Sector	Sector or proxy
Power generation	Sub-country energy consumption from GPED
Heat (auto producer)	Carbon emission total heating production*
Heat (public)	
Coal mines	Carbon emission mining and manufacturing*
Oil and gas extraction	
Blast furnaces	Sub-country energy consumption from GISD
Gas works	Carbon emission mining and manufacturing*
Gasification plants for biogases	
Coke ovens	Sub-country energy consumption from GISD
Patent fuel plants	Carbon emission mining and manufacturing*
BKB/peat briquette plants	
Oil refineries	
Coal liquefaction plants	
Liquefaction (LNG) / regasification plants	
Gas-to-liquids (GTL) plants	
Own use in electricity, CHP and heat plants	Carbon emission total electricity generation*
Charcoal production plants	Carbon emission mining and manufacturing*
Non-specified transformation industries	
Iron and steel	Sub-country energy consumption from GISD
Non-ferrous metals	Carbon emission total manufacturing*
Chemicals	
Pulp and paper	
Food and tobacco	
Cement	Sub-country energy consumption from GCED
Other non-metallic minerals	Carbon emission total manufacturing*
Transport equipment	
Machinery	
Mining and quarrying	Carbon emission mining and manufacturing*
Wood products	Carbon emission total manufacturing*
Construction	
Textile and leather	
Other non-specified industries	
International aviation	-

Domestic aviation	Carbon emission total domestic air transport*
Rail	Railway length*
International navigation	-
Domestic navigation	Carbon emission total coastal and inland waterways shipping*
Pipeline transport	Carbon emission total transport*
Other non-specified transport	
Agriculture and forestry	Population*
Fishing	
Cars	Carbon emission total road transport*
Light duty trucks	
Buses	
Heavy duty trucks	
Motorcycles	
Other fleet totals	
Commercial and institutional	Carbon emission total other*
Residential (rural)	
Residential (urban)	
Non-specified sectors	Population*
Process emissions in cement industry	Sub-country energy consumption from GCED

S15.6 France

MEIC Sector	Sector or proxy
Power generation	Sub-country energy consumption from GPED
Heat (auto producer)	Consumption of energy gross total
Heat (public)	
Coal mines	
Oil and gas extraction	
Blast furnaces	Sub-country energy consumption from GISD
Gas works	Consumption of energy gross total
Gasification plants for biogases	
Coke ovens	Sub-country energy consumption from GISD
Patent fuel plants	Consumption of energy gross total
BKB/peat briquette plants	
Oil refineries	
Coal liquefaction plants	
Liquefaction (LNG) / regasification plants	
Gas-to-liquids (GTL) plants	
Own use in electricity, CHP and heat plants	Consumption of energy total electricity
Charcoal production plants	Consumption of energy gross total

Non-specified transformation industries	
Iron and steel	Sub-country energy consumption from GISD
Non-ferrous metals	Consumption of energy gross total
Chemicals	
Pulp and paper	
Food and tobacco	
Cement	Sub-country energy consumption from GCED
Other non-metallic minerals	Consumption of energy gross total
Transport equipment	
Machinery	
Mining and quarrying	
Wood products	
Construction	
Textile and leather	
Other non-specified industries	
International aviation	-
Domestic aviation	GDP*
Rail	Railway length*
International navigation	-
Domestic navigation	GDP*
Pipeline transport	
Other non-specified transport	
Agriculture and forestry	Population*
Fishing	
Cars	GDP*
Light duty trucks	
Buses	
Heavy duty trucks	
Motorcycles	
Other fleet totals	
Commercial and institutional	Population*
Residential (rural)	
Residential (urban)	
Non-specified sectors	
Process emissions in cement industry	Sub-country energy consumption from GCED

S15.7 Italy

MEIC Sector	Sector or proxy
Power generation	Sub-country energy consumption from GPED
Heat (auto producer)	Consumption of energy total domestic
Heat (public)	

Coal mines	
Oil and gas extraction	
Blast furnaces	Sub-country energy consumption from GISD
Gas works	Consumption of energy total domestic
Gasification plants for biogases	
Coke ovens	Sub-country energy consumption from GISD
Patent fuel plants	Consumption of energy total domestic
BKB/peat briquette plants	
Oil refineries	
Coal liquefaction plants	
Liquefaction (LNG) / regasification plants	
Gas-to-liquids (GTL) plants	
Own use in electricity, CHP and heat plants	Consumption of energy electricity domestic
Charcoal production plants	Consumption of energy total domestic
Non-specified transformation industries	
Iron and steel	Sub-country energy consumption from GISD
Non-ferrous metals	Consumption of energy total domestic
Chemicals	
Pulp and paper	
Food and tobacco	
Cement	Sub-country energy consumption from GCED
Other non-metallic minerals	Consumption of energy total domestic
Transport equipment	
Machinery	
Mining and quarrying	
Wood products	
Construction	
Textile and leather	
Other non-specified industries	
International aviation	-
Domestic aviation	GDP*
Rail	Railway length*
International navigation	-
Domestic navigation	GDP*
Pipeline transport	
Other non-specified transport	
Agriculture and forestry	Population*
Fishing	
Cars	GDP*
Light duty trucks	

