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A global catalogue of CO_2 emissions and co-emitted species from power plants at a very high spatial and temporal resolution

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Abstract. We present a high-resolution global emission catalogue of CO_2 and co-emitted species (NO_x, SO_2, CO, CH_4) from thermal power plants for the year 2018. The construction of the database follows a bottom-up approach, which combines plant-specific information with national energy consumption statistics and fuel-dependent emission factors and emission ratios. The resulting catalog contains annual emission information for more than 16000 individual facilities at their exact geographical location. Each facility is linked to a specific temporal (i.e., monthly, day-of-the-week and hourly) and vertical distribution profile, which were derived from national electricity generation statistics and plume rise calculations that combine stack parameters with meteorological information. The combination of the aforementioned information allows to derive high-resolution spatial and temporal emissions for modelling purposes. Estimated annual emissions were compared against independent plant- and country-level inventories, including the Carbon Monitoring for Action (CARMA) and the Emissions Database for Global Atmospheric Research (EDGAR) databases, as well as officially reported emission data. An overall good agreement is observed between datasets when comparing the CO_2 emissions. The main discrepancies are related to the non-inclusion of auto-producer or heat-only facilities in certain countries due to lack of data. Larger inconsistencies are obtained when comparing emissions from co-emitted species due to uncertainties in the fuel-dependent emission ratios and gap-filling procedures. The temporal distribution of emissions obtained in this work was compared against traditional sector-dependent profiles that are widely used in modelling efforts. This highlighted important differences and the need to consider country dependencies when temporally distributing emissions. The resulting catalogue (https://doi.org/10.24380/mxjo-nram, Guevara et al., 2023) is developed in the framework of the Prototype System for a Copernicus CO_2 service (CoCO2) EU-funded project to support the development of the Copernicus CO_2 Monitoring and Verification Support capacity (CO2MVS).

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1 Introduction

Over 40% of fossil fuel related carbon dioxide (CO_2) emissions are caused by power plants that burn fuels to produce electricity and/or heat (Crippa et al., 2022). A correct representation of the spatial and temporal distribution of these point sources is important for verification of global CO_2 emissions through current and future satellite emission monitoring and inverse modelling efforts, like the envisioned European CO_2 Monitoring and Verification Support capacity (CO2MVS; Balsamo et al., 2021). The CO2MVS, which is planned to be fully operational by 2026, combines information from various observational data sets (i.e., satellite data from existing or new Copernicus Sentinel satellites and in situ data from various surface networks) and prior knowledge (i.e., mainly bottom-up emission estimates from inventories and reporting) with detailed Earth system modelling and data assimilation capabilities. The final goal of the CO2MVS capacity is to provide observation-based estimates of CO_2 emissions at multiple scales (i.e., from global to local industrial and urban hotspots) with a similar level of robustness that has proven critically important in other Copernicus Atmosphere Monitoring Service (CAMS) applications, such as air quality predictions (https://atmosphere.copernicus.eu/air-quality). To reduce the uncertainty in the inversion system and have higher accuracy in final predicted emission estimates, having high spatial and temporal resolution data for CO_2 emissions and co-emitted species (e.g., NO_x, CO), which are also used to derive observation-based CO_2 emissions as they can be detected more easily in satellite images (e.g., Kuhlmann et al., 2021), is a key element.

The spatial representation of large point sources in global state-of-the-art and/or widely used gridded emission inventories such as the Emissions Database for Global Atmospheric Research (EDGAR, Janssens-Maenhout et al., 2019) and the Open-Data Inventory for Anthropogenic Carbon dioxide (ODIAC, Oda et al., 2018) is sometimes inadequate as it is primarily based on the Carbon Monitoring for Action (CARMA; Wheeler and Ummel, 2008), which was build using plant-level information from 2009 and is no longer maintained. Moreover, these inventories do not report the emissions from facilities at their exact geographical locations, but in the centroid of the respective inventory grid cells which typically have resolution of 0.1x0.1 degrees. Subsequently deviations from their exact locations can be up to a few kilometres. The more recently developed GID-Power Emission Database (GPED, Tong et al., 2018) overcomes this limitation by providing up-to-date information and high-resolution CO_2 emissions from global power plants at the facility-level. However, the latitude and longitude coordinates of each facility is not publicly available, instead georeferenced data is distributed in gridded format at a 0.1x0.1 degrees resolution). Moreover, no information is provided on how to distribute the emissions from each plant temporally and vertically, two parameters that are also essential for modelling purposes (e.g., Brunner et al. 2019; Guevara et al., 2021).

Here we present a global catalogue of CO_2 emissions and co-emitted species (i.e., NO_x, SO_x, CO, CH_4) from power plants at high spatial and temporal resolution for the year 2018. The dataset contains annual emission information for individual thermal power plants that burn coal, natural gas, oil, solid biomass and municipal/industrial solid waste (hereinafter referred to as waste) to produce electricity or combined heat and electricity at their exact geographical location. Moreover, each facility is linked to a specific temporal (i.e., monthly, day-of-the-week and hourly) and vertical distribution profile, which allows to derive spatial- and temporal-resolved emissions for modelling efforts.

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Section 2 of the manuscript describes the methodology and databases considered for the construction of the global point source database, while Sect. 3 presents the main results and compares them against existing emission inventories at the country and plant-level. Section 4 provides a description of the data availability, and finally Sect. 5 presents the main conclusions.

2 Methodology

The approach to construct the global point source database is divided in five phases: 1) Selection of facilities and definition of associated geographical location (i.e., latitude and longitude coordinates), 2) fuel allocation per facility, 3) estimation of annual emissions of CO_2 and co-emitted species (i.e., NO_x, SO_x, CO, CH_4) per facility, 4) construction of the monthly, weekly (day-of-the-week) and hourly (hour-of-the-day) temporal profiles associated to each facility and 5) construction of the vertical distribution profiles associated to each facility.

The global point source database is a mosaic composed of a European (i.e., EU-27 plus United Kingdom, Norway, Switzerland and Serbia) and a non-European (rest of the world) dataset developed by The Netherlands Organization for Applied Scientific Research (TNO) and the Barcelona Supercomputing Center (BSC), respectively. The temporal and vertical profiles associated to each plant are constructed following a common approach that uses as a basis information on measured electricity statistics and plume rise calculations, respectively. The sources of information and approaches used to develop each dataset are described in the following sub-sections.

2.1 Selection of facilities and definition of geographical locations

To select and assign each individual power plant to its exact geographical location, several public and commercial datasets were combined. For the European database, the data sources used are the European Pollutant and Transfer Register database (E-PRTR_v18, EEA, 2020), the Large Combustion Plants database (LCP_v.5.2, EEA, 2019), the Platts World Electric Power Plant dataset (WEPP Europe, September 2015, Platts, 2015) and the integrated Industrial Reporting Database v.7 (EEA, 2022). For the non-European database, the main datasets considered included the Global Coal Plant Tracker (GCPTv2021_01; GEM, 2021), the Global Power Plant Database (GPPDv1.3.0; Global Energy Observatory et al., 2021), the IndustryAbout database (IndustryAbout, 2021), the Open Infrastructure Map (OpenInfraMap, 2022), the Emissions and Generation Resource Integrated Database (eGRIDv2018; US EPA, 2020), the Chinese Ministry of Ecology and Environment's domestic waste incineration power plant database (MIEE, 2022), the Tai biomass power plant database (DEDE; 2022), the Geocomunes Mexican power plant database (Geocomunes, 2020), the Taiwanese waste-to-energy plant database (Taiwan EPA, 2014), the electrical Japan power station database (Electrical Japan, 2022), the Argentinian renewable power plant database (MINEM, 2022) and the UNFCCC Clean Development Mechanism database (UNFCCC CMD, 2022). For both the European and non-European databases, substantial effort was put into identifying missing and incorrect facility geographical locations. Coordinates were checked or searched manually using Google Maps or other websites and added to the dataset as follows:

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- For Europe, the reported coordinates were consistently checked and corrected for the top-100 facilities (in terms of 2017 CO_2 emissions). Furthermore, all coordinates that did not fall within the correct country borders, or which were inconsistent between reported dataset versions, were manually checked and corrected. In addition, many other coordinates (likely about 400) were checked during the process of linking up facilities between datasets, identifying fuel types, and by looking at the resulting emission maps. In total, all checks resulted in 360 plants with corrected coordinates, including about 75 of the top-100 plants.
- For the non-European dataset, the review process was performed for selected countries that are among the top 30 countries in terms of installed power generation capacity and that are representative of coal (i.e., South Africa, Japan, Taiwan, Kazakhstan, Australia, Vietnam and Turkey), natural gas (i.e., Japan, Oman, Thailand, Bahrain, Algeria, Ukraine) and oil (i.e., Egypt, Iran, Iraq, Libya, Pakistan, Saudi Arabia) power plants. In both cases, some corrections improve the coordinates by only tens of meters or less, in other cases the original coordinates were further off. Multi-unit power plants were in most of the cases located at the same coordinates, since the distance between units is usually small (i.e., dozens of meters). However, in facilities where the distance between units was significant (i.e., few kilometres), original coordinates were edited and assigned to individual units. Despite these efforts, there may be some errors still present in the dataset, especially in the case of small plants.

2.2 Fuel allocation

Each of the emission values in the European power plant dataset is allocated to one of five fuel types (i.e., biomass, coal, oil, natural gas or waste). Three methods were used to allocate the fuel type:

1. Link with LCP dataset: As LCP reporting includes the reporting of fuel input (but not for waste), this could be used to allocate emissions to different fuels when there was a link between an E-PRTR and LCP facility. Still, as only one emission value is reported, in case of a multi-fuel plant (e.g., co-combustion of biomass in a coal-fired power plant), a proxy emission value for each fuel type was estimated using country- and fuel-specific emission factors from the IIASA GAINS model. The ratio between the proxy emission values was then used to allocate the actual emission values to specific fuel types.
2. Link with Platts WEPP dataset: If no LCP fuel data was available, for some plants the fuel type could be taken from a link with the Platts WEPP dataset. The Platts WEPP dataset contains a detailed fuel type for every electricity-producing unit and also lists the electric capacity for every unit. For those facilities that could not be successfully linked to an LCP plant, a link was made to electricity producing units in the Platts WEPP database. The listed power and fuel type of the units was used together with country- and fuel specific emission factors from the GAINS model to estimate a proxy emission value for each unit and attribute the emissions to different fuel types.
3. Manual search and allocation of fuel types for the remaining plants.

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For non-European power plants, we used the plant-level fuel information provided by the databases listed in Sect. 2.1, which only report the main fuel even in the cases of multi-fuel plants. Therefore, for each power plant all emissions are linked to one single fuel, as we did not have information to split emissions between fuels in multi-fuel plants, as done for the European dataset. To homogenise the results reported by the European and non-European datasets, we assigned to each European power plant the fuel with the largest contribution to total CO_2 emissions.

2.3 Estimation of annual CO_2 emissions and co-emitted species

2.3.1 Europe

For European power plants, annual emissions were derived as a first step from the E-PRTR_v18 database. However, for many facilities, gaps in the E-PRTR emission reporting were identified and had to be corrected following a gap filling routine (see below). The gaps are mainly due to the E-PRTR emission reporting thresholds, which obliges companies to report emissions from individual pollutants only if they are above the values summarised in Table 1. Given the pollutant-specific reporting threshold for companies, many facilities report emissions for only a small number of pollutants. NOx and CO_2 are the pollutants that are on average reported most often. CH_4 reporting is almost non-existent for power plants, while CO and SOx are reported for a limited number of facilities, and more often in the earlier years (2004 – 2010) and less in recent years, when annual emission may lie more often below the reporting threshold due to emission reduction technologies. Reporting for large combustion plants (LCP) is not dependent on an emission threshold but is mandatory for all combustion plants from 50 MW or higher thermal input capacity, excluding ovens and certain types of chemical reactors. For each LCP, annual reporting emissions of NO_x, SO_x, PM and fuel input by fuel type is required.

Table 1 Summary of the E-PRTR emission reporting thresholds per pollutant

Pollutant	E-PRTR threshold (ton/year)
CH_4	100
CO	500
CO_2	100000
NO_X	100
SO_X	150

To complete the reporting for all five pollutants, a 5-step gap filling routing was designed that follows several steps to estimate missing emission values:

1. In gap filling step 1, the E-PRTR and LCP reported values are compared for those years that reporting exists in both datasets for a specific plant. If the correlation between both series is >0.5, the LCP value is used, multiplied with the average ratio between the E-PRTR and LCP reported emission values. This way, if the EPRTR facility typically encompasses several smaller units that are not in the LCP dataset (i.e., <50MWth), the gap filled emission value incorporates this relatively fixed ratio between E-PRTR and LCP emissions. The gap filled emission value is capped

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at the highest reported emission value in the time series for this specific facility. When the correlation is <0.5, but the aggregated ratio of the series total emissions is between 0.9 - 1.1, or if the median ratio between individual emission values for each year is between 0.9 - 1.1, the LCP value is used directly, as the two time series are considered sufficiently consistent, but no adjustment ratio can be estimated.

2. In gap filling step 2, when no E-PRTR reporting for a specific pollutant is available for any year, or for none of the years where LCP reporting is available (which would allow a comparison), the LCP emission value is used directly when available.
3. After gap filling using LCP data, many gaps in the emission reporting remained. It was decided to gap fill these if emissions for at least one pollutant had been reported for the facility in a given year (implying activity). Gap filling step 3 was performed by calculating average ratios between reported CO_2 emissions and the reported emissions of other pollutants for the specific facility. When specific pollutant emissions were missing, but CO_2 emissions were available, the plant-specific ratio between CO_2 and the missing pollutant was used to estimate the missing emission. When fuel use information was not available, the use of pollutant ratios was also deemed the most appropriate method to gap fill missing CO_2 emissions. However, CO_2 was only gap filled in this step when a NOx value was reported, as this ratio is typically more constant than for the other co-emitted pollutants. Using the progression (e.g., lowering of SO_x/CO_2 ratio over time due to increased implementation of abatement technologies) of country-, fuel- and year-specific emission factors from the GAINS model, the emission ratios based on co-reporting in earlier years were corrected before using in later years to incorporate the effect of increasing use of abatement technologies.
4. In gap filling step 4, missing emission values were gap filled using the ratio between the IIASA GAINS model implied emission factors (IIASA, 2018) (e.g., CO_2/CO ratio) for a specific country, year, fuel type and pollutant, applied to a CO_2 value established from E-PRTR reporting or gap filling steps 1 or 2.
5. In gap filling step 5, all emission values that are still missing are gap filled, by applying the ratio between GAINS emission factors on values gap filled in steps 3 or 4. For CH_4, a separate fuel-specific CO_2/CH_4 ratio is used to gap fill emission values based on the Tier 1 emission factors reported by the IPCC guidelines (Eggleston et al., 2006).

As the gap filling steps progress, the gap filled emission value typically becomes more uncertain. To limit outlier values, gap filled values derived from gap filling steps 3 to 5 for all pollutants except CO_2 were capped at the E-PRTR reporting threshold value (assuming that the value has not been originally reported due to being below the reporting threshold).

2.3.2 Non-European countries

Plant-specific CO_2, NO_x, SO_2 and CH_4 emissions for all US power plants were obtained from the eGRID database. Most emissions of CO_2, NO_x and SO_2 are taken from monitored data from the Clean Air Markets Division Power Sector Emission Data. For all other units and for CH_4, the reported emissions are based on measured heat input multiplied by an emission factor, as described in US EPA (2020). Emissions of CO, which are not reported by eGRID, were estimated using fuel-dependent

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average ratios between NO_x and CO emissions derived from the continuous emission monitoring system (CEMS) database maintained by the Environmental Protection Agency (US EPA, 2021).

For the rest of the world, emissions per power plant were estimated following the steps below:

1. Estimation of CO_2 and CH_4 emissions per country, utility type (i.e., main or auto-producer plants) and fuel type combining the national energy statistics provided by the IEA World Energy Balances (IEA, 2021a) with the Tier 1 fuel-dependent emission factors reported by the IPCC guidelines (Eggleston et al., 2006).
2. Estimation of emissions of NOx and SOx by combining the CO_2 annual emissions estimated in step 1 with calculated fuel-dependent average ratios between CO_2 emissions and emissions of other pollutants (e.g., SO_x/CO_2 ratio) reported by the eGRID database.
3. Estimation of emissions of CO by combining the NO_x annual emissions estimated in step 2 with calculated fuel-dependent average ratios between NO_x and CO emissions derived from the US EPA CEMS database.
4. Assignation of estimated country- and fuel-dependent emissions derived from step 1, 2 and 3 to each facility as a function of the installed capacity and fuel information. The information on installed capacity per power plant is provided by the databases described in Sect. 2.1

Table 2 summarises the fuel-dependent CO_2 and CH_4 emission factors and average emission ratios calculated for co-emitted species for the main IEA fuel categories.

Table 2 Fuel-dependent CO_2 and CH_4 emission factors and emission ratios (SO_x/CO_2, NO_x/CO_2, CO/NO_x) considered for the main IEA fuel categories.

IEA fuel category	CO_2 EF [kg/TJ]	CH_4 EF [kg/TJ]	SOx/CO_2	NOx/CO_2	CO/NOx
Other bituminous coal	94600	1	6.78E-04	8.40E-04	2.21E-01
Sub-bituminous coal	96100	1	1.24E-03	7.39E-04	4.02E-01
Lignite	101000	1	1.94E-03	9.39E-04	4.47E-01
Anthracite	98300	1	6.78E-04	8.40E-04	2.21E-01
Natural gas	56100	1	1.35E-05	1.20E-03	5.19E-01
Crude oil	73300	3	3.40E-03	1.31E-03	2.87E-01
Fuel oil	77400	3	3.40E-03	1.31E-03	2.87E-01
Gas/diesel oil	74100	3	2.70E-03	5.22E-03	6.66E-02
Primary solid biofuel	100000	30	1.16E-04	6.85E-04	1.25E+00
Municipal waste	95850	30	2.78E-04	1.42E-03	2.29E+00

For coal-fired power plants we assumed that main and auto-producer facilities are correctly covered in all countries, as the GCPTv2021_01 database reports both public and industrial facilities. On the other hand, emissions from auto-producer plants using oil, natural gas, biomass or waste were only considered in those countries where the difference between the total installed capacity (main plus auto-producers) reported by our database and UN (2021) was lower than 10%. For countries where this difference was larger than 10%, we assumed that our database is only covering main activity producer plants and therefore auto-producer emissions were excluded from the country-to-plant assignation process (step 4).

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Figure 1 shows the relative differences between the total installed capacity reported by our database and the installed capacity reported by UN (2021) for main producers (red rectangles) and main plus auto-producers (blue circles) for the top 50 non-European CO_2 emitting countries. For each country, the marker without the transparency effect indicates whether emissions from main producers plus auto-producers (e.g., China, USA, South Korea, Saudi Arabia) or only from main producers (e.g., India, Russia, Japan, Iran) were considered.

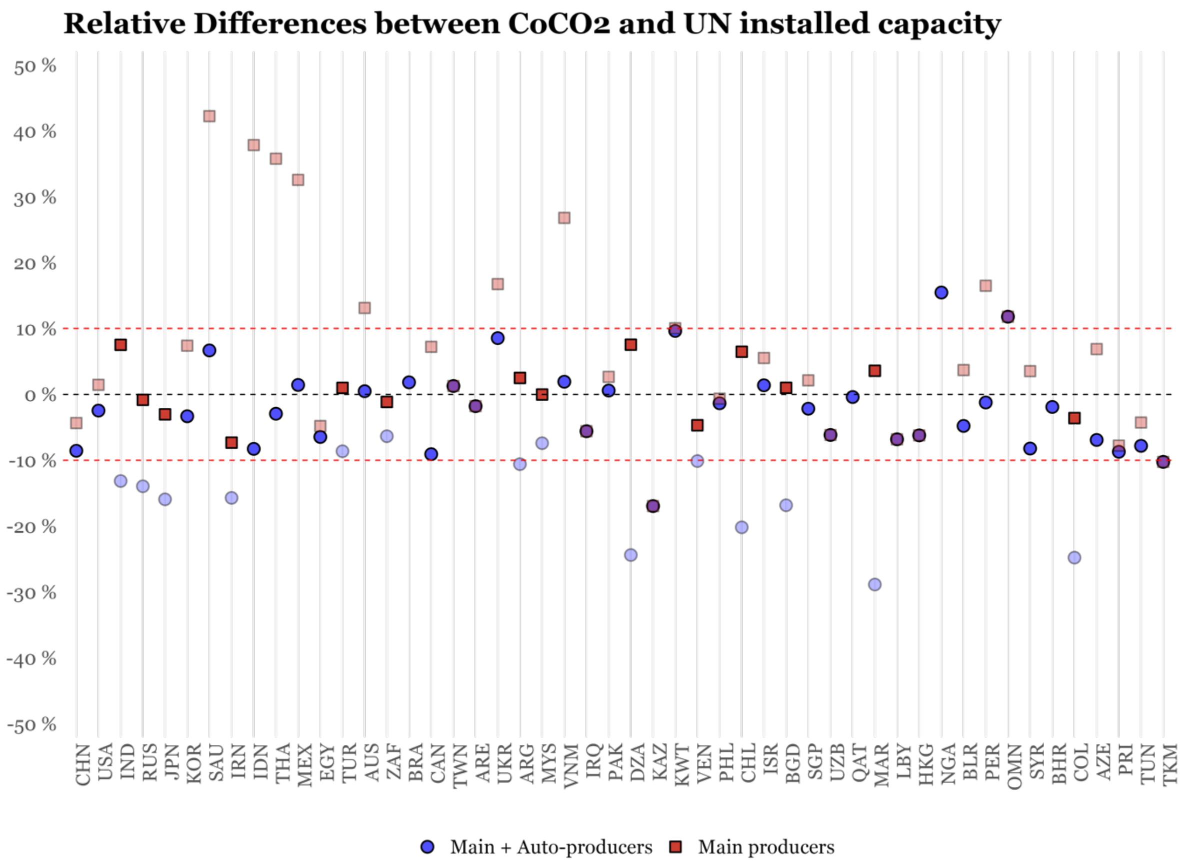

Figure 1 Relative differences [%] in the total installed capacity reported by the global point source database and the installed capacity reported by UN (2021) for main producers (red rectangles) and main plus auto-producers (blue circles) for the top 50 non-European CO_2 emitting countries. For each country, the marker without the transparency effect indicates whether emissions from main producers plus auto-producers or only from main producers were considered.

Overall, we could not include emissions from auto-producers in 35% of the countries considered. This translates into 4.1% of total estimated CO_2 emissions from the power sector that could not be allocated to the final non-European point source database due to the lack of information from auto-producers. Figure 2 represents the share of total national CO_2 emissions that could not be allocated per country. It is observed that most of the countries where information on auto-producers could not be found are in South America and Africa. Benin, El Salvador, Mali, Ecuador, Costa Rica and Madagascar are among the countries where the largest share of total CO_2 emissions remained unallocated (between 70% and 50%). Emissions from these countries are however not significant and therefore they have a very limited impact on the overall non-allocated emissions. In large

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emitting countries such as Russia, India or Japan, the share of national emissions that could not be assigned to individual facilities is much lower (i.e., 14% to 21%).

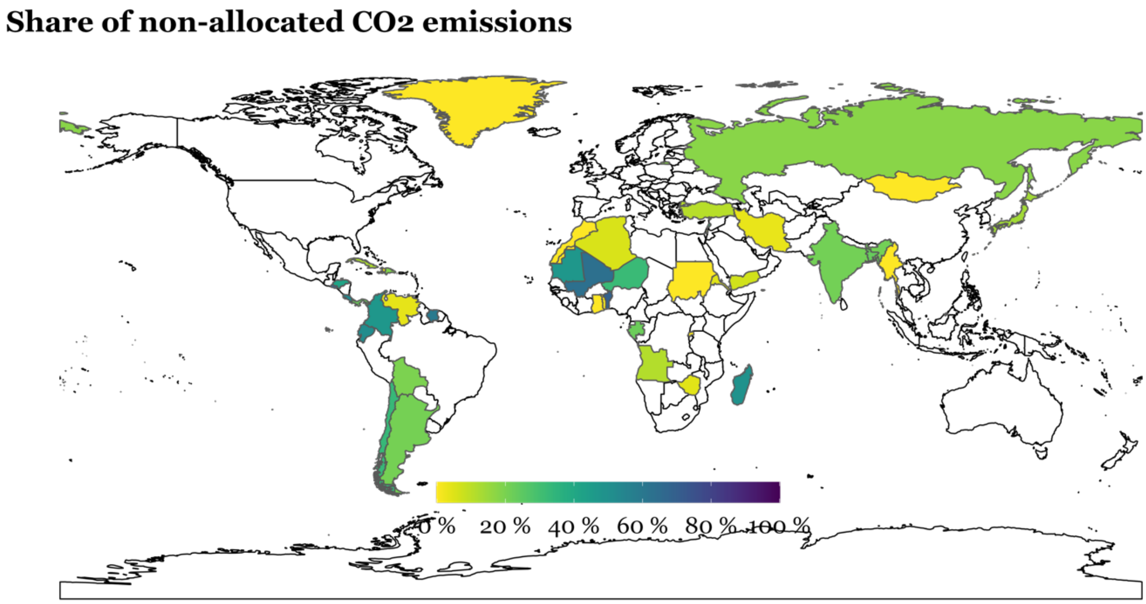

Figure 2 Share of total national CO_2 emissions [%] from the power sector that could not be allocated due to the lack of information from auto-producers. Countries where emissions from main producers and auto-producers could be allocated are represented in white.

2.4 Temporal profiles

Country- (state- for the US) and fuel-dependent monthly, weekly and hourly temporal profiles were constructed for all power plants (i.e., European and non-European datasets) using the electricity production statistics summarised in Table 3. For countries where electricity generation statistics are not disaggregated by fuel type, we assumed the same temporal distribution for all types of power plants. For countries with no information on electricity generation, or information only available at e.g., monthly scale but not at hourly scale, averaged profiles from countries belonging to the same world region were used. The definition of world regions was taken from the EDGARv5 emission inventory (Crippa et al., 2018). The resulting profiles were assigned to each facility as a function of the country and fuel type information.