Buses	
Heavy duty trucks	
Motorcycles	
Other fleet totals	
Commercial and institutional	Population*
Residential (rural)	
Residential (urban)	
Non-specified sectors	
Process emissions in cement industry	Sub-country energy consumption from GCED

S15.8 United Kingdom

MEIC Sector	Sector or proxy
Power generation	Sub-country energy consumption from GPED
Heat (auto producer)	Consumption of energy total
Heat (public)	
Coal mines	Consumption of energy industrial; CO_2 emission industrial*
Oil and gas extraction	
Blast furnaces	Sub-country energy consumption from GISD
Gas works	Consumption of energy industrial; CO_2 emission industrial*
Gasification plants for biogases	
Coke ovens	Sub-country energy consumption from GISD
Patent fuel plants	Consumption of energy industrial; CO_2 emission industrial*
BKB/peat briquette plants	
Oil refineries	
Coal liquefaction plants	
Liquefaction (LNG) / regasification plants	
Gas-to-liquids (GTL) plants	
Own use in electricity, CHP and heat plants	Consumption of energy total electricity
Charcoal production plants	Consumption of energy industrial; CO_2 emission industrial*
Non-specified transformation industries	
Iron and steel	Sub-country energy consumption from GISD
Non-ferrous metals	Consumption of energy industrial; CO_2 emission industrial*
Chemicals	
Pulp and paper	
Food and tobacco	
Cement	Sub-country energy consumption from GCED
Other non-metallic minerals	Consumption of energy industrial; CO_2 emission industrial*
Transport equipment	
Machinery	

Mining and quarrying	
Wood products	
Construction	
Textile and leather	
Other non-specified industries	
International aviation	-
Domestic aviation	CO_2 emission total transport other*
Rail	Railway length*
International navigation	-
Domestic navigation	CO_2 emission total transport other*
Pipeline transport	
Other non-specified transport	
Agriculture and forestry	Consumption of energy agriculture; CO_2 emission total agriculture*
Fishing	
Cars	Consumption of energy road transport
Light duty trucks	
Buses	
Heavy duty trucks	
Motorcycles	
Other fleet totals	
Commercial and institutional	Consumption of energy commercial; CO_2 emission total commercial*
Residential (rural)	Population*
Residential (urban)	
Non-specified sectors	
Process emissions in cement industry	Sub-country energy consumption from GCED

Table S16. Sub-country mapping of fuel type in energy data used to downscale activity rates in 8 large emitters. Note that some fuel types are not provided in energy data in some countries (represented as "Not distinguished").

S16.1 Australia

MEIC Fuel type	Fuel type
Anthracite	
Coking coal	
Other bituminous coal	
Sub-bituminous coal	
Lignite	
Patent fuel	
Coke oven coke	
Gas coke	
Coal tar	
BKB	
Gas works gas	
Coke oven gas	
Blast furnace gas	
Other recovered gases	
Crude oil	
Natural gas liquids	
Refinery feedstocks	
Additives/blending components	
Other hydrocarbons	Not distinguished
Refinery gas	
Ethane	
Liquefied petroleum gases (LPG)	
Motor gasoline excluding biofuels	
Aviation gasoline	
Gasoline type jet fuel	
Kerosene type jet fuel excluding biofuels	
Other kerosene	
Gas/diesel oil excluding biofuels	
Fuel oil	
Naphtha	
White spirit and SBP	
Lubricants	
Bitumen	
Paraffin waxes	
Petroleum coke	
Other oil products	
Natural gas	

Peat	
Peat products	
Oil shale and oil sands	
Industrial waste	
Non-renewable municipal waste	

S16.2 Canada

MEIC Fuel type	Fuel type
Anthracite	Coal
Coking coal	
Other bituminous coal	
Sub-bituminous coal	
Lignite	
Patent fuel	
Coke oven coke	
Gas coke	
Coal tar	
BKB	
Gas works gas	
Coke oven gas	
Blast furnace gas	
Other recovered gases	
Crude oil	Diesel and light fuel oil
Natural gas liquids	Natural gas
Refinery feedstocks	Diesel and light fuel oil
Additives/blending components	
Other hydrocarbons	
Refinery gas	
Ethane	
Liquefied petroleum gases (LPG)	
Motor gasoline excluding biofuels	
Aviation gasoline	
Gasoline type jet fuel	
Kerosene type jet fuel excluding biofuels	
Other kerosene	
Gas/diesel oil excluding biofuels	
Fuel oil	
Naphtha	
White spirit and SBP	
Lubricants	
Bitumen	
Paraffin waxes	
Petroleum coke	

Other oil products	
Natural gas	Natural gas
Peat	Coal
Peat products	
Oil shale and oil sands	Diesel and light fuel oil
Industrial waste	Not distinguished
Non-renewable municipal waste	

S16.3 Saudi Arabia

MEIC Fuel type	Fuel type
Anthracite	Not distinguished
Coking coal	
Other bituminous coal	
Sub-bituminous coal	
Lignite	
Patent fuel	
Coke oven coke	
Gas coke	
Coal tar	
BKB	
Gas works gas	
Coke oven gas	
Blast furnace gas	
Other recovered gases	
Crude oil	Diesel (Fuel Oil)
Natural gas liquids	Not distinguished
Refinery feedstocks	Diesel (Fuel Oil)
Additives/blending components	
Other hydrocarbons	
Refinery gas	
Ethane	
Liquefied petroleum gases (LPG)	
Motor gasoline excluding biofuels	
Aviation gasoline	
Gasoline type jet fuel	
Kerosene type jet fuel excluding biofuels	
Other kerosene	
Gas/diesel oil excluding biofuels	
Fuel oil	
Naphtha	
White spirit and SBP	
Lubricants	
Bitumen	