Table 3 Sources of electricity production statistics and corresponding characteristics

Country/Region	Source of information	Temporal resolution	Information per fuel
Uruguay	ADME (2021)	Hourly	yes
Australia	AEMO (2021)	Hourly	yes
Guatemala	AMM (2021)	Daily	yes
Indonesia	BPS (2021)	Monthly	no
Argentina	CAMMESA (2021)	Daily	yes

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Mexico	CENACE (2021)	Hourly	yes
Algeria, Botswana, Lebanon, Malawi, Sri Lanka, Qatar	CEIC Data (2021)	Monthly	no
Chile	CNE (2021)	Hourly	yes
Peru	COES (2021)	Daily	thermal/renewable
United Arab Emirate	DEWA (2021)	Monthly	yes
EU27 + UK	ENTSO-E (2021)	Hourly	yes
Thailand	EPPO (2021)	Monthly	yes
South Africa	ESKOM (2022a)	Hourly	yes
Malaysia	GSO (2021)	Monthly	yes
China, Canada, Colombia, South Korea, New Zealand	IEA (2021)	Monthly	yes
Kazakhstan	KOREM (2021)	Monthly	thermal/renewable
Kuwait	MEW (2021)	Monthly	no
Moldova	MOLDELECTRICA (2021)	Hourly	no
Oman	NCSI (2021)	Monthly	yes
India	NPP (2021)	Daily	yes
Japan (*)	OCCTO (2021)	Hourly	thermal/biomass/renewable
Brazil	ONS (2021)	Hourly	yes
Bangladesh	PGCB (2021)	Hourly	yes
Russia	SO-UPS (2021)	Monthly	thermal/renewable
Switzerland (*)	SWISSGRID (2021)	Hourly	no
Turkey	TEIAS (2021)	Daily	yes
Ukraine	UNEC (2021)	Hourly	yes
USA	US EPA (2021)	Hourly	yes

(*) Monthly data derived from IEA as it is reported by fuel type

Figure 3 illustrates, on the one hand, the countries for which specific monthly, weekly and hourly profiles were constructed based on the statistics compiled and, on the other hand, the resulting share of total CO_2 emissions for which specific monthly, weekly and hourly profiles were available. For the monthly profiles, the database constructed is covering a total of 96 countries plus 42 USA states, which translates into more than 90% of total CO_2 emissions from the power sector. For weekly and hourly profiles, the coverage in terms of total CO_2 emissions is much lower (approx. 46% and 36%, respectively) partially because no information on electricity production and the daily and hourly level was available for China. For this country, we assumed that the weekly cycle of emissions follows the pattern obtained for India, which shows no significant difference between weekdays and weekends. This assumption is in line with the results found by Wu et al. (2022), in which weekly profiles for Chinese power plants were constructed using measured emissions derived from continuous emission monitoring systems.

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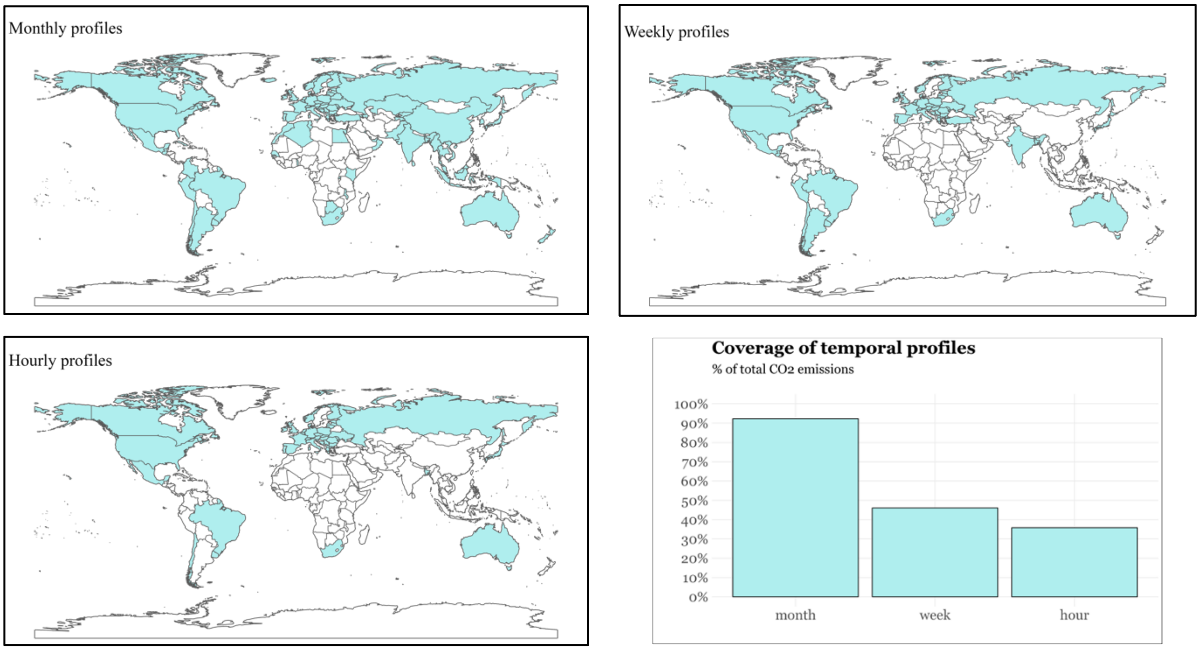

Figure 3 Spatial coverage of the constructed monthly, weekly and hourly temporal profile databases. Share of total CO_2 emissions [%] from the power sector for which specific monthly, weekly and hourly profiles were developed.

2.5 Vertical profiles

Hourly effective emission heights at the facility level were simulated by combining 2018 global hourly gridded meteorological information (i.e., air temperature at stack height, wind speed at stack height, surface temperature, boundary-layer height, friction velocity and Obukhov length) simulated by the MONARCH atmospheric chemistry model at 0.3x0.3 deg (Badia et al., 2017) with facility-level stack parameter information (i.e., height, diameter, exit velocity and exit temperature). Information on stack parameters were obtained from the following sources:

- The point source database of electric generation units (PTEGU), obtained from the US EPA emission modelling platform (US EPA, 2021), which reports plant-level stack parameter information for USA power plants.
- The HERMES Spanish power plant database (Guevara et al., 2013)
- Atmospheric emission licences of South African power plants (CER, 2022)
- The list of tallest chimneys worldwide reported by Wikipedia (2022a)
- The list of tallest chimneys in Poland reported by Wikipedia (2022b)
- The list of tallest chimneys in Czech Republic reported by Wikipedia (2022c)
- The list of tallest structures in Germany reported by Wikiwand (2022)

The Indian Ministry of Environment, Forest and Climate Change (MoEFCC, 2015) requires all coal-fired power plants with generation capacity of 500 MW and above to build a stack of minimum 275m; those between 210 MW and 500 MW to build a stack of minimum 220 m; and those with less than 210 MW to build a stack based on the estimated SO_2 emissions rate (Q in

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kg/hr) and a thumb rule of height = 14*(Q)0.3. Considering this information, we assumed that all coal-fired power plants in India with a generation capacity of 500 MW and above had a stack height of 275m, and those between 210 MW and 500 MW a stack height of 220m.

In some European coal -fired power plants built in recent years, which must be equipped with a flue gas cleaning system, the cooling tower also takes on the function of the chimney. Original chimneys were dismantled and now emissions are released through the cooling towers, which have different stack conditions. For Germany, we identified the list of power plants with cooling towers used as chimneys and associated stack height through Wikipedia (2022d), and we completed the information with the stack diameter, exit temperature and exit velocity reported by Brunner et al., (2019). This level of detail is not considered in facilities from other countries due to lack of information.

Fuel-dependent and CO_2 emission-weighted average stack parameters were calculated using the PTEGU dataset and assigned to all those facilities for which no specific information was found. For waste-to-energy power plants we considered the stack parameters reported by Pregger and Friedrich (2009) as the PTEGU dataset does not include this type of facility. Table 4 summarises the stack parameters proposed per fuel type and the associated number of units considered to calculate the values.

Table 4 Fuel-dependent and CO_2 emission-weighted average stack parameters assigned to facilities with no specific information and number of sources considered to calculate them.

Fuel	Stack height [m]	Stack diameter [m]	Exit temperature [ºC]	Exit velocity [m/s]	N units
Coal	182.6	7.7	91.8	21.0	675
Natural gas	53.0	5.6	143.5	20.0	1800
Oil	125.7	5.5	122.6	20.7	74
Biomass	72.6	2.8	147.6	28.5	33
Waste	103	2.5	118	8.5	230

Figure 4 illustrates, on the one hand, the facilities assigned with specific (red circles) or emission-weighted averaged (white circles) stack height information and, on the other hand, the share of total CO_2 emissions from the power sector assigned with specific stack parameter information. In terms of emission coverage, only 28% of total CO_2 emissions from the power sector are assigned with specific stack height values. The coverage is even lower for stack diameter, exit velocity and temperature (i.e., approx. 15% in all cases). These results indicate the current lack of stack parameters information.

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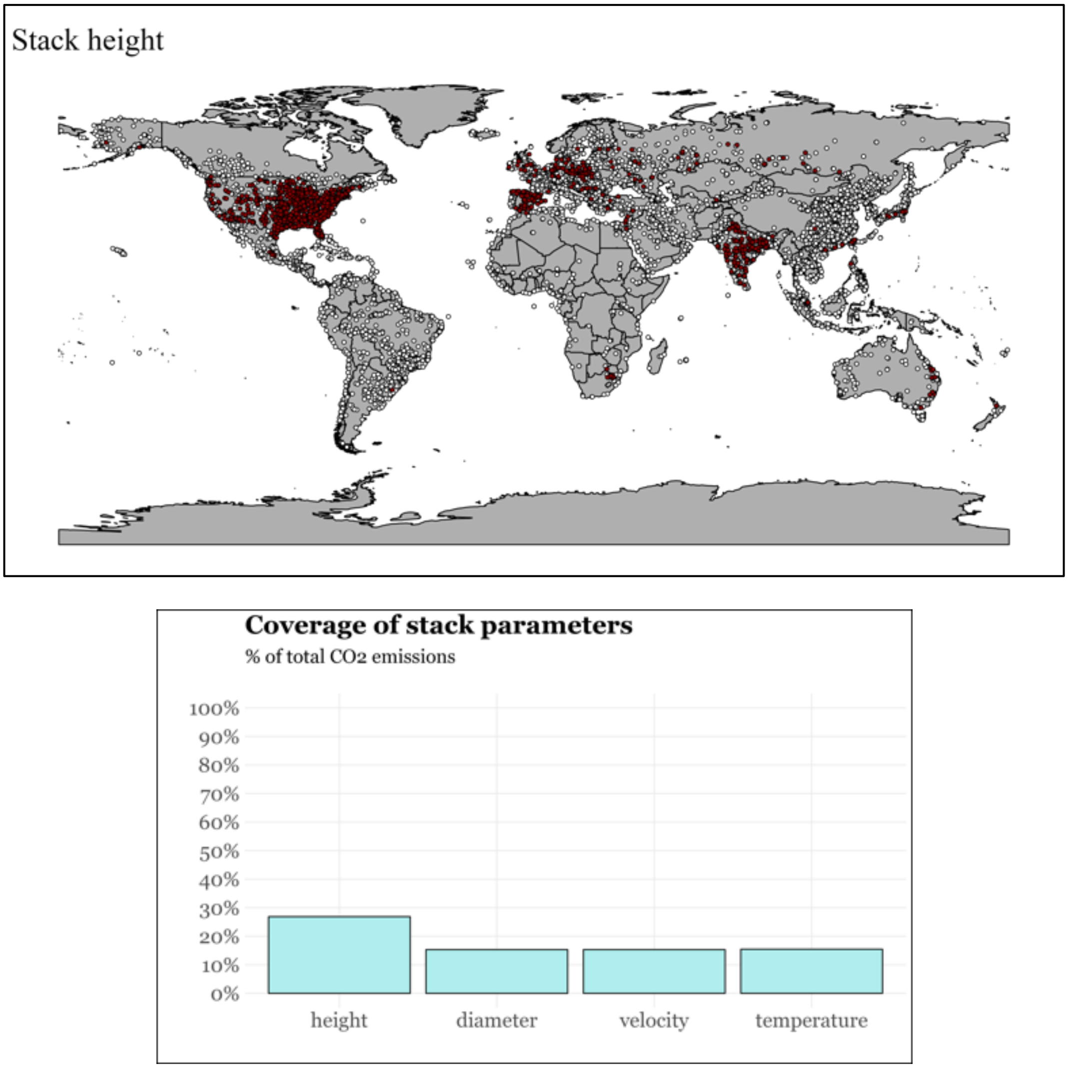

Figure 4 Facilities assigned with specific (red circles) or emission-weighted averaged (white circles) stack height information (top) and share of total CO_2 emissions [%] from the power sector for which specific stack parameters (height, diameter, exit velocity and exit temperature) were assigned (bottom).