Paraffin waxes	
Petroleum coke	
Other oil products	
Natural gas	Not distinguished
Peat	
Peat products	
Oil shale and oil sands	Diesel (Fuel Oil)
Industrial waste	Not distinguished
Non-renewable municipal waste	

S16.4 United States

MEIC Fuel type	Fuel type
Anthracite	Coal
Coking coal	
Other bituminous coal	
Sub-bituminous coal	
Lignite	
Patent fuel	
Coke oven coke	
Gas coke	
Coal tar	
BKB	
Gas works gas	
Coke oven gas	
Blast furnace gas	
Other recovered gases	
Crude oil	Petroleum
Natural gas liquids	Natural gas
Refinery feedstocks	Petroleum
Additives/blending components	
Other hydrocarbons	
Refinery gas	
Ethane	
Liquefied petroleum gases (LPG)	
Motor gasoline excluding biofuels	
Aviation gasoline	
Gasoline type jet fuel	
Kerosene type jet fuel excluding biofuels	
Other kerosene	
Gas/diesel oil excluding biofuels	
Fuel oil	
Naphtha	
White spirit and SBP	

Lubricants	
Bitumen	
Paraffin waxes	
Petroleum coke	
Other oil products	
Natural gas	Natural gas
Peat	Coal
Peat products	
Oil shale and oil sands	Petroleum
Industrial waste	Not distinguished
Non-renewable municipal waste	

S16.5 Germany

MEIC Fuel type	Fuel type
Anthracite	
Coking coal	
Other bituminous coal	
Sub-bituminous coal	
Lignite	
Patent fuel	
Coke oven coke	
Gas coke	
Coal tar	
BKB	
Gas works gas	
Coke oven gas	
Blast furnace gas	
Other recovered gases	
Crude oil	Not distinguished
Natural gas liquids	
Refinery feedstocks	
Additives/blending components	
Other hydrocarbons	
Refinery gas	
Ethane	
Liquefied petroleum gases (LPG)	
Motor gasoline excluding biofuels	
Aviation gasoline	
Gasoline type jet fuel	
Kerosene type jet fuel excluding biofuels	
Other kerosene	
Gas/diesel oil excluding biofuels	
Fuel oil	

Naphtha	
White spirit and SBP	
Lubricants	
Bitumen	
Paraffin waxes	
Petroleum coke	
Other oil products	
Natural gas	
Peat	
Peat products	
Oil shale and oil sands	
Industrial waste	
Non-renewable municipal waste	

S16.6 France

MEIC Fuel type	Fuel type
Anthracite	
Coking coal	
Other bituminous coal	
Sub-bituminous coal	
Lignite	
Patent fuel	
Coke oven coke	
Gas coke	
Coal tar	
BKB	
Gas works gas	
Coke oven gas	
Blast furnace gas	
Other recovered gases	Not distinguished
Crude oil	
Natural gas liquids	
Refinery feedstocks	
Additives/blending components	
Other hydrocarbons	
Refinery gas	
Ethane	
Liquefied petroleum gases (LPG)	
Motor gasoline excluding biofuels	
Aviation gasoline	
Gasoline type jet fuel	
Kerosene type jet fuel excluding biofuels	
Other kerosene	

Gas/diesel oil excluding biofuels	
Fuel oil	
Naphtha	
White spirit and SBP	
Lubricants	
Bitumen	
Paraffin waxes	
Petroleum coke	
Other oil products	
Natural gas	
Peat	
Peat products	
Oil shale and oil sands	
Industrial waste	
Non-renewable municipal waste	

S16.7 Italy

MEIC Fuel type	Fuel type
Anthracite	
Coking coal	
Other bituminous coal	
Sub-bituminous coal	
Lignite	
Patent fuel	
Coke oven coke	
Gas coke	
Coal tar	
BKB	
Gas works gas	
Coke oven gas	
Blast furnace gas	Not distinguished
Other recovered gases	
Crude oil	
Natural gas liquids	
Refinery feedstocks	
Additives/blending components	
Other hydrocarbons	
Refinery gas	
Ethane	
Liquefied petroleum gases (LPG)	
Motor gasoline excluding biofuels	
Aviation gasoline	
Gasoline type jet fuel	

Kerosene type jet fuel excluding biofuels	
Other kerosene	
Gas/diesel oil excluding biofuels	
Fuel oil	
Naphtha	
White spirit and SBP	
Lubricants	
Bitumen	
Paraffin waxes	
Petroleum coke	
Other oil products	
Natural gas	
Peat	
Peat products	
Oil shale and oil sands	
Industrial waste	
Non-renewable municipal waste	

S16.8 United Kingdom

MEIC Fuel type	Fuel type
Anthracite	Coal
Coking coal	
Other bituminous coal	
Sub-bituminous coal	
Lignite	
Patent fuel	
Coke oven coke	
Gas coke	
Coal tar	
BKB	
Gas works gas	
Coke oven gas	
Blast furnace gas	
Other recovered gases	
Crude oil	Petroleum
Natural gas liquids	Gas
Refinery feedstocks	Petroleum
Additives/blending components	
Other hydrocarbons	
Refinery gas	
Ethane	
Liquefied petroleum gases (LPG)	
Motor gasoline excluding biofuels	

Aviation gasoline	
Gasoline type jet fuel	
Kerosene type jet fuel excluding biofuels	
Other kerosene	
Gas/diesel oil excluding biofuels	
Fuel oil	
Naphtha	
White spirit and SBP	
Lubricants	
Bitumen	
Paraffin waxes	
Petroleum coke	
Other oil products	
Natural gas	Gas
Peat	Coal
Peat products	
Oil shale and oil sands	Petroleum
Industrial waste	Not distinguished
Non-renewable municipal waste	

Table S17. The mapping table between the fuel types in BP statistics and MEIC.

BP	MEIC
Coal	Anthracite
	Coking coal
	Other bituminous coal
	Sub-bituminous coal
	Lignite
	Patent fuel
	Coke oven coke
	Gas coke
	Coal tar
	BKB
	Gas works gas
	Coke oven gas
	Blast furnace gas
	Other recovered gases
	Peat
	Peat products
Oil	Crude oil
	Refinery feedstocks
	Additives/blending components
	Other hydrocarbons
	Refinery gas
	Ethane
	Liquefied petroleum gases (LPG)
	Motor gasoline excluding biofuels
	Aviation gasoline
	Gasoline type jet fuel
	Kerosene type jet fuel excluding biofuels
	Other kerosene
	Gas/diesel oil excluding biofuels
	Fuel oil
	Naphtha
	White spirit and SBP
	Lubricants
	Bitumen
	Paraffin waxes
	Petroleum coke
	Other oil products
	Oil shale and oil sands
Gas	Natural gas
	Natural gas liquids

Primary Energy	Industrial waste	
	Non-renewable municipal waste	

Table S18. The relative differences of CO_2 emissions from fossil fuel combustion between MEIC and other existing databases.

Year	CEDS	GCP	BP	IEA	EDGAR v70
1970	-6.4%	3.6%	3.7%	-	3.4%
1971	-5.3%	4.9%	4.4%	-1.4%	0.2%
1972	-5.6%	4.6%	4.3%	-1.4%	0.1%
1973	-5.8%	3.6%	3.9%	-1.7%	-0.1%
1974	-5.8%	3.3%	3.4%	-1.8%	-0.2%
1975	-5.9%	3.4%	2.7%	-2.0%	-0.5%
1976	-5.7%	3.5%	2.9%	-1.8%	-0.2%
1977	-5.5%	3.1%	2.8%	-1.7%	-0.3%
1978	-5.5%	2.9%	1.6%	-2.0%	-1.6%
1979	-5.7%	3.0%	1.7%	-2.0%	-1.5%
1980	-4.3%	4.8%	2.8%	-0.9%	-0.6%
1981	-4.4%	4.0%	2.9%	-1.0%	-0.5%
1982	-3.8%	4.4%	3.2%	-0.9%	-0.5%
1983	-3.7%	4.5%	3.3%	-0.9%	-0.5%
1984	-3.7%	4.9%	3.9%	-0.8%	-0.5%
1985	-4.1%	6.3%	3.9%	-1.3%	-1.1%
1986	-4.0%	6.1%	3.9%	-1.2%	-0.9%
1987	-4.1%	5.6%	3.4%	-1.4%	-1.1%
1988	-4.0%	6.2%	3.6%	-1.2%	-0.8%
1989	-4.2%	5.7%	3.3%	-1.4%	-1.0%
1990	-2.8%	6.4%	4.1%	0.3%	0.3%
1991	-2.9%	8.3%	3.8%	0.5%	0.5%
1992	-4.1%	4.4%	3.5%	-0.4%	-0.5%
1993	-3.3%	5.5%	3.8%	0.2%	0.1%
1994	-3.4%	5.5%	4.3%	0.1%	0.1%
1995	-3.6%	5.2%	3.4%	0.6%	0.5%
1996	-4.0%	5.4%	3.2%	-0.2%	-0.2%

1997	-3.2%	5.3%	3.3%	1.0%	0.9%
1998	-3.1%	4.3%	2.9%	1.1%	1.1%
1999	-3.7%	4.1%	2.8%	0.4%	0.3%
2000	-3.4%	4.1%	2.4%	0.7%	0.6%
2001	-3.1%	3.9%	2.8%	1.2%	1.2%
2002	-3.9%	3.5%	2.5%	0.0%	0.1%
2003	-3.2%	4.8%	3.7%	0.5%	0.6%
2004	-2.4%	5.2%	4.8%	1.2%	1.2%
2005	-3.3%	4.1%	4.4%	0.5%	0.5%
2006	-3.3%	3.9%	4.2%	0.4%	0.4%
2007	-4.0%	2.3%	3.3%	-0.4%	-0.3%
2008	-4.6%	2.6%	2.7%	-1.1%	-1.1%
2009	-4.5%	3.2%	2.7%	-0.4%	-0.4%
2010	-4.9%	2.8%	1.3%	-0.1%	-0.1%
2011	-5.2%	3.2%	1.3%	-0.1%	-0.1%
2012	-5.7%	3.3%	1.1%	-0.3%	-0.3%
2013	-4.5%	3.5%	2.0%	1.1%	1.1%
2014	-4.4%	3.8%	2.2%	1.1%	1.1%
2015	-4.9%	3.2%	1.5%	0.0%	0.0%
2016	-5.6%	2.3%	1.5%	-0.5%	-0.4%
2017	-5.9%	1.7%	0.9%	-0.6%	-0.6%
2018	-5.2%	2.0%	1.3%	0.1%	-0.1%
2019	-4.7%	2.1%	1.3%	-0.3%	-0.1%
2020	-	2.7%	1.5%	0.2%	0.0%
2021	-	-	1.6%	-	0.2%