The plume rise calculations at the hourly and facility level were performed using the HERMESv3 bottom-up emission system (Guevara et al., 2020), which includes plume rise formulas as described by Gordon et al. (2018). The HERMESv3 system was used to break down facility-level annual emissions into hourly resolution using of the temporal profiles described in Sect. 2.4, and to estimate hourly effective emission heights per plant considering the meteorological information provided by the nearest grid cell of MONARCH. Hourly plume top and plume bottom values per facility ($h_{top}(h,f)$, $h_{bot}(h,f)$) were derived from the estimated effective emission heights following the expressions reported by Bieser et al. (2011) (Eq. 1 and 2):

$$h_{top}(h,f) = h_s(f) + 1.5 * \Delta h(h,f) \quad (1)$$

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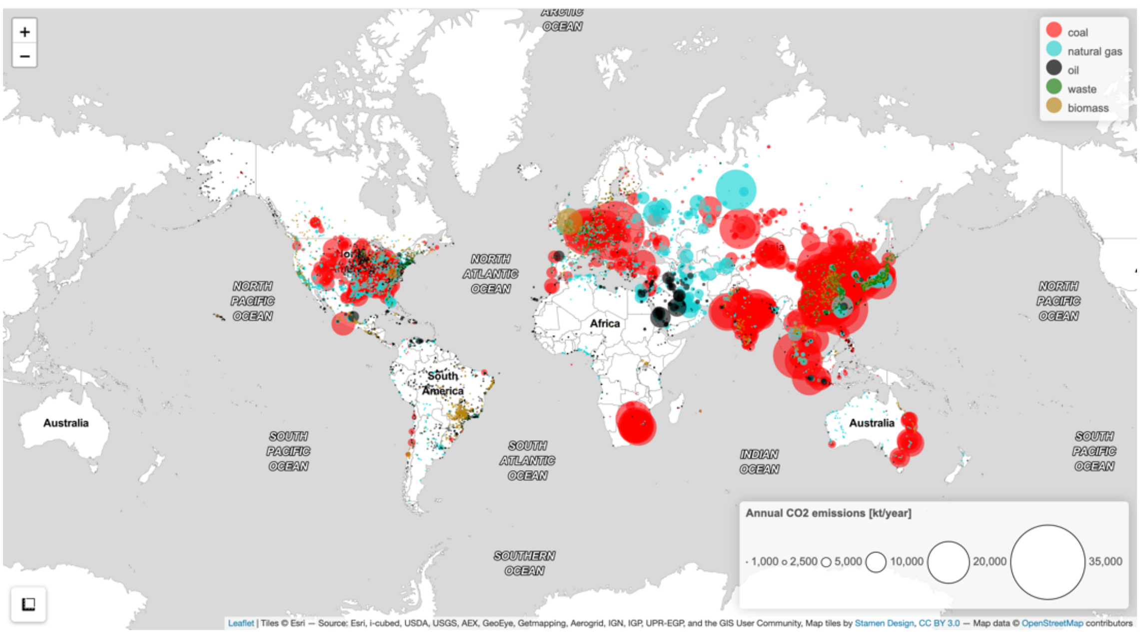
$$h_{bot}(h, f) = h_s(f) + 0.5 * \Delta h(h, f) \quad (2)$$

where $h_s(f)$ is the stack height of the facility f and $\Delta h(h, f)$ is the modelled effective emission height for the facility f and hour h.

3 Results

3.1 Annual emissions

Figure 5 shows the plant-level CO_2 and NO_x annual emissions as reported by the resulting global point source database. Results are distinguished by fuel type. It is observed that coal-fired power plants (red circles) are the main contributors to total CO_2 emissions, the top emitters being in China, India, US, Australia, South Africa, Central Europe and Indonesia. CO_2 emissions from natural gas power plants (blue circles) are dominant in Russia and some countries from the Middle East (e.g., Saudi Arabia and Iran). For NO_x, main contributors are also coal-fired power plants, but several oil-fired power plants (black circles) gain importance when compared to their contributions in the CO_2 emissions map, especially in the Middle East (i.e., Iran and Saudi Arabia), Indonesia, Venezuela and some countries in Northern Africa. In China, India, US, Australia, South Africa and Central Europe NOx emissions are mainly dominated by coal-fired power plants. For both pollutants it is observed that the number of large emitters in Africa and South America is rather scarce, expect for South Africa and some countries in North Africa as well as Venezuela. This is related to the fact that in both regions the electricity production is mainly dominated by renewable sources (e.g., hydro, solar) (IEA, 2021). Linked to this aspect, it is interesting to see the large amount of biomass power plants in Brazil (brown circles), as this fuel represents the second largest energy source in the country, just behind hydropower. A significant number of waste-to-energy plants (green circles) are reported in Japan and China, the two countries with the largest installed incineration capacity (Lu et al., 2017).



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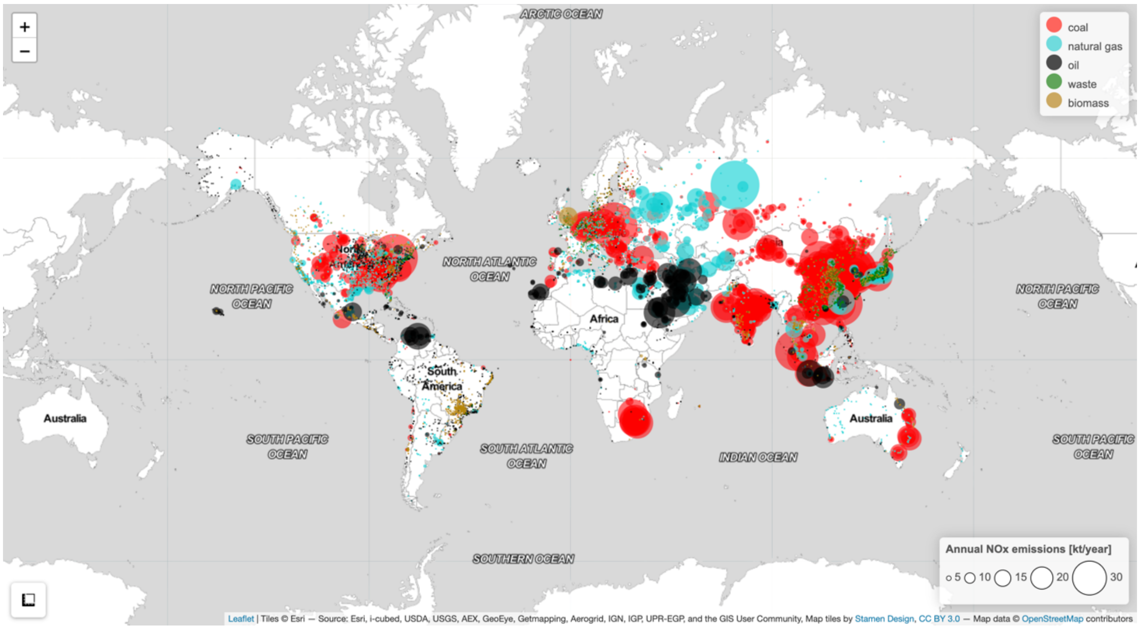

Figure 5 Plant-level CO_2 and NO_x annual emissions [kt/year] as reported by the resulting global point source database. Emissions are colour-classified according to the main fuel used: coal (red), natural gas (blue), oil (black), waste (green) and biomass (brown)

Table 5 and Table 6 list the top 15 CO_2 and NO_x emitting power plants worldwide and in EU27+UK.

At the global level, the Belchatów (Poland), Taean (South Korea), Taichung (Taiwan), Dangjin (South Korea) and Datang Tuoketuo (China) power plants are the top 5 CO_2 emitters. These five facilities are also the five largest coal-fired power stations in the world (with installed capacities between 6700MW and 5300 MW). All top 15 CO_2 emitters are coal-fired power plants, except for Surgutskaya GRES-2 (Russia), which is the largest combined-cycle natural gas-fired power station of Russia (8865MW) and supplies energy to nearly 40% of the population. Most of the top 15 CO_2 emitters are in Asian countries, including: South Korea (3), China (2), Taiwan (2), Malaysia (2), India (1) and Kazakhstan (1), while the rest are in Europe: Germany (2), Poland (1) and Russia (1). Seven out of the 10 top emitters identified in this work are also listed in the 2018 top ten CO_2 polluting power plants reported by Grant et al., (2021). At the EU27+UK, it is observed that most of the 15 top CO_2 emitters are in Germany (6) and Poland (3). Similarly to what is observed at the global scale, 14 out of 15 facilities are coal-fired power plants, the remaining worst polluter being the Drax biomass power station, the largest power plant in the UK (3906MW) that is also capable of co-firing petroleum coke. The largest emitter in EU27+UK (Belchatów, Poland) reports almost 5 times more CO_2 emissions than the fifteenth facility (As Pontes, Spain).

For NOx, the list of top emitters mainly consists of coal-fired power plants (13 out of 15). Twelve of these plants appear in both the CO_2 and NO_x top 15 emitters lists, including Surgutskaya GRES-2 (Russia), Belchatów (Poland), Taean (South Korea), Taichung (Taiwan), Dangjin (South Korea), Datang Tuoketuo (China), Manjung (Malaysia), Yeongheun (South Korea), Ekibastuz-1 (Kazakhstan), Waigaoqiao (China), Vindhyachal (India) and Tanjung Bin (Malaysia). The other top 15

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emitters are two auto-producers located in the USA (pulp and paper manufacturing plants) and one oil-fired plant located in Saudi Arabia (Shuaibah). At the EU27+UK level, Belchatów is again the largest emitter. Four out of the top five emitters are in Germany, all of them being coal-fired power plants. There are also four Spanish facilities, three of them being oil-fired internal combustion engines located in the Canary Islands. The other non-coal facilities that complete the European top 15 list are Drax (UK) and Atherinolakkos (Greece), the later also being operated with diesel engine units.

Additional information on the total emissions obtained at the country level is provided in Sect. 3.2.

Table 5 List of top 15 CO_2 [kt/year] and NO_x [t/year] emitting power plants worldwide.

Plant	Fuel	Country	CO_2 [kt/year]
Belchatów	coal	POL	38400
Taean	coal	KOR	35877
Taichung	coal	TWN	34499
Dangjin	coal	KOR	33859
Datang Tuoketuo	coal	CHN	31435
Manjung	coal	MYS	30418
Neurath	coal	DEU	29900
Yeongheung	coal	KOR	28477
Niederaussem	coal	DEU	27200
Surgutskaya GRES-2	natural gas	RUS	25640
Ekibastuz-1	coal	KAZ	25522
Vindhyachal	coal	IND	24733
Waigaoqiao	coal	CHN	24512
Mailiao	coal	TWN	24463
Tanjung Bin	coal	MYS	24068

Plant	Fuel	Country	NO_x [t/year]
Surgutskaya GRES-2	natural gas	RUS	30882
Belchatów	coal	POL	30100
Taean	coal	KOR	29807
Domtar Paper Company	coal	USA	29652
Taichung	coal	TWN	28320
Dangjin	coal	KOR	28130
Datang Tuoketuo	coal	CHN	26409
Manjung	coal	MYS	25555
Yeongheung	coal	KOR	23659
Ekibastuz-1	coal	KAZ	21463
Resolute Forest Products	coal	USA	20779
Waigaoqiao	coal	CHN	20593
Shuaibah	oil	SAU	20491
Vindhyachal	coal	IND	20404
Tanjung Bin	coal	MYS	20220

Table 6 List of top 15 CO_2 [kt/year] and NO_x [t/year] emitting power plants in EU27 + UK.

Plant	Fuel	Country	CO_2 [kt/year]
Belchatów	coal	POL	38400
Neurath	coal	DEU	29900
Niederaussem	coal	DEU	27200
Jänschwalde	coal	DEU	24000
Eschweiler	coal	DEU	19100
Kraftwerk Boxberg	coal	DEU	19100
Drax	biomass	GBR	16600
Kozienice	coal	POL	14100
Lippendorf	coal	DEU	11400
Maritsa East 2	coal	BGR	9574
Agioy Dhmhtrioy	coal	GRC	9230
Enea Połaniec	coal	POL	8220
Eemshaven	coal	NLD	8210
Torrevaldaliga Nord	coal	ITA	8081
As Pontes	coal	ESP	7940

Plant	Fuel	Country	NO_x [t/year]
Belchatów	coal	POL	30100
Neurath	coal	DEU	20200
Jänschwalde	coal	DEU	19000
Niederaussem	coal	DEU	18000
Kraftwerk Boxberg	coal	DEU	13500
Eschweiler	coal	DEU	13000
Drax	biomass	GBR	12200
Punta Grande	oil	ESP	11200
Atherinolakkos	oil	GRC	10700
Kozienice	coal	POL	9650
Las Salinas	oil	ESP	8220
Enea Połaniec	coal	POL	7760
Agioy Dhmhtrioy	coal	GRC	7100
Granadilla	oil	ESP	7030
As Pontes	coal	ESP	6360

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3.2 Comparison with independent inventories

The estimated annual emissions were compared against other independent plant- and country-level inventories. The following subsections present and discuss the results.

3.2.1 Plant level

Estimated plant level emissions were compared against information reported by the CARMAv3 global database. As mentioned in Sect. 1, and despite not being longer maintained, the CARMAv3 database is still used as a proxy for the spatial representation of power plant emissions in several state-of-the-art inventories and modelling systems, like the EDGAR inventory (Janssens-Maenhout et al., 2019) and the Carbon Cycle Fossil Fuel Data Assimilation System (CCFFDAS) (Asefi-Najafabady et al., 2014).