Table S19. The relative differences of CO_2 emissions from fossil fuel combustion and process in cement industry between MEIC and other existing databases.

Year	CEDS	GCP	EDGAR v70
1970	-6.5%	3.7%	3.6%
1971	-5.4%	5.0%	0.4%
1972	-5.8%	4.6%	0.4%
1973	-5.9%	3.6%	0.1%
1974	-6.0%	3.4%	0.0%
1975	-6.0%	3.4%	-0.2%
1976	-5.8%	3.5%	0.0%
1977	-5.7%	3.1%	-0.1%
1978	-5.6%	2.9%	-1.5%
1979	-5.8%	3.0%	-1.4%
1980	-4.5%	4.7%	-0.4%
1981	-4.5%	3.9%	-0.4%
1982	-3.9%	4.3%	-0.4%
1983	-3.9%	4.4%	-0.4%
1984	-3.9%	4.8%	-0.4%
1985	-4.3%	6.2%	-1.0%
1986	-4.2%	5.9%	-0.8%
1987	-4.2%	5.5%	-1.0%
1988	-4.2%	6.1%	-0.7%
1989	-4.4%	5.5%	-0.9%
1990	-3.0%	6.3%	0.4%
1991	-3.0%	8.2%	0.6%
1992	-4.1%	4.4%	-0.2%
1993	-3.4%	5.5%	0.4%
1994	-3.4%	5.6%	0.5%
1995	-3.5%	5.3%	0.9%
1996	-3.9%	5.5%	0.1%
1997	-3.2%	5.3%	1.2%
1998	-2.9%	4.4%	1.3%
1999	-3.5%	4.3%	0.6%
2000	-3.2%	4.3%	1.0%
2001	-2.9%	4.1%	1.6%
2002	-3.7%	3.7%	0.5%
2003	-3.0%	5.0%	1.1%
2004	-2.2%	5.4%	1.7%
2005	-3.0%	4.4%	1.1%
2006	-3.1%	4.2%	1.0%
2007	-3.8%	2.5%	0.4%
2008	-4.2%	2.9%	-0.3%

2009	-4.1%	3.4%	0.3%
2010	-4.6%	3.0%	0.6%
2011	-4.9%	3.3%	0.6%
2012	-5.4%	3.4%	0.4%
2013	-4.5%	3.5%	1.0%
2014	-4.3%	3.8%	0.9%
2015	-4.8%	3.1%	-0.1%
2016	-5.5%	2.3%	-0.4%
2017	-5.7%	1.9%	-0.5%
2018	-5.0%	2.3%	0.1%
2019	-4.5%	2.4%	0.1%
2020	-	3.1%	0.3%
2021	-	-	0.4%

Table S20. The NME and NMB of country-based CO_2 emissions in different magnitude groups between MEIC and the ensembled average of other existing databases in Fig. 6.

NME	**1970**	**1980**	**1990**	**2000**	**2010**	**2019**
0-0.1 Mt	70.7%	73.1%	58.7%	73.0%	75.2%	74.6%
0.1-1 Mt	62.6%	48.2%	34.6%	33.7%	41.1%	42.4%
1-10 Mt	24.5%	21.0%	19.3%	15.6%	18.6%	23.8%
10-100 Mt	13.9%	12.7%	8.6%	5.4%	7.1%	7.4%
100-1000 Mt	4.3%	4.8%	4.0%	4.8%	3.7%	5.9%
>1000 Mt	4.8%	3.5%	3.3%	2.2%	2.3%	1.9%
All	6.1%	5.3%	4.3%	3.6%	3.3%	3.8%
NMB	**1970**	**1980**	**1990**	**2000**	**2010**	**2019**
0-0.1 Mt	-50.7%	-17.2%	-25.5%	-64.6%	-72.4%	-67.1%
0.1-1 Mt	-30.7%	-11.4%	-7.6%	-11.0%	-23.8%	-28.7%
1-10 Mt	-17.3%	-8.7%	-15.5%	-6.0%	-7.4%	-7.3%
10-100 Mt	-1.0%	-0.1%	-0.6%	-0.2%	0.8%	0.5%
100-1000 Mt	0.2%	0.7%	-1.3%	-0.3%	1.2%	0.0%
>1000 Mt	-1.0%	-1.2%	-1.7%	-1.3%	-0.5%	0.8%
All	-0.8%	-0.5%	-1.6%	-0.9%	0.1%	0.4%

Table S21. The sector mapping used for comparison in Fig. S10.

Aggregated sector	Sector
Power	Power generation
	Heat (auto producer)
	Heat (public)
Industry	Coal mines
	Oil and gas extraction
	Blast furnaces
	Gas works
	Gasification plants for biogases
	Coke ovens
	Patent fuel plants
	BKB/peat briquette plants
	Oil refineries
	Coal liquefaction plants
	Liquefaction (LNG) / regasification plants
	Gas-to-liquids (GTL) plants
	Own use in electricity, CHP and heat plants
	Charcoal production plants
	Non-specified transformation industries
	Iron and steel
	Non-ferrous metals
	Chemicals
	Pulp and paper
	Food and tobacco
	Cement
	Other non-metallic minerals
	Transport equipment
	Machinery
	Mining and quarrying
	Wood products
	Construction
	Textile and leather
	Other non-specified industries
Transport	International aviation
	Domestic aviation
	Rail
	International navigation
	Domestic navigation
	Pipeline transport
	Other non-specified transport
	Cars

	Light duty trucks
	Buses
	Heavy duty trucks
	Motorcycles
	Other fleet totals
Residential, commercial, and other non-specified	Commercial and institutional
	Residential (rural)
	Residential (urban)
	Non-specified sectors
	Agriculture and forestry
	Fishing
Cement industry process	Process emissions in cement industry

Table S22. Income groups of countries/territories used for division of rural and urban residential energy consumption as described in Text S1 [75].

Country/territory	Income group	Country/territory	Income group
Afghanistan	Low income	Kyrgyzstan	Lower middle income
Albania	Upper middle income	Laos	Lower middle income
Algeria	Lower middle income	Latvia	High income
Angola	Lower middle income	Lebanon	Upper middle income
Anguilla	High income	Lesotho	Lower middle income
Antigua and Barbuda	High income	Liberia	Low income
Argentina	Upper middle income	Libya	Upper middle income
Armenia	Upper middle income	Lithuania	High income
Aruba	High income	Luxembourg	High income
Australia	High income	Madagascar	Low income
Austria	High income	Malawi	Low income
Azerbaijan	Upper middle income	Malaysia	Upper middle income
Bahamas	High income	Maldives	Upper middle income
Bahrain	High income	Mali	Low income
Bangladesh	Lower middle income	Malta	High income
Barbados	High income	Martinique	High income
Belarus	Upper middle income	Mauritania	Lower middle income
Belgium	High income	Mauritius	Upper middle income
Belize	Lower middle income	Mexico	Upper middle income
Benin	Lower middle income	Moldova	Upper middle income
Bermuda	High income	Mongolia	Lower middle income
Bhutan	Lower middle income	Montenegro	Upper middle income
Bolivia	Lower middle income	Montserrat	Upper middle income
Bonaire, Sint Eustatius and Saba	High income	Morocco	Lower middle income
Bosnia and Herzegovina	Upper middle income	Mozambique	Low income
Botswana	Upper middle income	Myanmar	Lower middle income
Brazil	Upper middle income	Namibia	Upper middle income
Brunei Darussalam	High income	Nepal	Lower middle income
Bulgaria	Upper middle income	Netherlands	High income
Burkina Faso	Low income	New Caledonia	High income
Burundi	Low income	New Zealand	High income
Cape Verde	Lower middle income	Nicaragua	Lower middle income
Cambodia	Lower middle income	Niger	Low income
Cameroon	Lower middle income	Nigeria	Lower middle income
Canada	High income	North Macedonia	Upper middle income
Cayman Islands	High income	Norway	High income
Central African	Low income	Oman	High income

Republic			
Chad	Low income	Pakistan	Lower middle income
Chile	High income	Palau	High income
China (including Hong Kong, Macao, and Taiwan)	Upper middle income	Palestine	Lower middle income
Colombia	Upper middle income	Panama	Upper middle income
Comoros	Lower middle income	Papua New Guinea	Lower middle income
Democratic Republic of Congo	Low income	Paraguay	Upper middle income
Congo	Lower middle income	Peru	Upper middle income
Cook Islands	High income	Philippines	Lower middle income
Costa Rica	Upper middle income	Poland	High income
Croatia	High income	Portugal	High income
Cuba	Upper middle income	Puerto Rico	High income
Curacao	High income	Qatar	High income
Cyprus	High income	Romania	Upper middle income
Czech Republic	High income	Russia	Upper middle income
Côte d'Ivoire	Lower middle income	Rwanda	Low income
Denmark	High income	Reunion	High income
Djibouti	Lower middle income	Saint Kitts and Nevis	High income
Dominica	Upper middle income	Saint Lucia	Upper middle income
Dominican Republic	Upper middle income	Saint Pierre and Miquelon	High income
Ecuador	Upper middle income	Saint Vincent And Grenadines	Upper middle income
Egypt	Lower middle income	Samoa	Lower middle income
El Salvador	Lower middle income	Sao Tome and Principe	Lower middle income
Equatorial Guinea	Upper middle income	Saudi Arabia	High income
Eritrea	Low income	Senegal	Lower middle income
Estonia	High income	Serbia	Upper middle income
Swaziland	Lower middle income	Seychelles	High income
Ethiopia	Low income	Sierra Leone	Low income
Falkland Islands	High income	Singapore	High income
Fiji	Upper middle income	Sint Maarten	High income
Finland	High income	Slovakia	High income
France	High income	Slovenia	High income
French Guiana	High income	Solomon Islands	Lower middle income
French Polynesia	High income	Somalia	Low income
Gabon	Upper middle income	South Africa	Upper middle income
Gambia	Low income	South Sudan	Low income
Georgia	Upper middle income	Spain	High income