Table 7 summarises the comparison between total number of power plants and associated CO_2 emissions reported by CARMAv3 and this work for selected countries, including China, the United States, India, Germany, South Korea, South Africa, Australia, Taiwan and Poland. For China the present work reports 79% more facilities and 92% more emissions than CARMAv3. This result is in line with the fact that CARMAv3 was build using information from 2009, and during the last decade the number of power plants in China and associated emissions has significantly increased (IEA, 2023). For USA the number of plants reported by each database is almost the same (-1%) but emissions are lower in this work when compared to CARMAv3 (-17%). This difference is mainly related to the transition from coal to natural gas and renewables that occurred during the last decade (EIA, 2021). Greenhouse gas emissions for electricity generation from natural gas are generally lower than those from oil and coal due to a more beneficial heat per carbon density and higher combustion efficiencies (e.g., IPCC, 2011). For Germany, South Africa, Poland and Australia it is observed that despite including less facilities (differences between -47% and -63%), total CO_2 emissions reported by this work are generally in line with CARMAv3 values (differences between -12% and 0%). This is because CARMAv3 is mostly based on Platts WEPP (Platts, 2015), which contains many small size auto-producer units (e.g., boilers located in commercial and institutional buildings such as hospitals or airports) with very low emission levels associated to them that are not considered in the present work. Moreover, and as shown below, CARMAv3 includes power plants that are not currently operating as they were shut down during the last decade. For India the present catalogue reports 81% more emissions than CARMAv3 despite including -30% less facilities, which indicates that the additional plants considered in CARMAv3 are low-level emission small plants. This hypothesis is confirmed when comparing the median CO_2 annual emission values of each dataset, the one reported by the present catalogue (154669 kt $CO_2 \cdot year^{-1}$) being almost 18 times larger than CARMAv3 (8839 kt $CO_2 \cdot year^{-1}$).

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Table 7 Comparison between total number of facilities and associated CO_2 emissions [kt·year^{-1}] reported by CARMAv3 and this work for selected countries (China, the United States, India, Germany, South Korea, South Africa, Australia, Taiwan and Poland.

ISO3	Number of plants			CO_2 [kt/year]		
	this work	CARMAv3	diff	this work	CARMAv3	diff
CHN	1744	977	79%	4732145.0	2469937.5	92%
USA	2847	2866	-1%	1928603.6	2315648.5	-17%
IND	450	641	-30%	1185786.9	653460.9	81%
DEU	365	997	-63%	298746.1	297996.3	0%
KOR	113	107	6%	294318.4	213915.2	38%
ZAF	22	43	-49%	224744.1	224515.0	0%
AUS	190	368	-48%	188235.9	215089.9	-12%
TWN	58	92	-37%	161218.5	111306.1	45%
POL	150	282	-47%	146717.6	148787.1	-1%

Figure 6 shows a plant-to-plant comparison between the top 20 emitters reported by this work and CARMAv3 for selected countries (i.e., United States, Taiwan, South Africa and Poland). In all of them it is observed that CARMAv3 reports emissions for plants that are not included in the current catalogue as they are currently retired or not operating (e.g., Jenwu power station in Taiwan, Adamow power station in Poland). Except for the case of United States (i.e., the Monticello Steam Electric Station), most of these plants were already reporting low emissions in 2009, which could indicate that they were already in the process of being disconnected from the grid. The good agreement in South Africa, Poland and Taiwan (R^2 between 0.86 and 0.97) indicates that the level of emissions from the top emitters in these countries remained stable between 2009 and 2018 (e.g., Kendal power plant in South Africa, Belchatów power station in Poland). On the contrary, significant discrepancies are observed in the United States (R^2 = 0.41), the results reported by this work being consistently lower than CARMAv3 for all top emitters. As mentioned before, these differences are mainly driven by the replacement or conversion of coal-fired plants to natural gas during the last decade.

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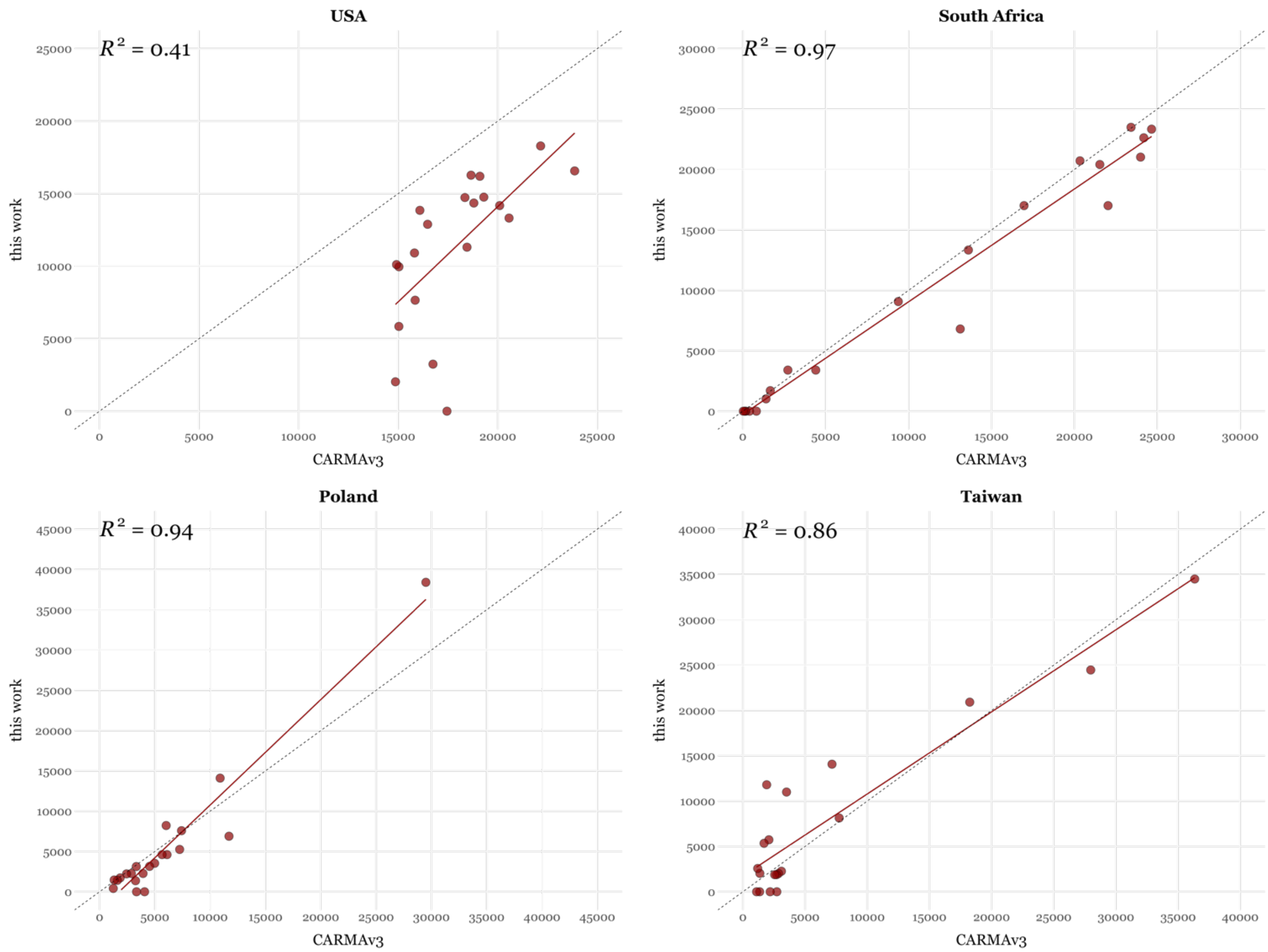

Figure 6 Plant-to-plant CO_2 annual emission comparison between top 20 emitters reported by this work and CARMAv3 for United States, Taiwan, South Africa and Poland (dashed line represents the 1:1 line).

Besides comparing total annual emissions, we also compared the geographical location reported by the present catalogue and CARMAv3 for each one of the top 20 emitters in the nine countries listed in Table 7. We found 6 facilities in which the location reported by CARMAv3 was off by hundreds of kilometres (between 120km and 337km), while in 24 cases the locations provided by CARMAv3 were displaced from the right coordinates by tens of kilometres (between 11km and 79km). Most of these cases (22 out of 30) correspond to units in China, Taiwan and India. The differences between locations reported in this work and CARMAv3 are much lower when looking at European (Poland and Germany) and USA facilities, where the average distance between geographical coordinates reported by each dataset is of approximately 600m, and the maximum discrepancy is of 5.7km. The wrongly allocated CARMAv3 power plants tend to be assigned to nearby city centres (Fig. S1). This pattern is consistent with the fact that the Platts WEPP, which CARMAv3 built upon, does not report the coordinates of the units, but

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only the name of the closest city to the facility, which was then used by the CARMA team to get approximate latitude and longitude values. The geographical dislocation of CARMAv3 facilities described here is consistent with other recent investigations (e.g., Zhang et al., 2022).

Additionally, we also performed a plant-to-plant comparison between the top CO_2 100 emitters reported by this work and the Central Electricity Authority (CEA, 2022) for India and the National Pollutant Release Inventory (NPRI, 2022) for Canada for the year 2018, finding overall a good agreement between the datasets (R^2 between 0.79 and 0.81, Fig. S2).

3.2.2 Country level

Estimated country-level emissions were compared against information reported by the EDGARv7 greenhouse gases (CO_2 and CH_4) and EDGARv6.1 air pollutant (NO_x and SO_2) global inventories, as well as national estimates reported by the EMEP Centre on Emission Inventories and Projections (CEIP, 2022), the national inventory submissions to the UNFCCC (UNFCCC, 2022) and other national databases including the USA National Emission Inventory (EPA, 2021), the Chinese Multi-resolution Emission Inventory model for Climate and air pollution research (MEICv1.3 for air pollutants and MEICv2.0 for CO_2; Li et al., 2017; Zheng et al., 2018), Cropper et al., (2021) and the GHG Platform-India (2022) for India, the South African Atmospheric Emission License reports (AEL; ESKOM, 2022b), the Mexican National Emission Inventory (INEM; SEMARNAT, 2021), the Australian National Pollution Inventory (NPI; DCCEEW, 2022), the South Korean Clean Air Policy Support System (CAPSS; Choi et al., 2020) and the Taiwan Air Pollutant Discharge Inventory (TEDS; EPA Taiwan, 2021). For all cases the reference year is 2018 except for the national estimates reported for the USA (2017), China (2017), Mexico (2016) and Taiwan (2019). Figure 7 shows the comparison for CO_2, CH_4, NO_x and SO_2 emissions in the top 20 emitting countries.

A general good agreement is observed between the CO_2 emissions reported by this work and EDGARv7. The largest differences are observed in Russia, Japan and China, where the present catalogue reports lower emissions (-34%, -15% and -9%, respectively) as it does not include auto-producers (Japan and India) and heat-only plants (Russia). The UNFCCC and independent national estimates are also generally in line with our work, the differences in China, USA and India being of 10%, 9% and -8%, respectively. The discrepancies observed in China and USA could be related to the fact that the national estimates reported by MEICv2.0 and UNFCCC, respectively do not include emissions from auto-producers.

For CH_4, EDGARv7 tends to report larger emissions than this work, especially in Russia (-59%), India (-52%) and USA (-29%). In the case of Russia, national estimates are more aligned with EDGARv7 (21%) than the present catalogue (-50%). Oppositely, in India and the USA national emissions are more in line with estimates from this work than EDGARv7, the former presenting substantially higher values (32% in the USA and 122% in India). In Europe sometimes the CH_4 emissions from this work matches with UNFCCC reported values (e.g., Italy, Germany), but under and overestimations also occur (e.g., Poland, UK). Generally speaking, the share of the power sector to total national CH_4 emissions is small, often around or below 1% (e.g., 0.24% for Italy, 0.19% for Poland, 1.1% for Sweden; UNFCCC, 2022). Hence, the deviations have a negligible influence

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on national total CH_4 emissions and are not further investigated. Moreover, CH_4 emissions in power plants are scarcely measured and that corresponding emission factors are associated to very large uncertainties (IPCC, 2019).

EDGARv6.1 reports larger NO_x emissions than this work in almost all countries (up to 4.5 times in India). The emissions reported by our catalogue are more in line with national estimates in USA, China, Russia and Mexico, where EDGARv6.1 report significant larger values (e.g., approx. 2 times in USA). Oppositely, emissions reported by EDGARv6.1 in India, South Africa and Australia are much closer to the national values than our estimates, which are between 3 and 4.5 times lower. As described in Sect.2.2, The NO_x/CO_2 emission ratios considered in this work (Table 2) to estimate NO_x emissions in non-European countries are based on data from the USA and may not correctly represent the reality of certain countries in terms of emission legislation and emission technologies associated to the power generation industry. As a matter of fact, the NO_x emission standards for coal-fired power plants in USA (117mg·m^{-3} for plants built after 2005; 160 mg·m^{-3} for plants built between 1997-2005) and China (100mg·m^{-3} for plants built 2004-2011; 200mg·m^{-3} for plants built before 2004) are much stricter than the ones established in South Africa (1020mg·m^{-3}), Australia (856 mg·m^{-3}) and India (600 mg·m^{-3} for units installed before 2003, 300 mg·m^{-3} for units installed between 2004 and 2016 and 100 mg·m^{-3} for units after 2017), and therefore the associated emission factors/ratios in these three countries are probably larger than the ones considered in the present work, leading to an underestimation of the estimate NO_x emissions.

For SO_2, comparison results are very similar to what is observed for NO_x. Emissions reported by this work are in general much lower than the EDGARv6.1 values (up to 7.5 times in India and almost 4 times in USA). When compared to national estimates, this study is mostly in line for China, USA and Russia. The comparisons performed for India, South Africa, Turkey and Mexico indicate that the emissions estimated by EDGARv6.1 are closer to the national estimates whereas the present catalogue reports significant lower values for these countries (between 5.6 and 14.4 times lower). As previously mentioned, we believe that these discrepancies are related to the SO_2/CO_2 emission ratios considered in this work, which are representative of countries where strict emission standards are implemented such as USA (160mg·m^{-3} for power plants commissioned after 2005 and 190 mg·m^{-3} for power plants commissioned between 1978 and 2005) or China (200 mg·m^{-3} for all existing plants and 35 mg·m^{-3} for plants built after 2020), but not for countries where limit values are more relax such as Turkey (1000 mg·m^{-3} in operation between 2004 and 2019), South Africa (680 mg·m^{-3}), India (600 mg·m^{-3} for units commissioned before 2003, 200 mg·m^{-3} for units commissioned between 2004 and 2016 and 100 mg·m^{-3} for units after 2017) or Australia, where no national or state-wide limits exist. Differences in the amounts of sulphur contained in the coal used in each country may also be playing a role in the observed discrepancies.

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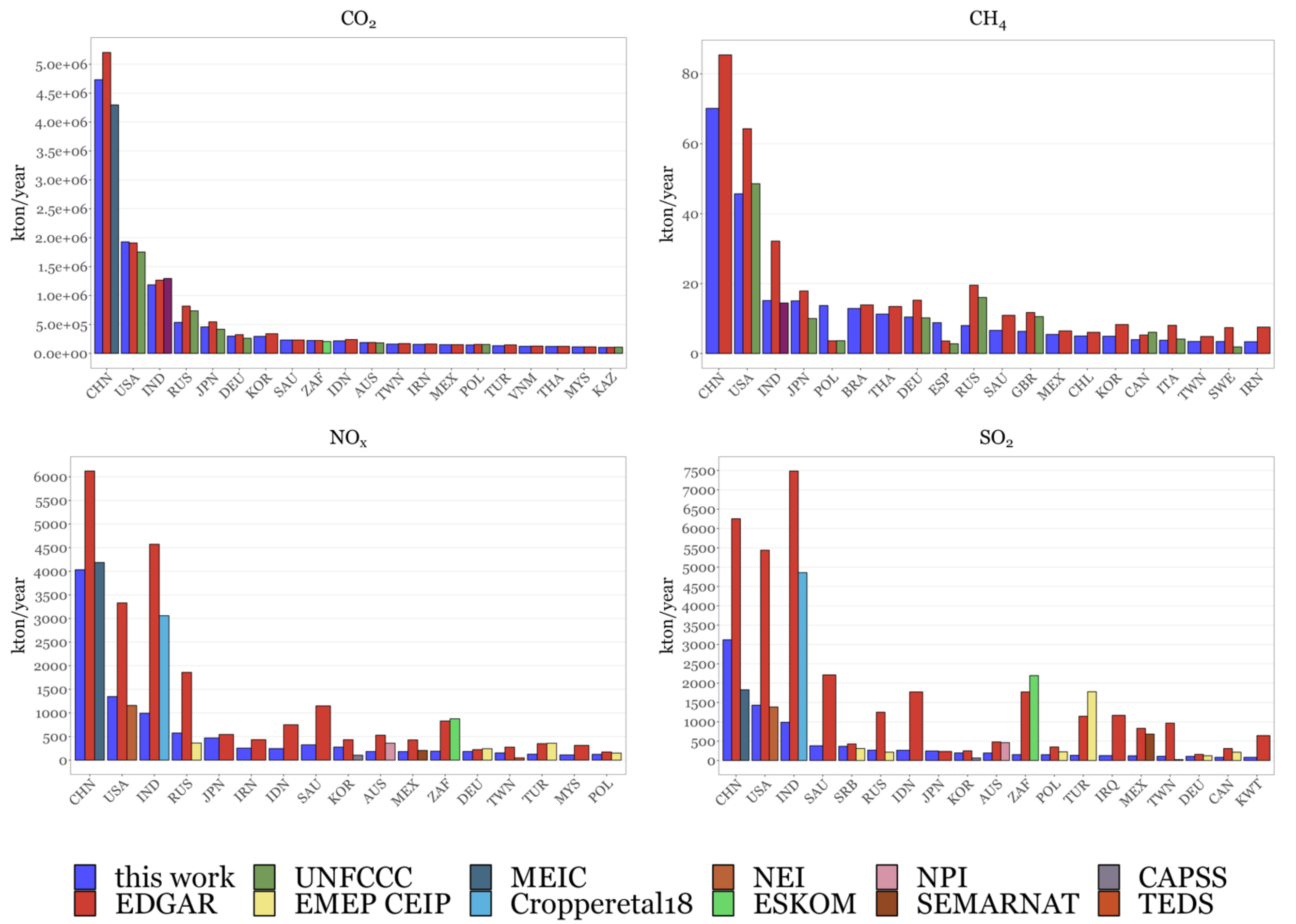

Figure 7 Comparison between country-level CO_2, CH_4, NO_x and SO_2 annual emissions kt/year] estimated for the power sector by this work and reported by independent inventories. Results are shown for the top 20 emitters.

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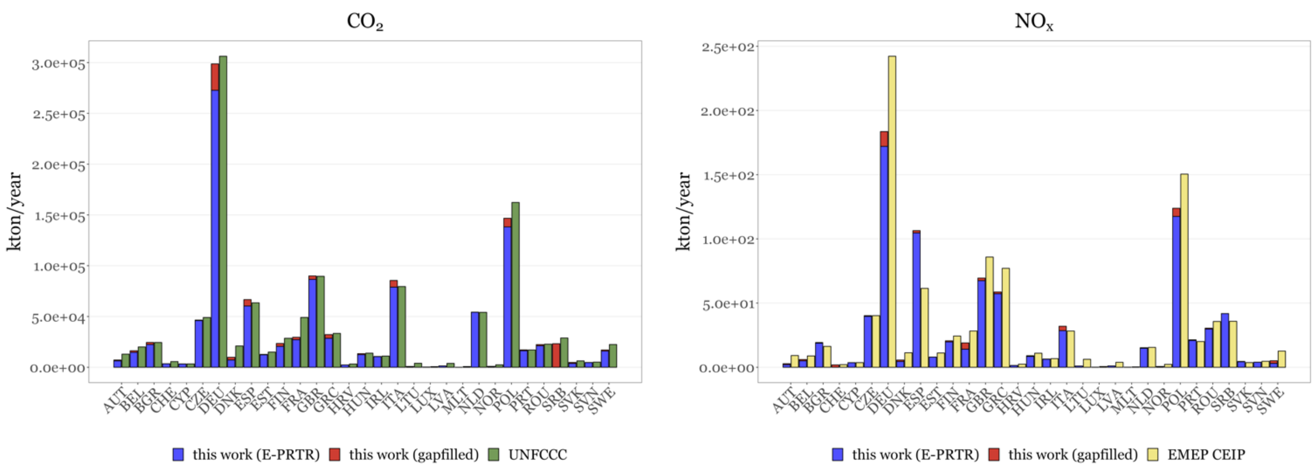

Figure 8 shows the comparison of national CO_2 and NO_x emissions reported by the present catalogue and officially estimates (UNFCCC and EMEP CEIP, respectively) for EU27+UK. Results from this work are distinguished between emissions directly obtained from the E-PRTR_v18 database and derived following the gap filling routine described in Sect. 2.2.

For most countries there is a good agreement with the nationally reported CO_2 total for the energy sector, which is not surprising since most countries will include the emission reporting by facilities in their national inventory. There are several countries, however, where the current catalogue sums up to less than 60% of the reported CO_2 national total: France, Denmark, Luxembourg, Austria, Lithuania, Latvia, Malta and Norway. When looking into more detail at the CO_2 emissions by fuel type (Fig. 9), the discrepancies for these countries appear to be caused by a significantly lower contribution of biomass CO_2 emissions. For example, for France, Austria and Denmark, but also for Germany, the national inventory has much higher CO_2 emissions included from biomass combustion. The biomass/biogas power plants responsible for this contribution, however, mostly cannot be found in the EPRTR/LCP or the other plant specific databases that were consulted for this work (see Sect. 2.1). This suggests these are mostly small size plants that fall below the reporting thresholds.

For NO_x, the differences are a bit larger than for CO_2, with the current catalogue covering on average about 88% of the national total NO_x emissions. For Spain, the combined reporting of EPRTR facilities already substantially exceeds (by 73%) the national reporting of energy sector emissions, which is related to the fact that national estimates reported to EMEP CEIP do not include emissions from the Canary Islands, as they are located outside of the geographical scope of EMEP. As shown in Sect. 3.1, NO_x emissions from power plants located in the Canary Island are significantly large as they are operated by internal combustion diesel engines. For both CO_2 and NO_x, the influence of the gap filling of emissions appears limited on the national level.

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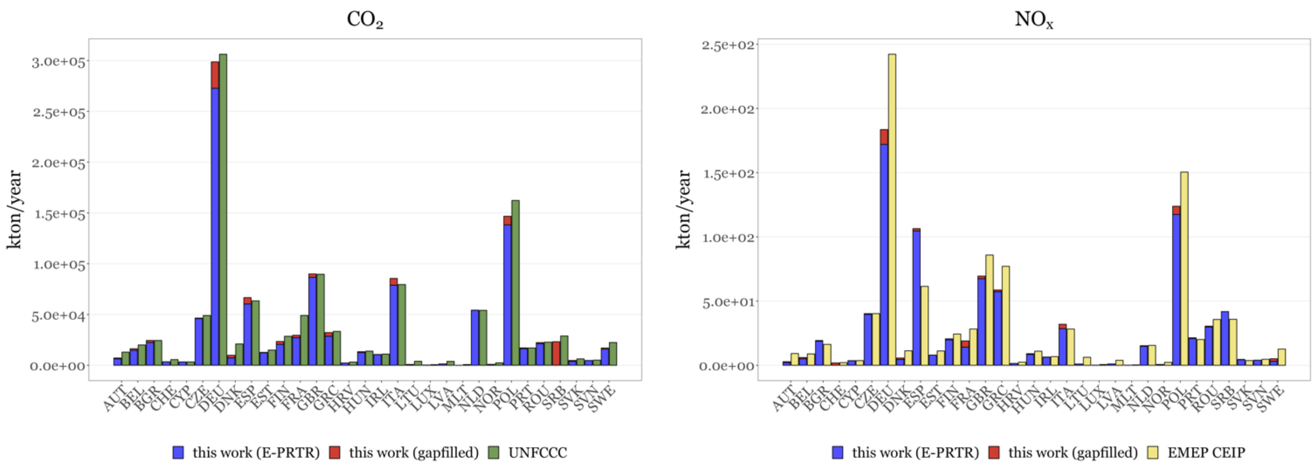

Figure 8 Comparison between country-level CO_2 and NO_x annual emissions kt/year] estimated for the power sector by this work and reported by EMEP CEIP and UNFCCC for EU27+UK. Results from this work are distinguished between emissions directly obtained from the E-PRTR_v18 database and derived following the gap filling routine.

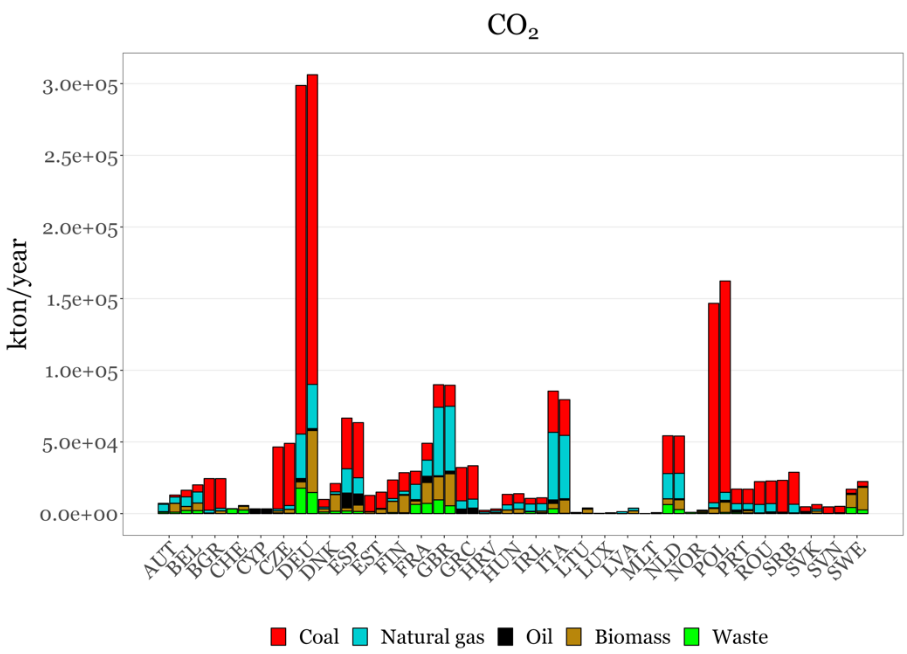

Figure 9 Comparison between country-level CO_2 annual emissions kt/year] estimated for the power sector by this work (left columns) and reported by UNFCCC (right columns) for EU27+UK by fuel type (coal, natural gas, oil, biomass, waste).

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3.3 Temporal distribution

Figure 10 illustrates with an example the plant-level hourly CO_2 emission estimates (kg·h^{-1}) obtained when combining the information on total annual emissions with the temporal profiles reported in the resulting catalogue. We used the HERMESv3 emission system (Guevara et al., 2020) to combine the total annual emissions per facility (Sect. 2.2) with the corresponding country- and fuel-dependent profiles (Sect. 2.4) and derive hourly emissions for the year 2018. The results shown in Fig. 10 correspond to four coal-fired power plants: As Pontes (Spain), Belchatów (Poland), Jänschwalde (Germany) and Matimba (South Africa). The Matimba power plant is the facility that presents the flattest distribution, the results indicating that it is a base load power source. On the other hand, emissions from Belchatów, Jänschwalde and As Pontes present a clear seasonality, with emissions peaking during February, coinciding with a European cold spell that caused below average temperatures in most European countries (C3S, 2018) and, in the case of As Pontes, also during summer, when energy demand increases due to the use of air conditioning systems. A weekend effect is also clearly observed for all facilities, with emissions significantly dropping during Saturday and Sunday when compared to the weekdays.

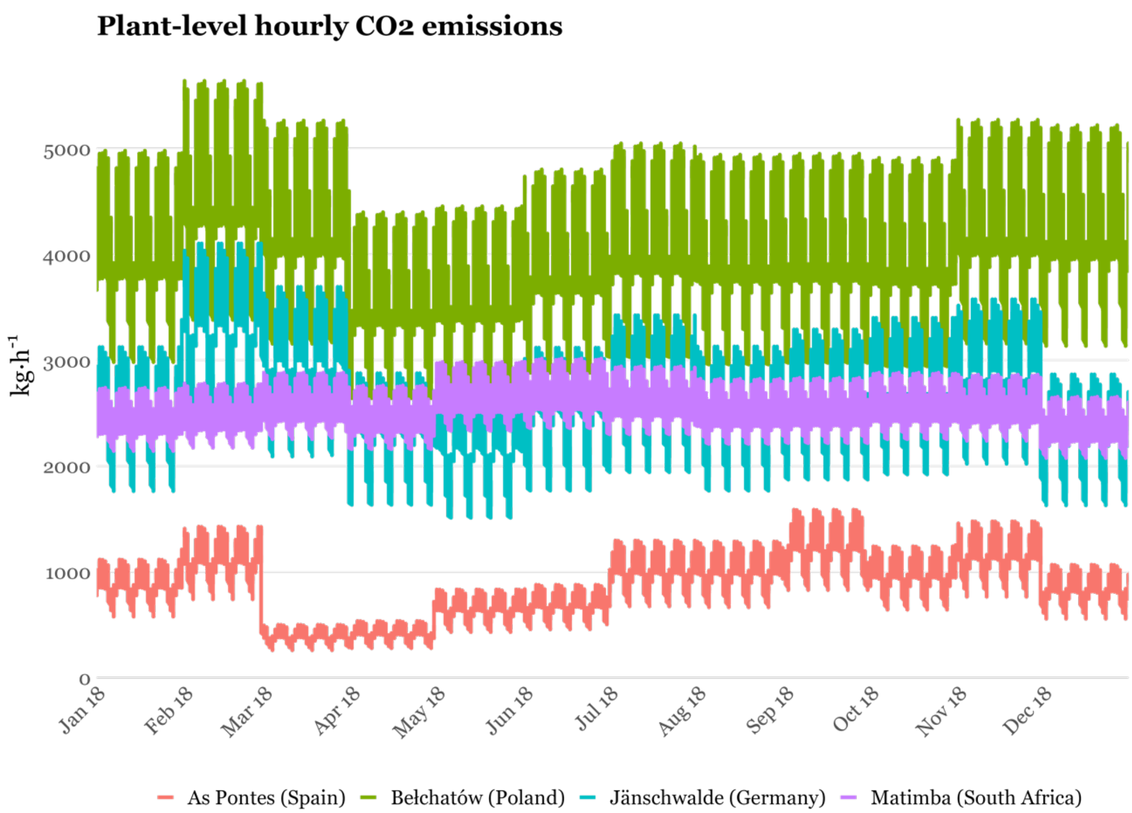

Figure 10 Estimated hourly CO_2 emissions [kg/h] for the As Pontes (Spain), Belchatów (Poland), Jänschwalde (Germany) and Matimba (South Africa) coal-fired power plants.

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Country-dependent monthly, weekly and hourly profiles were constructed using as a basis the estimated plant-level hourly emissions. The resulting emissions were aggregated at the country level and normalised to derive the corresponding temporal profiles. Results were compared against the temporal profiles reported by Denier van der Gon et al. (2011) for the power industry sector (hereinafter referred to as the TNO profiles), which are widely used in the modelling community to quantify observation-based emission estimates (e.g., Kuhlmann et al., 2021). Figure 11 shows an example of monthly, weekly and hourly profiles constructed for the power sector for selected countries and comparison against the TNO profiles.

At the monthly level, large variations are observed between countries. Profiles for United Arab Emirates (ARE) and Kuwait (KWT) present a clear peak during summer, coinciding with the intensive use of air conditioning systems. In the case of USA Pennsylvania (USA-PA), we identify two types of peaks, one related to space cooling needs during July and August, and another one linked to space heating needs during January and December. In Germany (DEU) and Poland (POL) we also distinguish the peaks during wintertime, while the increase of emissions during summer is much lower than the previous cases as these countries are in higher latitudes where the summers are not too hot. The seasonality in India (IND), China (CHN), South Africa (ZAF) and Australia (AUS) are much flatter. The TNO profiles were designed for Europe and the mismatch for countries with different climatic regimes such as United Arab Emirates and Kuwait is to be expected. Nevertheless, we can see that all the profiles differ significantly with the TNO profile, which reports a V-shape seasonality, with emissions peaking during wintertime and presenting their lowest value during summer, and therefore not capturing the peak related to space cooling needs, which is also relevant in Europe.

Concerning the weekly variability, profiles constructed for European countries (i.e., Germany and Poland) are in line with the TNO profile, showing a strong weekend effect, with emissions being reduced more than 20% between weekdays and Sundays. On the other hand, profiles estimated for USA Pennsylvania, South Africa and Australia are much flatter (5 to 10% differences between weekdays and weekends), while India shows almost no differences between weekdays and weekends.

Finally, constructed hourly profiles are quite consistent between countries, all of them showing a rather flat variation, with emissions being slightly larger (10-15%) during daytime (between 07:00h and 20:00h). Similarly to what we see for the monthly profiles, large inconsistencies are observed between the constructed profiles and the TNO profiles, the latter showing a much larger variation between emission levels during night- and daytime and not reproducing the afternoon peak reported by the constructed profiles in most of the countries.

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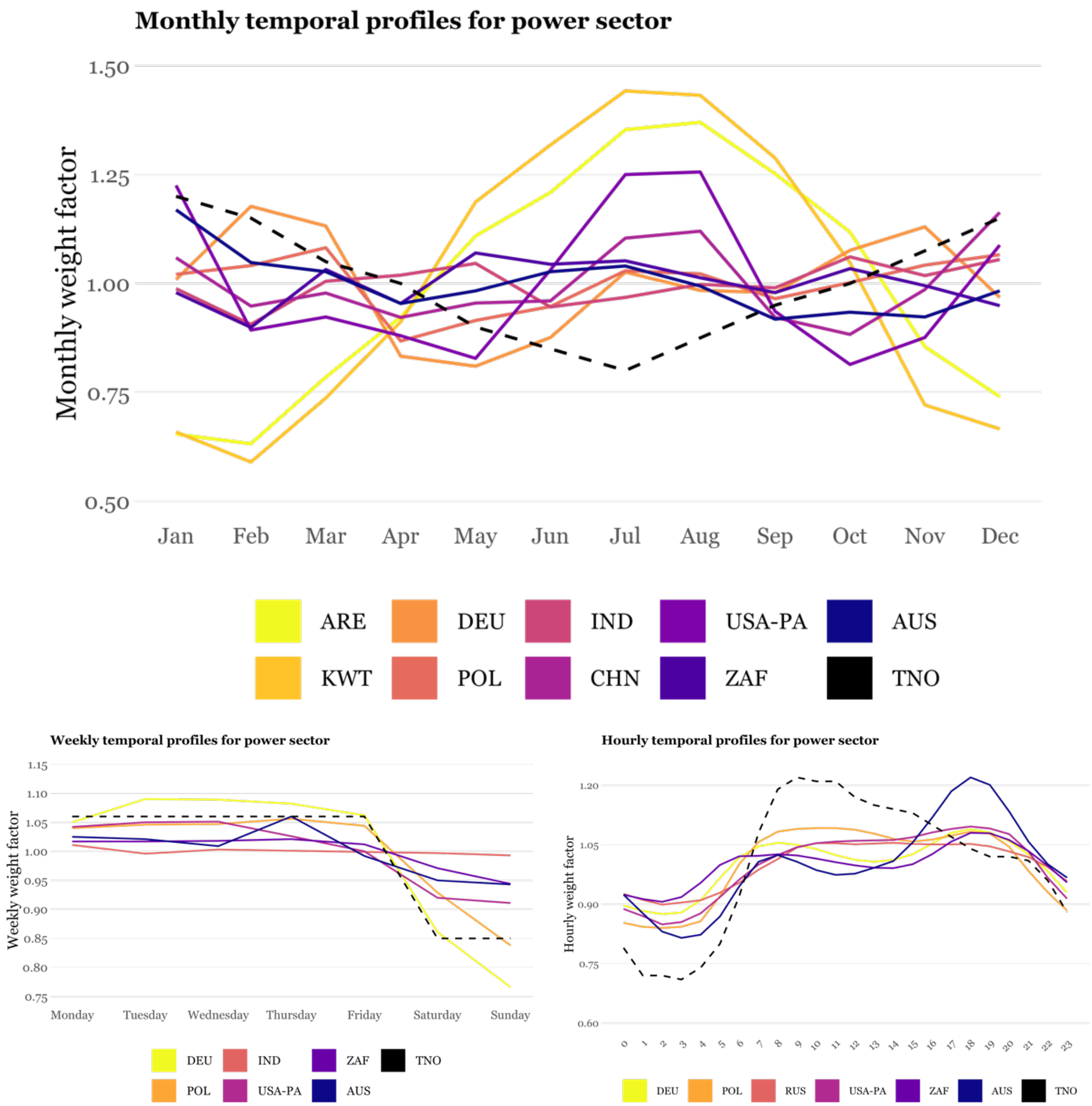

Figure 11 Power sector monthly, weekly and hourly profiles constructed for selected countries, including Arab Emirates (ARE), Kuwait (KWT), Germany (DEU), Poland (POL), India (IND), China (CHN), USA Pennsylvania (USA-PA), South Africa (ZAF) and Australia (AUS). For each temporal resolution, estimated profiles are compared against the profiles reported by Denier van der Gon et al. (2011) (TNO).

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3.4 Vertical allocation

Figure 12 shows an example of the daily bottom (blue) and top (red) plume values [m] at the Matimba (South Africa) and Bełchatów (Poland) coal-fired power plants estimated by the HERMESv3 model for the year 2018. Dashed lines indicate the stack height of each facility (i.e., 250m for Matimba and 300m for Bełchatów). Large month-to-month and day-to-day variations are observed for both the bottom and top plume heights at the two facilities, which are related to changes in the meteorological parameters and atmospheric stability driving the plume rise calculations, mainly the air temperature at the stack height and the boundary-layer height (Guevara et al., 2020). The bottom plume heights are, on average, 41% (Bełchatów) and 70% (Matimba) higher than the corresponding physical stack heights, while top plume height values are on average 124% (Bełchatów) and 206% (Matimba) higher.

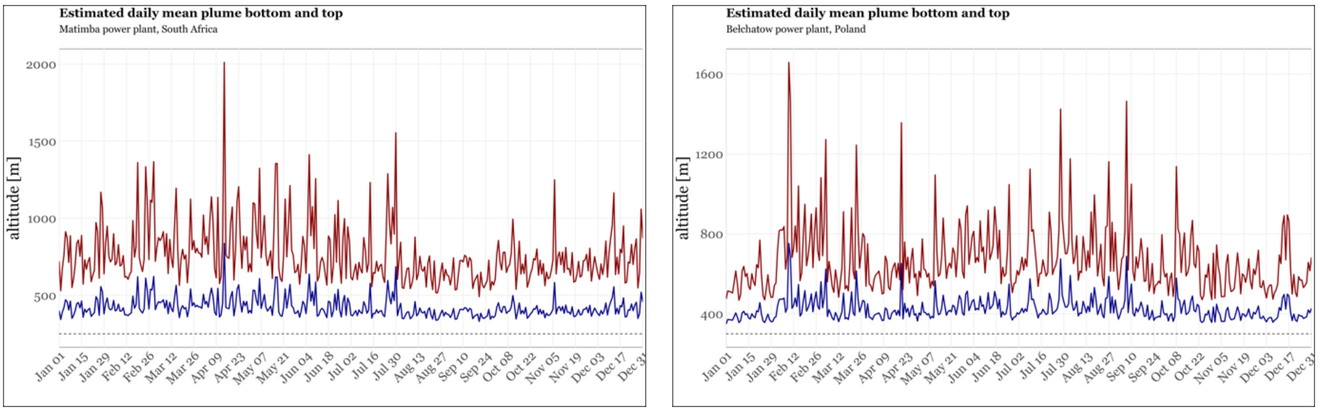

Figure 12 Estimated daily bottom (blue) and top (red) plume values [m] at the Matimba (South Africa) and Belchatów (Poland) coal-fired power plants for the year 2018. Dashed grey lines indicate the stack height of each facility.

For each facility, the estimated CO_2 hourly emissions were first uniformly allocated across 16 vertical layers (from 0m up to 1500m with breaks every 100m, and above 1500m) considering the modelled hourly plume top and bottom values, then summarised to the annual level and finally normalised to 1 to derive annual and emission-weighted vertical profiles. Figure 13 shows the emission-weighted average annual vertical profiles computed for the As Pontes (Spain), Belchatów (Poland), Jänschwalde (Germany) and Matimba (South Africa) coal-fired power plants. Jänschwalde is the power plant with the largest share of emissions occurring in lower layers (i.e., 78% of total emissions allocated between 100 and 300m). This is due to the fact that emissions from this facility are released through the cooling towers, which have a height of only 120m. On the other hand, As Pontes is the facility with the largest share of emissions allocated between 400m and 600m (76%), as it is the power plant with the highest chimney in Europe (365.5m). Belchatów and Matimba present rather similar vertical distribution profiles, partially because both facilities have stacks of similar height (300m and 250m, respectively). Matimba is the power plant allocating the largest share of emissions across the top layers (8% of total emissions above 1000m). This is related to the

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larger exit velocity of the gases when compared to e.g. As Pontes (i.e., 26m/s versus 21m/s, almost 25% larger) as well as to differences in the local climatological conditions.

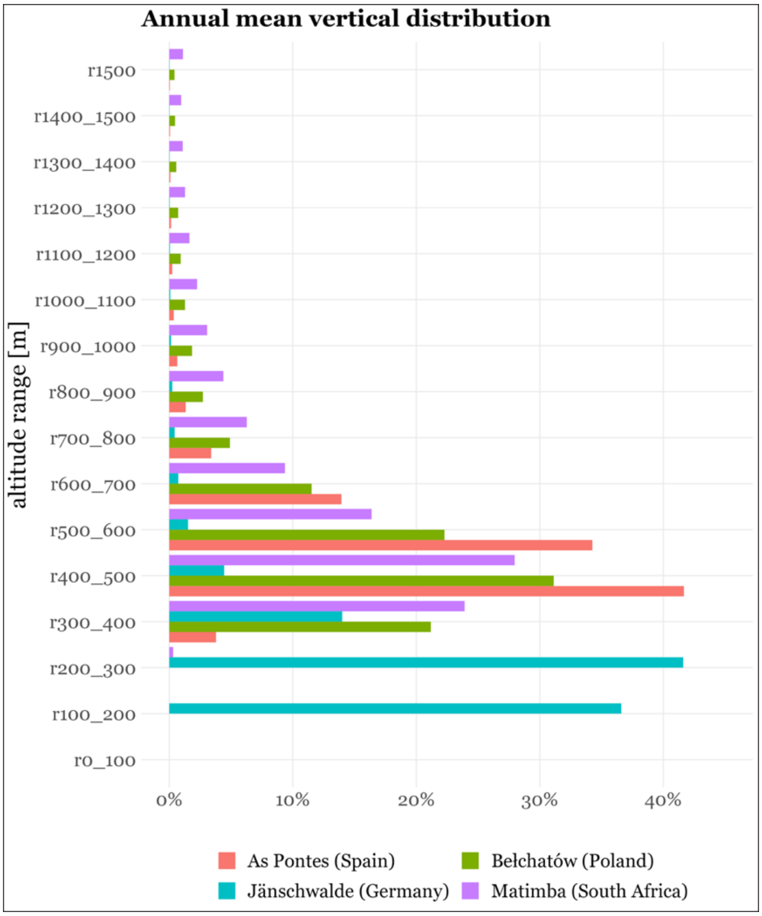

Figure 13 CO_2 emission-weighted average annual vertical profiles estimated for the As Pontes (Spain), Belchatów (Poland), Jänschwalde (Germany) and Matimba (South Africa) coal-fired power plants. For each facility we represent the associated vertical weight factors [%] across 16 vertical layers (from 0m up to 1500m with breaks every 100m, and above 1500m)

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4 Data availability

The global point source database, including plant-level total annual CO_2, NO_x, SO_2, CO and CH_4 emissions, information on fuel type, geographical location (latitude and longitude coordinates) and associated temporal (monthly, weekly, hourly) and vertical profiles, is provided in a collection of CSV files through the CAMS document repository (https://doi.org/10.24380/mxjo-nram, Guevara et al., 2023). The catalogue is provided together with a README file that contains a description of each file and associated fields of information.

5 Conclusions

We present a high-resolution catalogue of CO_2 emissions and co-emitted species (NO_x, SO_2, CO, CH_4) from thermal power plants for the year 2018. The construction of the database follows a bottom-up approach, which combines plant-specific information with national energy consumption statistics and fuel-dependent emission factors and emission ratios. Annual emissions are provided for each plant at their exact geographical locations. Each facility is linked to a specific temporal (i.e., monthly, day-of-the-week and hourly) and vertical distribution profile, which allows to derive spatial- and temporal-resolved emissions for modelling purposes. The resulting catalogue has been developed in the framework of the Prototype System for a Copernicus CO_2 service (CoCO2) EU-funded project to support the development of the CO2MVS capacity. Results from the catalogue were compared to widely used and state-of-the-art emission inventories like the Carbon Monitoring for Action (CARMA) and the Emissions Database for Global Atmospheric Research (EDGAR) databases, as well as officially reported emission data.

5.1 Limitations of the dataset

The current catalogue provides an updated and high-resolution global picture of the spatial (horizontal and vertical) and temporal characterization of emissions from power plants. Despite all the efforts, there are, however, some limitations associated with the current version of the dataset that potential users should consider:

- Emissions from non-European auto-producer facilities are not consistently included across countries due to the lack of information. Overall, we could not include emissions from auto-producers in 35% of the non-EU countries considered, which translates into 4.1% of total estimated CO_2 emissions that could not be allocated to specific point sources. The most relevant countries affected by this limitation are Russia, India and Japan, the share of national emissions that could not be assigned to individual facilities for these countries is between 14% and 21%.
- For the non-European dataset, heat-only facilities are not included due to the lack of information. This gap may be relevant in countries where the share of fossil fuels used to produce heat only is significant, mainly Ukraine (25%), Russia (20%), Belarus (20%), Kyrgyzstan (18%) and Uzbekistan (10%).

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- We identified a list of countries for which we found the location of their power plants but that we could not include in the final catalogue since their energy balances are not reported by the IEA World Energy Balances database, and subsequently corresponding emissions could not be estimated. It's important to note that most of these missing countries are small island countries (e.g., Aruba, Anguilla, Samoa Nord-americana, Antigua and Barbuda, Bahamas, Fiji, Cabo Verde, Cayman Islands), which have a very limited contribution to total CO_2 emissions from the power sector (i.e., 0.03% according to Tong et al., 2018).
- For the European dataset, a substantial number of emission values was gap filled using a tiered routine, using facility-specific-, or more generic pollutant ratios to estimate emissions. This could lead to under- or overestimations of emissions for individual plants. Similarly, for the non-European dataset emissions from co-emitted species (NO_x, SO_2, CO) were estimated using fuel-dependent emission ratios derived from a North American database, and the underlying emission abatement technologies considered may not be representative for certain countries such as India, South Africa or Australia, where legislation to control emissions from plants is less restrictive. Future work should include the construction of region-dependent emission ratios that reflect local emission standard aspects.
- For the non-European dataset, plant-level emissions were estimated by distributing fuel-dependent national emissions among facilities as a function of their installed capacity, which in some cases may not be representative of their actual activity (i.e., capacity factor) and may lead to over- or underestimations.
- For the European dataset, there was mostly good agreement with the national inventory totals for the energy sector in case of CO_2 and NO_x. The main source of discrepancies appeared to be the missing biomass power plant capacity in the dataset. These plants are likely too small to be included in official reporting and most public power plant datasets, for example because they fall below reporting thresholds. A more in-depth look into these biomass plants is needed to improve coverage and completeness.
- The final catalogue of power plants covers the main fuels used to produce energy and heat, including coal, natural gas, oil, solid biomass and solid waste. However, we are still missing some fuels that are relevant in specific countries and for emissions from certain species (e.g., CH_4) such as biogas (e.g., Thailand, India, Turkey, Australia) and liquid biofuel (e.g., South Korea).
- The comparison between geographical locations reported by the present catalogue and the CARMAv3 database indicate that the location of current top emitters is better represented in this work, especially in Asian countries such as China, Taiwan and India. Despite putting substantial efforts in correcting the location of facilities that are originally reported with wrong coordinates, there may be some error still present in the dataset, especially in the case of small and medium sized plants.
- The temporal profiles assigned to the power plants are country and fuel-dependent, but not facility-dependent. Large differences between the emission temporal distribution of plants belonging to the same country may occur, e.g., if

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they are used for electricity only or electricity and heat. However, information to develop such detailed level of temporal profiles is very scarce and limited only to certain regions (e.g., EU27).

- The final database provides plant-level annual mean vertical profiles that consider meteorology and stack parameters information. However, large variations in the vertical distribution of emissions may occur between seasons, days of the year and hours of the day due to changes in the meteorological parameters that influence the atmospheric stability and the corresponding vertical dispersion of the emissions.
- Despite identifying several power plants in which emissions are released through the cooling towers instead of the traditional chimneys (mainly in Germany), there may still be multiple facilities in the catalogue that are not correctly flagged. Moreover, for power plants using the cooling towers to release the emissions, we considered the same plume rise formulas as the ones used for traditional stack chimneys. According to Brunner et al. (2019), this assumption may entail an underestimation of the resulting effective emissions height of 20% to 100% due to the combination of several factors, including the additional release of latent heat from cooling towers or the interaction of plumes from cooling towers located next to each other.
- The stack parameters information used to perform the plume rise calculations has a limited coverage (e.g., only 28% of total CO_2 emissions have specific stack height information, and only 15% specific exit velocity data), which may bring an additional uncertainty to the estimated vertical profiles. According to the sensitivity runs performed by Bieser et al. (2011), changes in estimated emission heights are almost linear with changes in stack height and exit velocity, indicating a large influence of these parameters on the result.
- Caution should be taken when combining the global point source dataset with other existing gridded emission inventories (e.g., EDGAR) to avoid issues of double counting or incompleteness. Avoiding these problems can be challenging if, for instance, the sector classification of the gridded inventory is broad (e.g., emissions from power plants are included together with emissions from refineries and other energy industries under the same sector). A reclassification of the gridded emissions may be needed in these cases to ensure an appropriate combination of datasets.

5.2 Future perspective

The current point source catalogue represents an effort to improve the spatial (horizontal and vertical) and temporal characterization of emissions from CO_2 and co-emitted species derived from power plants to be used for modelling efforts. Future work should focus on overcoming the limitations currently identified (see Sect. 5.10) and extending the temporal coverage to more recent years in order to capture, on the one hand, the impact of the decarbonisation efforts that are occurring in several countries and regions such as EU27, UK or USA and, on the other hand, the large uptick in commissioning of new coal power plants that is happening in China (https://www.carbonbrief.org/mapped-worlds-coal-power-plants/). In parallel, other large CO_2 emitting industries that are detected by satellite instruments, including cement and steel and iron plants, should be added in future versions of the global point source database.

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The current catalogue does not report prediction intervals or standard errors of the estimated emissions for each plant. Hence, uncertainty information, which is a key information for inverse modelling studies, is unknown. The comparison against independent inventories indicates good agreement for CO_2 but also important discrepancies for certain co-emitted species in individual countries (e.g., NO_x and SO_x in South Africa and India), highlighting that the co-emitted species estimates and their uncertainty deserve more attention in future research.

The present work revealed that information on stack parameters is currently limited not only in developing countries but also in developed regions such as EU27. Efforts should be put to compile this information from individual national environmental permits and centralised it in a European database, at least for the large point sources considered under the European Industrial Emissions Directive (2010/75/EU). Furthermore, flagging the power plants that channel emissions through cooling towers should be assessed to better represents the vertical distribution of these emissions.

6 Author contribution

MG conceived and coordinated the development of the global point source emission database. SD and HDvdG constructed the European point source database and contributed to the analysis and discussion of the results. SE contributed to the construction of the non-European point source database and the construction of the temporal profiles. SE and CT contributed to the construction of the vertical profiles. OJ and CPGP helped conceive the dataset and supervised the work. MG prepared the paper with contributions from all co-authors.

7 Competing interests

The authors declare that they have no conflict of interest.

8 Acknowledgements

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