Germany	High income	Sri Lanka	Lower middle income
Ghana	Lower middle income	Sudan	Low income
Gibraltar	High income	Suriname	Upper middle income
Greece	High income	Sweden	High income
Greenland	High income	Switzerland	High income
Grenada	Upper middle income	Syria	Low income
Guadeloupe	High income	Tajikistan	Lower middle income
Guatemala	Upper middle income	Tanzania	Lower middle income
Guinea	Low income	Thailand	Upper middle income
Guinea-Bissau	Low income	Timor-Leste	Lower middle income
Guyana	Upper middle income	Togo	Low income
Haiti	Lower middle income	Tonga	Upper middle income
Honduras	Lower middle income	Trinidad and Tobago	High income
Hungary	High income	Tunisia	Lower middle income
Iceland	High income	Turkey	Upper middle income
India	Lower middle income	Turkmenistan	Upper middle income
Indonesia	Lower middle income	Turks and Caicos Islands	High income
Islamic Republic of Iran	Lower middle income	Uganda	Low income
Iraq	Upper middle income	Ukraine	Lower middle income
Ireland	High income	United Arab Emirates	High income
Israel	High income	United Kingdom	High income
Italy	High income	United States	High income
Jamaica	Upper middle income	Uruguay	High income
Japan	High income	Uzbekistan	Lower middle income
Jordan	Upper middle income	Vanuatu	Lower middle income
Kazakhstan	Upper middle income	Venezuela	Lower middle income
Kenya	Lower middle income	Vietnam	Lower middle income
Kiribati	Lower middle income	British Virgin Islands	High income
Democratic People's Republic of Korea	Low income	Yemen	Low income
Republic of Korea	High income	Zambia	Lower middle income
Kuwait	High income	Zimbabwe	Lower middle income

References:

[1] H. Chen, Y. Huang, H. Shen, et al., Modeling temporal variations in global residential energy consumption and pollutant emissions, Appl. Energy 184 (2016) 820-829.

[2] R. Gelaro, W. Mccarty, M.J. Suárez, et al., The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), J. Clim. 30 (14) (2017) 5419-5454.

[3] European Environmental Agency, Heating Degree Days, (2022). https://www.eea.europa.eu/data-and-maps/figures/heating-degree-days#:~:text=The%20heating%20degree%20days%20index%20represents%20a%20proxy,March%20%28see%20the%20ETC-CCA%20Technical%20Paper%20for%20details%29.

[4] U.S. Energy Information Administration (EIA), Degree Days, (2022). https://www.eia.gov/energyexplained/units-and-calculators/degree-days.php#:~:text=Heating%20degree%20days%20%28HDD%29%20are%20a%20measure%20of,total%20of%2050%20HDD%20for%20the%20two-day%20period.

[5] United Nations, Department of Economic and Social Affairs, Population Division, World Urbanization Prospects: The 2018 Revision, (2018). https://www.un-ilibrary.org/content/books/9789210043144

[6] World Bank, Indicators, (2022). https://data.worldbank.org.cn/indicator

[7] United Nations, Department of Economic and Social Affairs, Population Division, World Population Prospects 2019, (2019). https://population.un.org/wpp/Download/Standard/Population/

[8] C. Cui, S. Li, W. Zhao, et al., Energy-related CO_2 emission accounts and datasets for 40 emerging economies in 2010–2019, Earth Syst. Sci. Data 15 (3) (2023) 1317-1328.

[9] The National Institute of Statistics and Censuses, Argentina. https://www.indec.gob.ar/indec/web/Institucional-Indec-QuienesSomosEng

[10] International Energy Agency (IEA), Global Engagement. https://www.iea.org/about/global-engagement

[11] Ministerio de Hidrocarburos y Energías, Bolivia. https://www.mhe.gob.bo/

[12] Instituto Nacional de Estadística. https://www.ine.gob.bo/

[13] Intergovernmental Panel on Climate Change (IPCC), Emission Factor Database (EFDB). https://www.ipcc-nggip.iges.or.jp/EFDB/main.php

[14] Energy Research Office, Brazil. https://www.epe.gov.br/en

[15] Instituto Brasileiro de Geografia e Estatística. https://ibge.gov.br/

[16] Energía Abierta - Comisión Nacional de Energía, Chile. http://energiaabierta.cl/

[17] Instituto Nacional de Estadísticas. https://www.ine.gob.cl/

[18] Unidad de Planeación Minero Energética, Columbia. https://www1.upme.gov.co/

[19] Ministerio de Energía y Minas, Ecuador. https://www.recursosyenergia.gob.ec/.

[20] Instituto Nacional de Estadística y Censos. https://www.ecuadorencifras.gob.ec/estadisticas/

[21] Statistics Estonia. https://www.stat.ee/en

[22] United Nations Framework Convention on Climate Change (UNFCCC), National Inventory Submissions, (2022). https://di.unfccc.int/flex_annex1

[23] Central Statistical Agency, Ethiopia. https://www.statsethiopia.gov.et/

[24] Energy Commission, Ghana. http://www.energycom.gov.gh/
[25] Ghana Statistical Services. https://statsghana.gov.gh/
[26] Ministerio de Energía y Minas, Guatemala. https://mem.gob.gt/
[27] Instituto Nacional de Estadística Guatemala. https://www.ine.gob.gt/
[28] Ministry of Statistics and Programme Implementation, India. https://www.mospi.gov.in/
[29] GHG Platform India. https://www.ghgplatform-india.org/
[30] Badan Pusat Statistik, Indonesia. https://www.bps.go.id/
[31] CEIC, CEIC Global Database, (2020). https://www.ceicdata.com/en
[32] United Nation Statistics Division, UN Stats. https://unstats.un.org/UNSDWebsite/
[33] Kenya National Bureau of Statistics. https://www.knbs.or.ke/
[34] Mongolian Statistical Information Service. https://beta.1212.mn/en
[35] Sistema Nacional de Información Ambiental, Peru. https://sinia.minam.gob.pe/
[36] Instituto Nacional de Estadística e Informática. https://www.gob.pe/inei
[37] ЕМИСС Government Statistics. https://www.fedstat.ru/
[38] Department of Energy, South Africa. https://www.energy.gov.za/
[39] African Energy Commission (AFREC), Africa Energy Database. https://au-afrec.org/
[40] Tanzania National Bureau of Statistics. https://www.nbs.go.tz/index.php/en/
[41] World Energy Council Turkish National Committee. https://www.worldenergy.org/world-energy-community/members/entry/turkey
[42] Turkish Statistical Institute. https://www.tuik.gov.tr/en/
[43] Uganda Bureau of Statistics. https://www.ubos.org/
[44] Economic Research Institute for ASEAN and East Asia (ERIA), Energy Balance Tables. https://www.eria.org/RPR_FY2015_No.8_Chapter_2.pdf
[45] Asian Development Bank, Economic Indicators: Input-Output Tables. https://www.adb.org/what-we-do/data/regional-input-output-tables
[46] National Institute of Statistics of Djibouti. http://www.instad.dj/accueil.php
[47] Ministry of Science, Energy & Technology, Jamaica. https://www.mset.gov.jm/
[48] Statistical Institute of Jamaica. https://statinja.gov.jm/
[49] Minister of Energy and Mineral Resources, Jordan. https://www.memr.gov.jo/Default/En
[50] Department of Statistics, Jordan. www.dos.gov.jo
[51] Laos Statistical Information Service. https://www.lsb.gov.la/en/home/
[52] Statistical databank, Moldova. https://statistica.gov.md/en
[53] Instituto Nacional de Estadística, Paraguay. https://www.ine.gov.py/
[54] Department of Alternative Energy Development and Efficiency, Thailand. http://weben.dede.go.th/webmax/
[55] Instituto Nacional de Estadística, Uruguay. https://www.gub.uy/instituto-nacional-estadistica/
[56] Australian Bureau of Statistics. https://www.abs.gov.au/
[57] Department of Industry, Science, Energy and Resources. https://www.dcceew.gov.au/
[58] Statistics Canada. https://www.statcan.gc.ca/
[59] Institut national de la statistique et des études économiques (INSEE).

https://www.insee.fr/fr/statistiques/1893198

[60] Statistisches Bundesamt. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Bevoelkerungsstand/Publikationen/Downloads-Bevoelkerungsstand/bevoelkerungsfortschreibung-2010130207005.html

[61] Istituto nazionale di statistica (Istat). http://dati.istat.it/Index.aspx

[62] Saudi Arabian Bureau of Statistics. https://www.stats.gov.sa/

[63] United States Geological Survey (USGS). https://www.usgs.gov/

[64] U.S. Energy Information Adminstrative (EIA). https://www.eia.gov/

[65] Bureau of Economic Analysis. https://www.bea.gov/

[66] U.S. Department of Agriculture. https://www.usda.gov/

[67] Office for National Statistic. https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/populationestimatesforukenglandandwalesscotlandandnorthernireland

[68] Department for Business, Energy & Industrial Strategy. https://www.gov.uk/search/research-and-statistics?parent=%2Fenvironment%2Fclimate-change-energy&topic=62e08e6f-9161-42c6-b9dd-0cf8fcab2c69

[69] X. Qin, D. Tong, F. Liu, et al., Global and regional drivers of power plant CO_2 emissions over the last three decades, Earth's Future 10 (10) (2022) e2022EF002657.

[70] United States Geological Survey (USGS), Cement Statistics and Information, (2022). https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information

[71] World Steel Assoiciation, Steel Statistical Yearbooks 1978-2020, (2021). https://worldsteel.org/steel-topics/statistics/steel-statistical-yearbook/

[72] United Nation Statistics Division, Gross Domestic Production (2021). https://unstats.un.org/UNSDWebsite/

[73] United Nation Statistics Division, UN Statistical Yearbooks 1970-2020 (2021). https://unstats.un.org/UNSDWebsite/Publications/StatisticalYearbook/

[74] OAG Schedule Analyser. https://www.oag.com/schedules-analyser

[75] World Bank, World Bank Country and Lending Groups, (2022). https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups