CO2MVS RESEARCH ON SUPPLEMENTARY OBSERVATIONS

D1.2 Improved global point source emissions dataset

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1 Executive Summary

This document presents an updated and improved version of the global point source dataset that was constructed in the framework of the CoCO2, and that provides emissions of CO_2 and co-emitted species (NO_x, CO, SO_2, CH_4) for power plants by fuel type (coal, natural gas, oil, biomass and waste), cement plants and iron and steel plants at their exact geographical location for the year 2021, as well as associated temporal (i.e., monthly, weekly, hourly) and vertical distribution profiles to support modelling efforts. The document presents the methodologies and sources of information considered to construct the catalogue of point sources, their emissions and associated profiles, as well as an overview of the results, including intercomparisons against independent existing bottom-up and top-down emission inventories. The resulting database will be used in CORSO T1.3 to perform comparison works against the satellite-based emission information developed by EMPA, TNO and UT3 in WP2. The results of this evaluation and validation work will provide feedback for the improvement and adjustment of the prior emissions.

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2 Introduction

2.1 Background

To enable the European Union (EU) to move towards a low-carbon economy and implement its commitments under the Paris Agreement, a binding target was set to cut emissions in the EU by at least 40% below 1990 levels by 2030. European Commission (EC) President von der Leyen committed to deepen this target to at least 55% reduction by 2030. This was further consolidated with the release of the Commission's European Green Deal on the 11th of December 2019, setting the targets for the European environment, economy, and society to reach zero net emissions of greenhouse gases in 2050, outlining all needed technological and societal transformations that are aiming at combining prosperity and sustainability. To support EU countries in achieving the targets, the EU and European Commission (EC) recognised the need for an objective way to monitor anthropogenic CO_2 emissions and their evolution over time.

Such a monitoring capacity will deliver consistent and reliable information to support informed policy- and decision-making processes, both at national and European level. To maintain independence in this domain, it is seen as critical that the EU establishes an observation-based operational anthropogenic CO_2 emissions Monitoring and Verification Support (MVS) (CO2MVS) capacity as part of its Copernicus Earth Observation programme.

The CORSO research and innovation project will build on and complement the work of previous projects such as CHE (the CO2 Human Emissions), and CoCO2 (Copernicus CO2 service) projects, both led by ECMWF. These projects have already started the ramping-up of the CO2MVS prototype systems, so it can be implemented within the Copernicus Atmosphere Monitoring Service (CAMS) with the aim to be operational by 2026. The CORSO project will further support establishing the new CO2MVS addressing specific research & development questions.

The main objectives of CORSO are to deliver further research activities and outcomes with a focus on the use of supplementary observations, i.e., of co-emitted species as well as the use of auxiliary observations to better separate fossil fuel emissions from the other sources of atmospheric CO_2. CORSO will deliver improved estimates of emission factors/ratios and their uncertainties as well as the capabilities at global and local scale to optimally use observations of co-emitted species to better estimate anthropogenic CO_2 emissions. CORSO will also provide clear recommendations to CAMS, ICOS, and WMO about the potential added-value of high-temporal resolution $^{14}CO_2$ and APO observations as tracers for anthropogenic emissions in both global and regional scale inversions and develop coupled land-atmosphere data assimilation in the global CO2MVS system constraining carbon cycle variables with satellite observations of soil moisture, LAI, SIF, and Biomass. Finally, CORSO will provide specific recommendations for the topics above for the operational implementation of the CO2MVS within the Copernicus programme.

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverables

The objective of this deliverable is to further develop the global point source dataset that was constructed in CoCO2, and that provides emissions of CO_2 and co-emitted species (NO_x, CO, SO_2, CH_4) for power plants by fuel type (coal, natural gas, oil, biomass and waste) at their exact geographical location for the year 2018, as well as associated temporal (i.e., monthly, weekly, hourly) and vertical distribution profiles.

2.2.2 Work performed in this deliverable

The work for this deliverable has resulted in an updated version of the global point sources catalogue. The improvements performed are as follows:

- Reference year of the emissions updated from 2018 to 2021.
- Update of the temporal profiles (monthly, weekly, hourly) for power plants.
- Review of the emission ratios considered to estimated emissions of co-emitted species for the non-European power plants
- Review and upgrade of the databases considered to derive the geographical location and characteristics (e.g., fuel type, installed capacity) of power plants
- Inclusion of additional large CO_2 emitting industrial sources previously not considered, namely cement and iron/steel plants.
- Inclusion of country-dependent monthly temporal profiles to describe the seasonality of cement and iron & steel plant emissions.
- Improvement of processing chain for assigning fuel types and filling emission gaps in reported industrial emissions from the EEA Industrial Reporting Database.

The resulting annual emissions for CO_2 and co-emitted species obtained for each of the industrial sectors were compared against independent bottom-up global, regional, national and plant-level emission inventories, as well as estimates derived from satellite observations.

The updated global point source database will be used in T1.3 to perform a comparison against the satellite-based emission information developed by EMPA, TNO and UT3 in WP2. The results of this evaluation and validation work will provide feedback for the improvement and adjustment of the prior emissions.

2.2.3 Deviations and counter measures

No deviations from original planned task.

2.3 Project partners

Partners	
EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS	ECMWF
AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZICA W KRAKOWIE	AGH
BARCELONA SUPERCOMPUTING CENTER - CENTRO NACIONAL DE SUPERCOMPUTACION	BSC
COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	CEA
KAMINSKI THOMAS HERBERT	iLab
METEO-FRANCE	MF
NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	TNO
RIJKSUNIVERSITEIT GRONINGEN	RUG
RUPRECHT-KARLS-UNIVERSITAET HEIDELBERG	UHEI
LUNDS UNIVERSITET	ULUND
UNIVERSITE PAUL SABATIER TOULOUSE III	UT3-CNRS
WAGENINGEN UNIVERSITY	WU
EIDGENOSSISCHE MATERIALPRUFUNGS- UND FORSCHUNGSANSTALT	EMPA
EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH	ETHZ
UNIVERSITY OF BRISTOL	UNIVBRIS
THE UNIVERSITY OF EDINBURGH	UEDIN

3 Global point source database

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 sources of information and approaches used to develop each dataset for each industrial source (i.e., power plants, cement plants and iron and steel plants) are described in the following sub-sections. The estimated emissions are for the year 2021, as it was the most recent year with available data on e.g., energy consumption statistics and official reported emissions at the time of starting the construction of the database.

3.1 Power plants

For this industrial source, we include combustion-related emissions occurring in electricity and combined electricity and heat power plants that burn coal, natural gas, oil, biomass or waste. The catalogue considers public power plants as well as auto-producers (i.e., facilities managed by an industrial or commercial entity that generate electricity partly for their own use and that are connected to the electric grid to exchange excess generation) to the extent of possible, since not all the auto-producers are included in the databases used as input. For the European countries, heat-only plants are also included when available in the datasets used. The coverage of small power and heat plants is relatively poor in the European countries, as the facility-level reporting is dependent on both emission level thresholds (e.g. 100 kton CO_2/year) or plant thermal input capacity thresholds (> 50 MW thermal), leading to smaller plants being omitted from the inventory. A similar situation occurs for non-European power plants, with units with capacities < 50 MW thermal not being considered due to lack of data.

3.1.1 Selection of facilities and definition of geographical location

To compile information on each individual power plant (i.e., name, exact geographical location, installed capacity, fuel type) several datasets were combined.

For the European power plant catalogue, the data source used is the integrated Industrial Reporting Database (EEA, 2024) which contains annual facility (i.e., European pollutant release and transfer register: EPRTR) and plant (i.e., large combustion plant: LCP) level reporting under the EU Industrial Emission Directive (IED; (2010/75/EU)). It includes data for all EU-27 countries, Switzerland and Serbia, and historic data for the UK (up to 2019) and Norway (i.e. up to 2017). Recent facility-level emission data for the UK is taken from DEFRA (2024). The selection of facilities was based on the NACE and Main Activity fields in the IRD dataset, with substantial efforts being put in correcting and completing sector allocation when sector fields were missing or conflicting. The power and heat sector also includes all CO_2 and NO_x emissions from landfills, anaerobic digestion, wastewater treatments, and all emissions from waste incineration plants, as these are all typically combined with power generation.

In addition, the Platts WEPP dataset (Platts, 2015) was used to assign fuel types for some facilities. The IIASA GAINS dataset (IIASA, 2018) and CEDS dataset (Hoesly et al., 2024) were both used to derive pollutant ratios at different levels of aggregation (preferably sector-, country-, year- and fuel-specific ratios were derived).

For the non-European power plant catalogue, the main datasets considered were:

- The Global Coal Plant Tracker (GCPTv2021_01; GEM, 2024a)
- The Global Oil and Gas Plant Tracker (GCPTv2021_01; GEM, 2024b)
- The Global Bioenergy Power Tracker (GBPTv2024; GEM, 2024c)

These global datasets were complemented with the following national databases;
- The Emissions and Generation Resource Integrated Database (eGRIDv2021; US EPA, 2023)
- 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)

For both the European and non-European databases, substantial effort was put into identifying missing and incorrect facility coordinates. These were searched manually using Google Maps or other websites and added to the dataset. For Europe, at least the top 100 facilities (in terms of CO_2 emissions) were manually checked. In addition, visual inspection of plotted maps to identify emission locations in illogical places (e.g. outside Europe, in the sea, or in the wrong country) was used to check and correct obvious errors. For the non-European dataset, the review process was performed for those GEM facilities for which the precision of their coordinates is identified as “approximate” and that have a capacity larger than 300MW.

3.1.2 Estimation of emissions for CO_2 and co-emitted species

For European power plants, annual emissions were derived as a first step from the EU integrated Industrial Reporting Database, combining both the facility- and plant-level data into one location total. For many facilities, gaps in the emission reporting were identified and were complemented using a gap filling routine (see below). The gaps are mainly due to the E-PRTR emission reporting thresholds, which obliges companies to report annual emissions from individual pollutants only if they are above the threshold levels summarised in Table 1. Given the pollutant-specific reporting threshold for companies, many facilities report emissions for only a small number of pollutants. NO_x 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 SO_x are reported for a limited number of facilities, and more often in the earlier years (2007 – 2010) and less often in recent years, when annual emission may lie below the reporting threshold due to emission reduction technologies. Reporting for large combustion plants (LCP) is not dependent on emission thresholds 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

- In **gap filling step 1**, plant level CO_2 emissions are calculated using the reported fuel input by fuel type, using generic CO_2 emission factors. Then, emissions of CO and CH_4 are estimated using country- and fuel specific emission ratios derived from the GAINS and CEDS datasets.

- In **gap filling step 2**, the facility and plant total reported values are compared for those years that reporting exists for both levels for a specific location. If the average ratio between reported values is smaller than 2.5, and the standard deviation is smaller than 0.25, the total plant value is used, multiplied by the average ratio between the facility and plant reported emission values. This way, if the facility typically encompasses several smaller units that are not in the plant dataset (i.e. <50MWth), the gap filled emission value incorporates this relatively fixed ratio between facility and plant-level emissions. When no facility reporting for a specific year is available, the plant emission value is used directly when available.
- After gap filling using plant-level 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 location 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 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 NO_x 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 application to later years to simulate the effect of increasing use of abatement technologies. The gap filled emission values are capped at the highest reported emission value in the time series for this specific facility.
- In **gap filling step 4**, after assigning emission values to individual fuel types (see section 3.1.3), missing emission values were gap filled using country-, year-, sector- and fuel specific pollutants ratios derived from the GAINS and CEDS datasets (e.g., CO_2/CO ratio), applied to emissions values established from reporting or gap filling steps 1 to 3.

As the gap filling steps progress, the gap filled emission value typically becomes more uncertain. Care has been taken to check a large number of gap filled emission values that are filled above the pollutant-specific reporting threshold value (see table 1), to verify that it is indeed plausible that the emission value was above the threshold level (which means that it should have been reported), and to finetune the gap filling process based on the findings. Still, in some cases there may be outliers from gap filled emission values that, upon closer inspection, may be unrealistic for a given facility.

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 (2023).

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

1. Estimation of annual 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, 2023) with the Tier 1 fuel-dependent emission factors reported by the IPCC guidelines for stationary combustion in the energy industries (Eggleston et al., 2006) (Table 2).

2. Estimation of annual NO_x, SO_2 and CO emissions from coal-, natural-gas- and oil-fired power plants combining the CO_2 annual emissions estimated in step 1 with fuel- and country-dependent average emission ratios derived from the 2021 CEDS emission inventory (Hoesly et al., 2024) (Figure 1). These emission ratios replace the GAINS 2015 emission ratios (Amann et al., 2011; Klimont et al., 2017) used in the CoCO2 catalogue. The CO_2-to-CO emission ratios for US are used to complete the eGRID database.
3. Estimation of annual NO_x, SO_2 and CO emissions from biomass- and waste-fired power plants combining the CO_2 annual emissions estimated in step1 with fuel-dependent average emission ratios reported by the European power plant database. The same ratios are assumed for all the countries due to the lack of more detailed information.
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, which is obtained from the databases described in Sect. 3.1.1.

Emissions could not be estimated in those countries not covered by the IEA energy statistics (e.g., Aruba, Afghanistan). However, we decided to keep the facilities reported by the datasets described in section 3.1.1 in the final catalogue and report their location, as it may be relevant for inverse modelling exercises.

Table 2 Tier 1 IPCC CO_2 and CH_4 emission factors for stationary combustion in the energy industries considered for each IEA fuel category.

IEA fuel category	CO_2 EF [kg/TJ]	CH_4 EF [kg/TJ]
Other bituminous coal	94600	1
Sub-bituminous coal	96100	1
Lignite	101000	1
Anthracite	98300	1
Natural gas	56100	1
Crude oil	73300	3
Fuel oil	77400	3
Gas/diesel oil	74100	3
Primary solid biofuel	100000	30
Municipal waste	95850	30

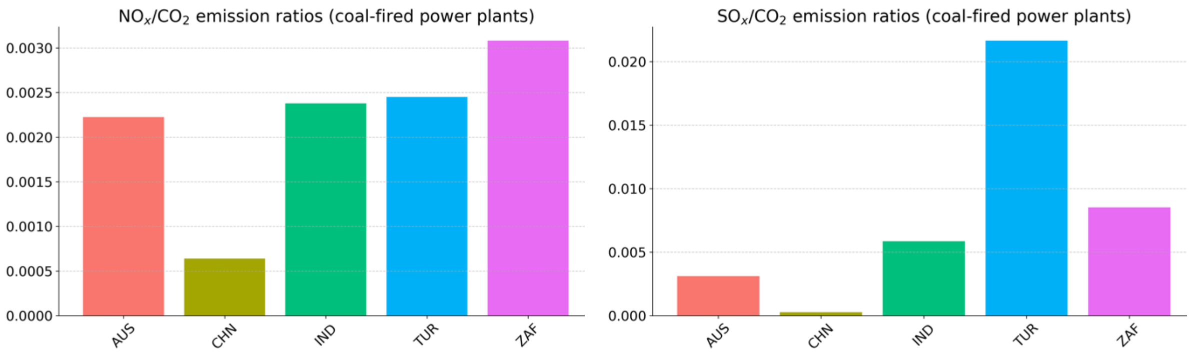

Figure 1 Example of country-dependent NO_x/CO_2 and SO_x/CO_2 emission ratios for coal-fired power plants obtained from the CEDS inventory

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 (2023) 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).

Figure 2 shows the countries where emissions from both public and auto-producers could be allocated, as well as the ones where only emissions from public producers were considered due to the discrepancies between our total installed capacity and the one reported by the UN (2023). European countries are removed from this analysis as the emissions were estimated by TNO following the approach mentioned above. Non-European countries with no classification refer to those for which the IEA statistics do not report information on national energy statistics and therefore emissions could not be estimated.

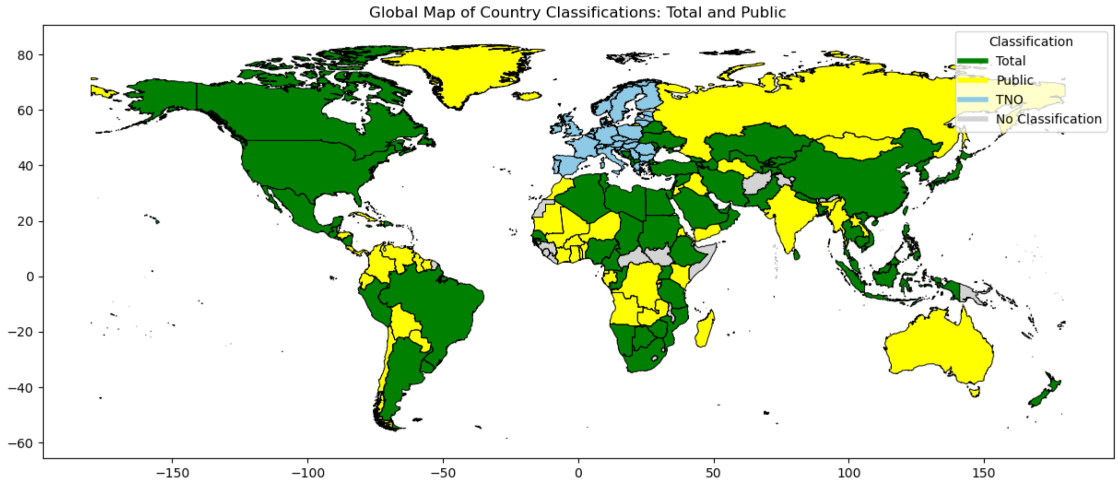

Figure 2 Countries classified according to the coverage of power plants and corresponding emissions considered. Total: public plants + auto-producers (green), Public: public plants (yellow). European countries are excluded from this analysis as the emissions are estimated by TNO (countries highlighted in blue). Non-European countries with no classification (grey) refer to those for which the IEA (2023) statistics do not report information on national energy statistics and therefore emissions could not be estimated.

3.1.3 Fuel allocation

Each of the emission values in the European power and heat 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. Fuel input from LCP plant reporting (for large combustion plants >50 MWth): As LCP reporting includes the reporting of fuel input (but not for waste), this could be used to allocate emissions to different fuels. 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 do not have associated LCP reporting, 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 remaining plants.
4. Automatic allocation based on the facility subsector, e.g. allocation to waste for waste incineration plants, and allocation to biomass for landfills and anaerobic digestion plants.

For non-European power plants, we considered the plant-level fuel information provided by the databases listed in Sect. 3.1.1. For GEMS dual-fuel plants using both natural gas and oil, we: i) duplicated them, ii) assigned one single fuel to each duplicate (i.e., oil or natural gas) and iii) split the total installed capacity according to the oil versus natural gas consumption reported by IEA in the country where the plant is located. We applied this duplication approach to dual-fuel plants located in countries where the ratio of oil versus natural gas consumption in the electricity generation sector is greater than 10%. These countries are: Saudi Arabia, Indonesia, Iraq, Kuwait, Libya, Pakistan, Egypt, Bangladesh, Iran, Thailand, the United Arab Emirates and Argentina.

3.2 Cement plants

For this industrial source, we include process- and combustion-related emissions occurring in cement plants.

3.2.1 Selection of facilities and definition of geographical location

To compile information on each individual cement plant (i.e., name, exact geographical location, installed capacity) several public and commercial datasets were combined.

For the European inventory, the main data source used is the integrated Industrial Reporting Database (EEA, 2024) which contains annual facility- and plant level reporting under the EU Industrial Emission Directive (IED; (2010/75/EU)). It includes data for all EU-27 countries, Switzerland and Serbia, and historic data for the UK and Norway. Recent facility-level emission data for the UK is taken from DEFRA (2024).

In addition, the ClimateTRACE dataset on cement production (Isabirye and Sinha, 2023) was used in the emission gap filling process for individual facilities, as well as for comparing and correcting facility coordinates. The IIASA GAINS dataset (IIASA, 2018) and CEDS dataset (Hoesly et al., 2024) were both used to derive pollutant ratios at different levels of aggregation (preferably sector-, country-, and year-specific ratios were derived).

For the non-European database, information on the location and installed capacity of cement plants was derived from the ClimateTRACE database (Sinha and Crane, 2024). For the USA, the information provided by ClimateTRACE was replaced with list of cement manufacturing plants reported by the National Emission Inventory (NEI) data (US EPA, 2022). The ClimateTRACE catalogue was complemented with 38 facilities reported by The Global Cement Report with a production capacity larger than 1000 Mt cement/year and located in the top 10 CO_2 cement emitter countries. In all cases we considered both plants producing only clinker or clinker plus cement (integrated plants). Plants that do not produce clinker (grinding plants) were excluded as no combustion emissions occur, and process emissions are mainly related to particulate matter due to the processing and manipulation of the material to produce cement.

3.2.1 Estimation of emissions for CO_2 and co-emitted species

For European cement plants, annual emissions were derived as a first step from the EU integrated Industrial Reporting Database, combining both the facility- and plant- level data into one location total, similar to the power and heat sector data (see section 3.1). The first three gap filling steps are identical to the gap filling process for power plants. Then, three additional gap filling steps are performed for cement facilities specifically:

- Cement production locations were matched manually with locations in the Climate TRACE cement production dataset. When IRD CO2 emissions were missing for all years available in the Climate TRACE dataset (2015-2023), the Climate TRACE CO2 value was copied directly as a gap filled emission value. When only some years were missing, the Climate TRACE data was using to scale historic reported emissions using the trend in its CO2 emission data.
- Missing emission values are then gap filled using facility-specific ratios from historic years (identical to step 3 described in section 3.1.2, but now including the CO2 emission values gap filled using the Climate TRACE dataset).

- Finally, remaining gaps were filled using country-, year- and sector specific pollutants ratios derived from the CEDS inventory (e.g., CO_2/CO ratio), applied to emission values established in previous gap filling steps.

For non-European cement plants, CO_2 annual emissions at the national level were derived from different sources as a function of their origin:

- For process-based emissions, which are produced during the calcination process when carbonates (largely CaCO3) are decomposed into oxides (largely CaO) and CO_2 to produce clinker, annual emissions for each individual country were directly obtained from Andrew (2019 and 2023a) for the year 2021. The dataset reports annual emissions based on the official submissions to the UNFCCC for the reporting countries and a combination of annual clinker production values and emission factors for the non-reporting countries (e.g., China). The IPCC clinker production default emission factors are considered for the latter case, except for China and Argentina, for which officially reported emission factors are used.
- For combustion-based emissions, which are produced during the burning of fossil and biofuels to generate the energy required to decompose the carbonates in the production of clinker, we considered country-dependent process-to-combustion CO_2 emission ratios derived from the Global Energy Infrastructure Emissions Database (GID; Tong et al., 2018). For each country, we computed the median of the ratios between process and combustion CO_2 emissions reported for each facility. A more direct estimation of these emissions considering a combination of energy balances statistics and emission factors could not be performed as the IEA database reports the consumption of fossil and biofuels of cement plants under the general category “non-metallic minerals industry”, which also reports consumption statistics related to the production of ceramics, glass and lime products, among others.

Estimation of annual NO_x, SO_2, CO and CH_4 emissions per country were obtained by combining the estimated CO_2 annual emissions with country-dependent average emission ratios derived from the CEDS emission inventory (Hoesly et al., 2024). For the USA, emission ratios were obtained from the NEI data (US EPA, 2022).

The estimated country- and process-dependent emissions are distributed across cement plants as a function of their installed capacity, which is obtained from the databases described in Sect. 3.2.1.

3.3 Iron and steel plants

For this industrial source, we include process- and combustion-related emissions occurring in the multiple units that integrate iron and steel plants, which include the manufacturing of metallurgical coke, direct reduced iron, sinter, pig iron and crude steel.

3.3.1 Selection of facilities and definition of geographical location

To compile information on each individual iron and steel plant (i.e., name, exact geographical location, installed capacity) several datasets were combined.

For the European power plant catalogue, the main data source used is the integrated Industrial Reporting Database (EEA, 2024) which contains annual facility- and plant level reporting under the EU Industrial Emission Directive (IED; (2010/75/EU)). It includes data for all EU-27 countries, Switzerland and Serbia, and historic data for the UK and Norway. Recent facility-level emission data for the UK is taken from DEFRA (2024).

As in the case of cement plants (see Section 3.2.1), the ClimateTRACE dataset on steel production (Sinha and Crane, 2024) was used in the emission gap filling process for individual facilities, while the IIASA GAINS (IIASA, 2018) and CEDS dataset (Hoesly et al., 2024) were considered to derive pollutant ratios at sector-, country-, and year-specific level.

For the non-European database, we use the Global Steel Plant Tracker (GSPTv2024; GEM, 2024), which provides information on global crude iron and steel production plants operating with a capacity of 500 Mt/year or more of crude iron or steel. The database provides for each plant information on the installed capacity for coke production, direct-reduced iron, sinter production, pig iron production and for the different routes that are typically used to produce steel, including the blast furnace and basic oxygen furnace or open-hearth furnace route and the electricity arc furnace route.

3.3.2 Estimation of emissions for CO_2 and co-emitted species

For European iron and steel plants, annual emissions were derived as a first step from the EU integrated Industrial Reporting Database, combining both the facility- and plant- level data into one location total, similar to the power and heat sector data (see section 3.1). The first three gap filling steps are identical to the gap filling process for power plants**.** Then, three additional gap filling steps are performed for iron/steel facilities specifically:

- Steel production locations were matched manually with locations in the Climate TRACE cement production dataset. When IRD CO_2 emissions were missing for all years available in the Climate TRACE dataset (2015-2023), the Climate TRACE CO_2 value was copied directly as a gap filled emission value. When only some years were missing, the Climate TRACE data was using to scale historic reported emissions using the trend in its CO_2 emission data.
- Missing emission values are then gap filled using facility-specific ratios from historic years (identical to step 3 described in section 3.1.2, but now including the CO2 emission values gap filled using the Climate TRACE dataset).
- Finally, remaining gaps were filled using country-, year- and sector specific pollutants ratios derived from the CEDS inventory (e.g., CO_2/CO ratio), applied to emission values established in previous gap filling steps.

For non-European iron and steel plants, country level annual emissions for CO_2 and co-emitted species were estimated following different approaches as a function of their origin (process or combustion-related) and source (Figure 3).

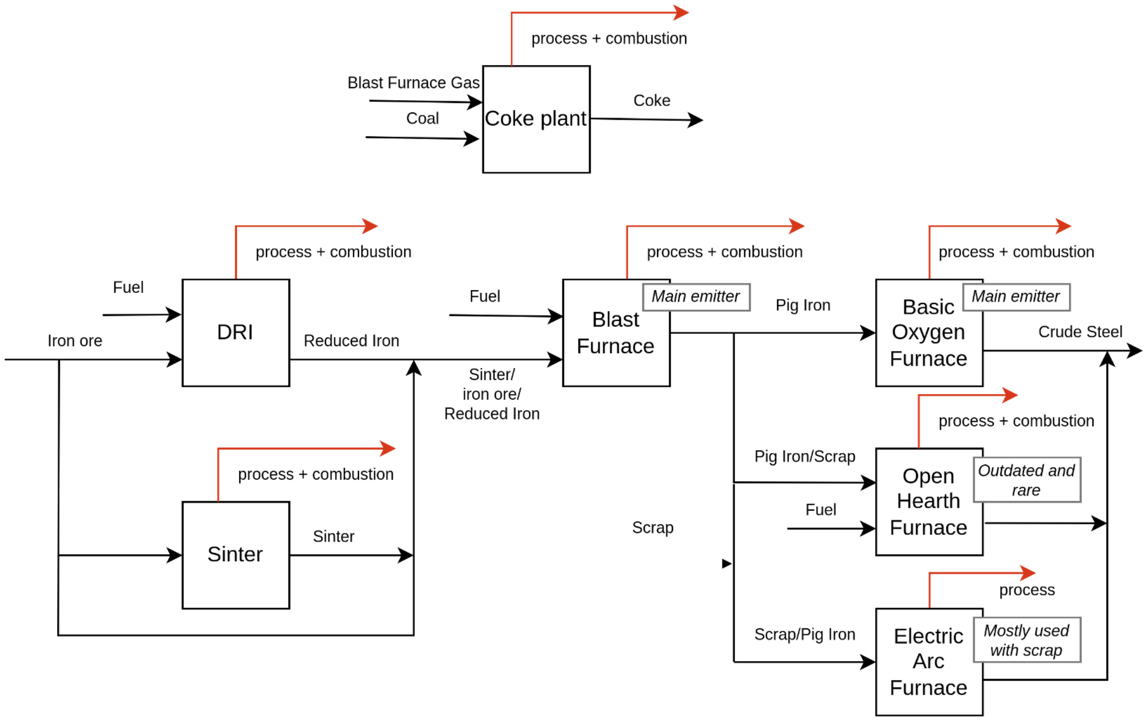

Figure 3 Process scheme for iron and steel plants

Process-related CO_2 and CH_4 emissions were computed for a total of five sources:

- Coke production: Emissions were computed by combining the global metallurgical coke production statistics provided by the Energy Information Administration (EIA, 2023) with the IPCC Tier 1 emission factors reported for this process (Table 3).
- Reduced iron making: Emissions were computed by multiplying the global direct reduce iron statistics provided per country by the World Steel Association (Worldsteel, 2023) with the IPCC default emission factor reported for this process (Table 3).
- Crude steel making: Emissions were computed by multiplying the global crude steel production statistics provided per country and technology (i.e., basic oxygen furnace, open hearth furnace and electric arc furnace) by the World Steel Association (Worldsteel, 2023) with the corresponding technology-dependent IPCC Tier 1 emission factors reported for this process (Table 3). For the electric arc furnace technology, we assumed that scrap steel is used as primary feedstock in all plants. While in some cases pig iron is also used, the majority of electric arc furnace tend to use this metal (Yang et al., 2014). The global averaged CO_2 emission factor reported by IPCC is used in those plants were GSPTv2024 does not indicate which technology is being used to produce crude steel.
- Pig-iron making: The IPCC Tier 1 emission factors for Basic Oxygen Furnaces and open-hearth furnace crude steelmaking include CO_2 process emissions from blast furnace pig iron production. Therefore, emissions for this process were only estimated for those iron and steel plants that produce pig iron but do not produce crude steel or, in other words, those iron and steel plants for which GSPTv2024

reports pig iron capacity but no crude steel capacity. For these cases, the IPCC Tier 1 emission factor reported for this process was considered (Table 3).

- Sinter making: Due to the lack on global sinter production statistics per country, we derived this information from the installed sinter making capacities reported by GSPTv2024. The original capacities reported for each plant were multiplied by the ratio of crude steel production reported by the World Steel Association versus crude steel making capacity reported by GSPTv2024. The resulting activity factors were combined with the IPCC Tier 1 emission factor reported for this process (Table 3).

For those countries not covered by World Steel Association but for which GSPTv2024 reports active iron and steel power plants for 2021, annual production statistics for the different products (e.g., sinter, reduced iron, pig iron and crude steel) were derived by multiplying the plant capacities reported by GSPTv2024 by 0.85. In other words, we assumed that iron and steel plants in these countries where operating at 85% of their capacity. This assumption is derived from the analysis performed on the ratio between steel produced and steel production capacity over the top 10 steel producing countries with available information from World Steel Association and GSPTv2024. As seen in Figure 4, the extrapolation of activity data based on installed capacity was applied to only 2 countries (highlighted in yellow). The countries highlighted in red are those where World Steel Association reports steel production but GSPTv2024 does not report information facilities. In these countries no emissions are estimated due to the lack of information on the location and characteristics (installed capacity) of the industrial plants.

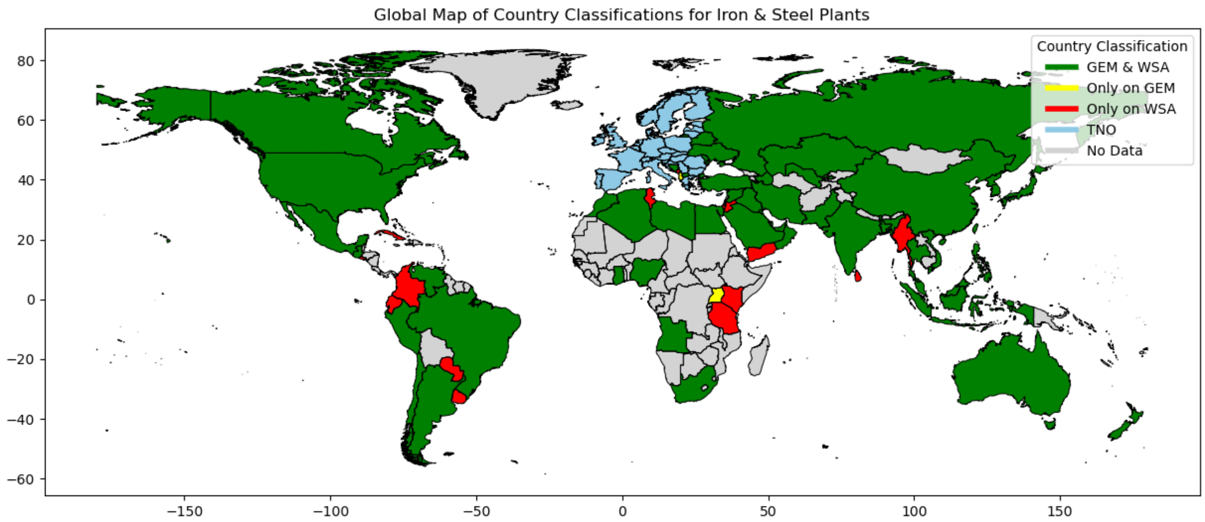

Figure 4 Countries classified according to the World Steel Association (WSA) statistics and Global Steel Plant Tracker coverages (GEM). GEM & WSA: countries with information from both databases; Only GEM: countries for which only location and characteristics of iron&steel plants is available. Only WSA: countries for which only steel production is available. European countries are excluded from this analysis as the emissions are estimated by TNO (blue). In the other non-EU countries, no iron and steel industry exist (grey)

Table 3 Summary of the IPCC Tier 1 process-related CO_2 and CH_4 emission factors considered for the iron and steel industry (IPPC Table 4.1 and 4.2, Volume 3, Chapter 4)

Process	EF CO_2	units	EF CH_4	units
Coke production	0.56	t/t metallurgical coke	0.1	g/t metallurgical coke
Sinter making	0.2	t/t sinter	0.07	kg/t sinter
Reduced iron making (DRI)	0.7	t/t reduced iron	-	
Pig iron making – blast furnace (BF)	1.35	t/t pig iron	-	
Basic Oxygen Furnace (BOF)	1.46	t/t crude steel	-	
Open Hearth Furnace (OHF)	1.72	t/t crude steel	-	
Electric Arc Furnace (EAF)	0.005* / 0.08**	t/t crude steel	-	
Global Average Factor (65% BOF, 30% EAF, 5% OHF)	1.06	t/t crude steel	-	

* using pig iron as feedstock
**using scrap steel as feedstock

Process-related CO and NO_x and SO_x emissions in iron and steel plants were computed for basic oxygen furnaces, electric arc furnaces and blast furnaces as well as for the production of coke using the EF reported in Table 4. Emissions of CO from open hearth furnaces are assumed to originate from the combustion activities in the blast furnaces and therefore are not included here (EMEP/EEA, 2023). A global averaged emission factor is considered for those iron and steel facilities for which GSPTv2024 does not indicate which technology is being used to produce crude steel.

Table 4 CO, NO_x and SO_x process-related emission factors for iron and steel plants

Process	EF CO	EF NO_x (**)	EF SO_x (***)	units	Source of information
Pig iron making – blast furnace (BF)	4.2	-	-	kg/Mg pig iron	NAEI (2023)
Basic Oxygen Furnace (BOF)	8*	-	-	kg/Mg crude steel	EMEP/EEA, (2023) – Chapter 2.C.1, Table 3-14
Electric Arc Furnace (EAF)	3.9*	130	60	kg/Mg crude steel (g for NO_x and SO_x)	EMEP/EEA, (2023) – Chapter 2.C.1, Table 3-15
Global Average Factor (65% BOF, 30% EAF, 5% OHF)	6.37	39	18	kg/Mg crude steel (g for NO_x and SO_x)	Derived from EMEP/EEA, (2023) – Chapter 2.C.1, Table 3-14 and 3-15
Coke production	460	0.9	0.8	g/Mg coke	EMEP/EEA, (2023) – Chapter 1.B.1.b, Table 3-1

(*) Upper value considered
(**) Expressed as NO_2
(***) Expressed as SO_2

Combustion-related CO_2 and CH_4 emissions in iron and steel plants related to the production of pig iron and crude steel were computed by combining the national energy statistics provided by the IEA World Energy Balances (IEA, 2023) for the iron and steel sector with the Tier 1 fuel-dependent emission factors reported by the IPCC guidelines for stationary combustion in manufacturing industries (Eggleston et al., 2006). Coke consumption statistics were excluded from the estimation of combustion emissions, as this fuel is mainly used for the iron decarbonization process as carbon input into the furnaces and therefore is included in the process-related IPCC emission factors reported in Table 5.

Table 5 Tier 1 IPCC CO_2 and CH_4 emission factors for stationary combustion in manufacturing industries considered for each IEA fuel category.

IEA fuel category	CO_2 EF [kg/TJ]	CH_4 EF [kg/TJ]
Other bituminous coal	94600	1
Sub-bituminous coal	96100	1
Lignite	101000	1
Anthracite	98300	1
Natural gas	56100	1
Crude oil	73300	3
Fuel oil	77400	3
Gas/diesel oil	74100	3
Primary solid biofuel	100000	30
Municipal waste	95850	30

For the co-emitted species (i.e., NO_x, CO and SO_x) we combined the national IEA energy statistics with fuel-dependent emission factors reported by EMEP/EEA (2023) (Table 6).

Table 6 Combustion related NO_x, CO and SO_x emission factors for iron and steel plants for each fuel category

EMEP/EEA fuel category	NO_x EF [g/GJ] (*)	CO EF [g/GJ]	SO_x EF [g/GJ] (**)	Source of information
Solid fuel	173	931	900	EMEP/EEA, (2023) – Chapter 1.A.2, Table 3-2
Natural gas	74	29	0.67	EMEP/EEA, (2023) – Chapter 1.A.2, Table 3-3
Liquid fuel	513	66	47	EMEP/EEA, (2023) – Chapter 1.A.2, Table 3-4
Biomass	91	570	11	EMEP/EEA, (2023) – Chapter 1.A.2, Table 3-5
(*) Expressed as NO_2 (**) Expressed as SO_2				

The estimated country-, process and source-dependent emissions are distributed across iron and steel plants as a function of the information on installed capacities reported by GSPTv2024.

3.4 Overview of the results

Figure 5 to Figure 7 show the plant-level annual CO_2, NO_x and CO emissions as reported by the resulting global point source database, with zooms over Europe, South-East Asia, the USA and the Middle East. Results are distinguished by industry type (power, cement and iron and steel). It is observed that power plants are the main contributors to total CO_2 and NO_x emissions. For CO_2 the top emitters are mostly linked to coal-fired power plants located in China, India, US, Australia, South Africa, Central Europe and Indonesia, while for NO_x the main contributors are oil-fired power plants, the largest emitters being in the Middle East (i.e., Iran, Iraq and Saudi Arabia). For CO, iron and steel plants dominate total emissions, the largest sources being reported in South-East Asian (India and China).

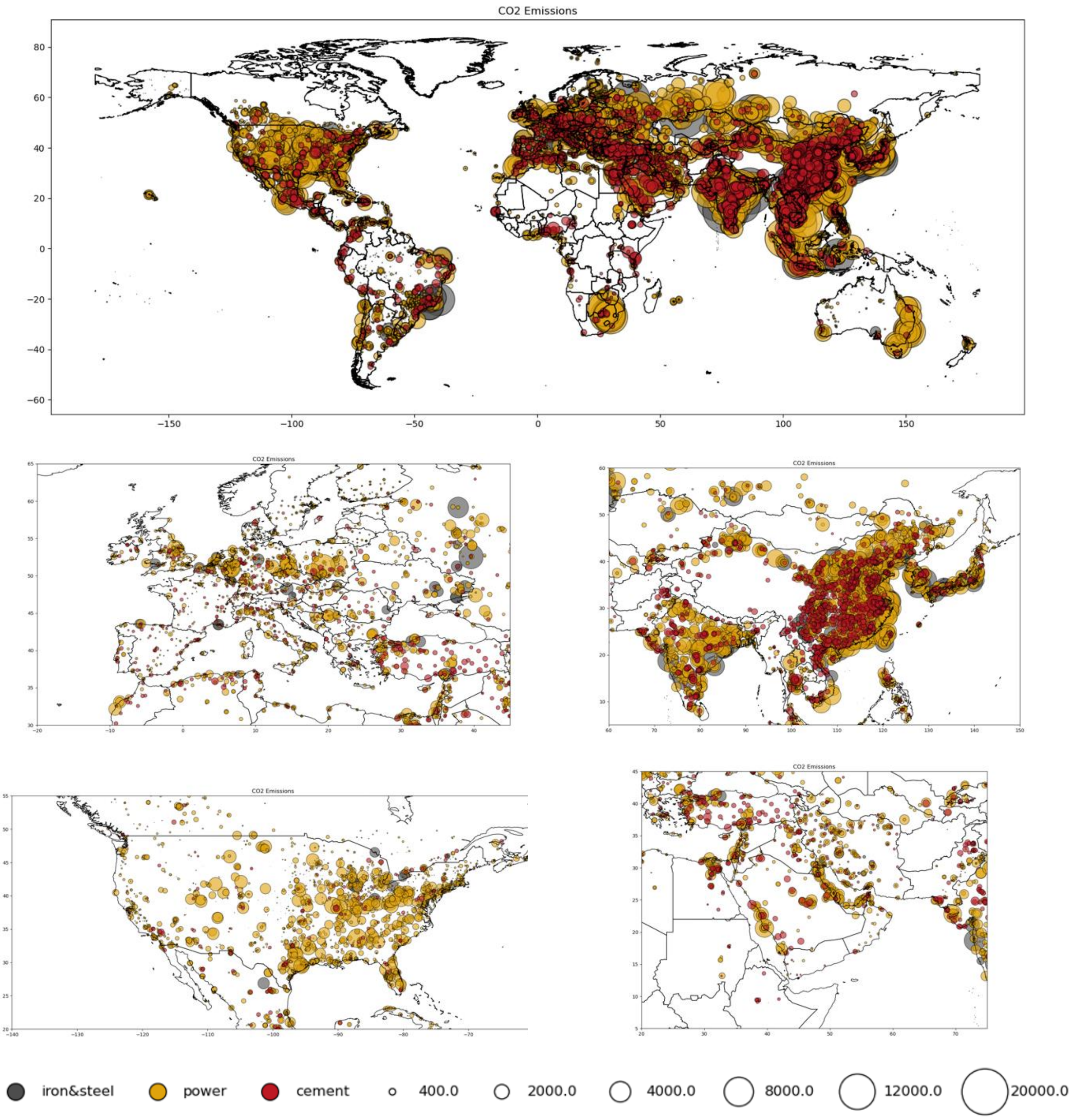

Figure 5 Plant-level annual CO_2 emissions (kt/year) reported by the CORSO global point source database, with zooms over Europe, South-East Asia, the USA and the Middle East.

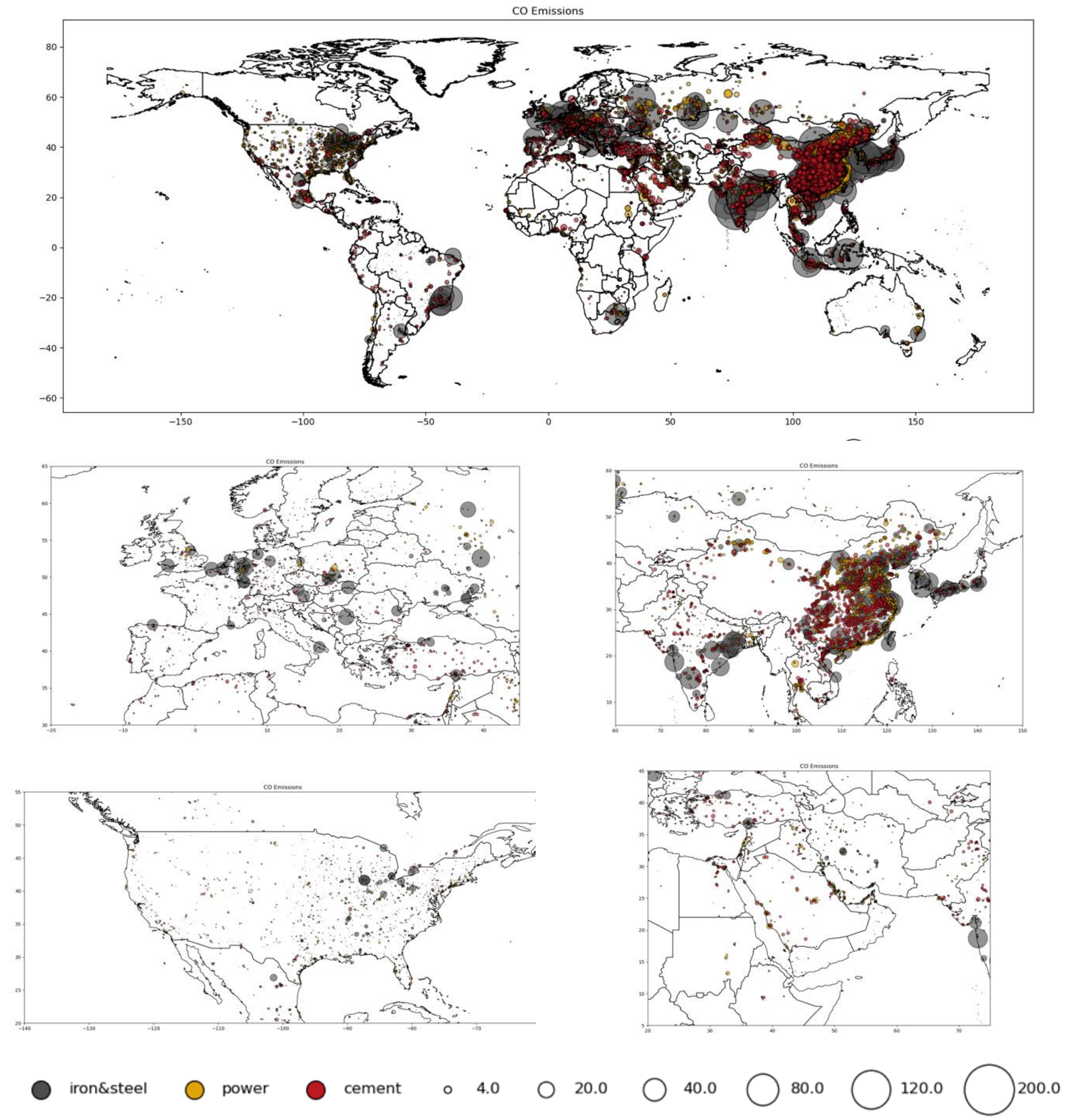

Figure 6 Plant-level annual CO emissions (kt/year) reported by the CORSO global point source database, with zooms over Europe, South-East Asia, the USA and the Middle East.

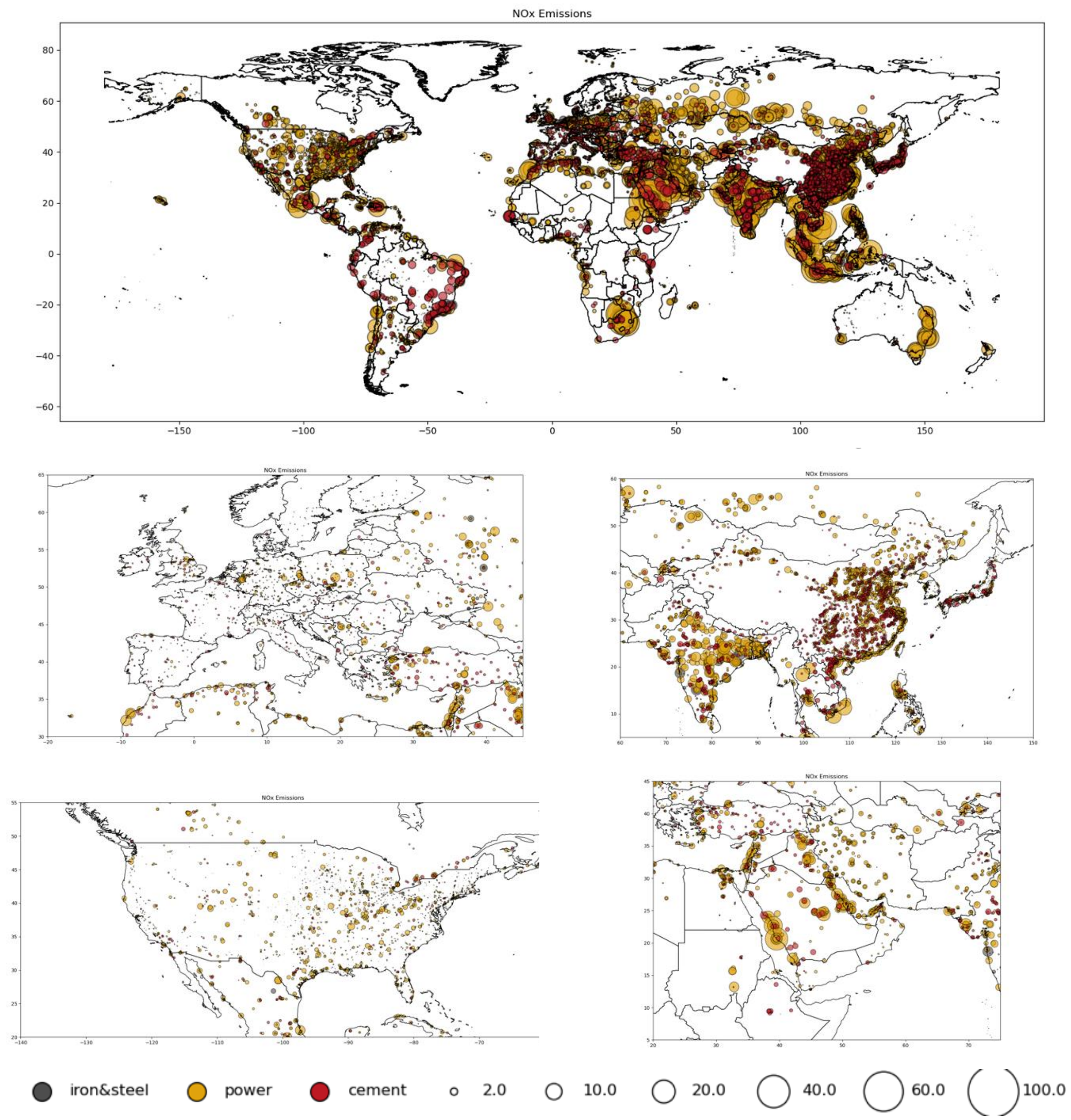

Figure 7 Plant-level annual NO_x emissions (kt/year) reported by the CORSO global point source database, with zooms over Europe, South-East Asia, the USA and the Middle East.

Figure 8 shows the relative contribution of each industrial sector to total CO_2, NO_x and CO emissions at the global scale and for specific regions and countries (i.e., EU27+UK, China and India). For the power sector the contributions are split by fuel type (coal, natural gas, oil, biomass and waste).

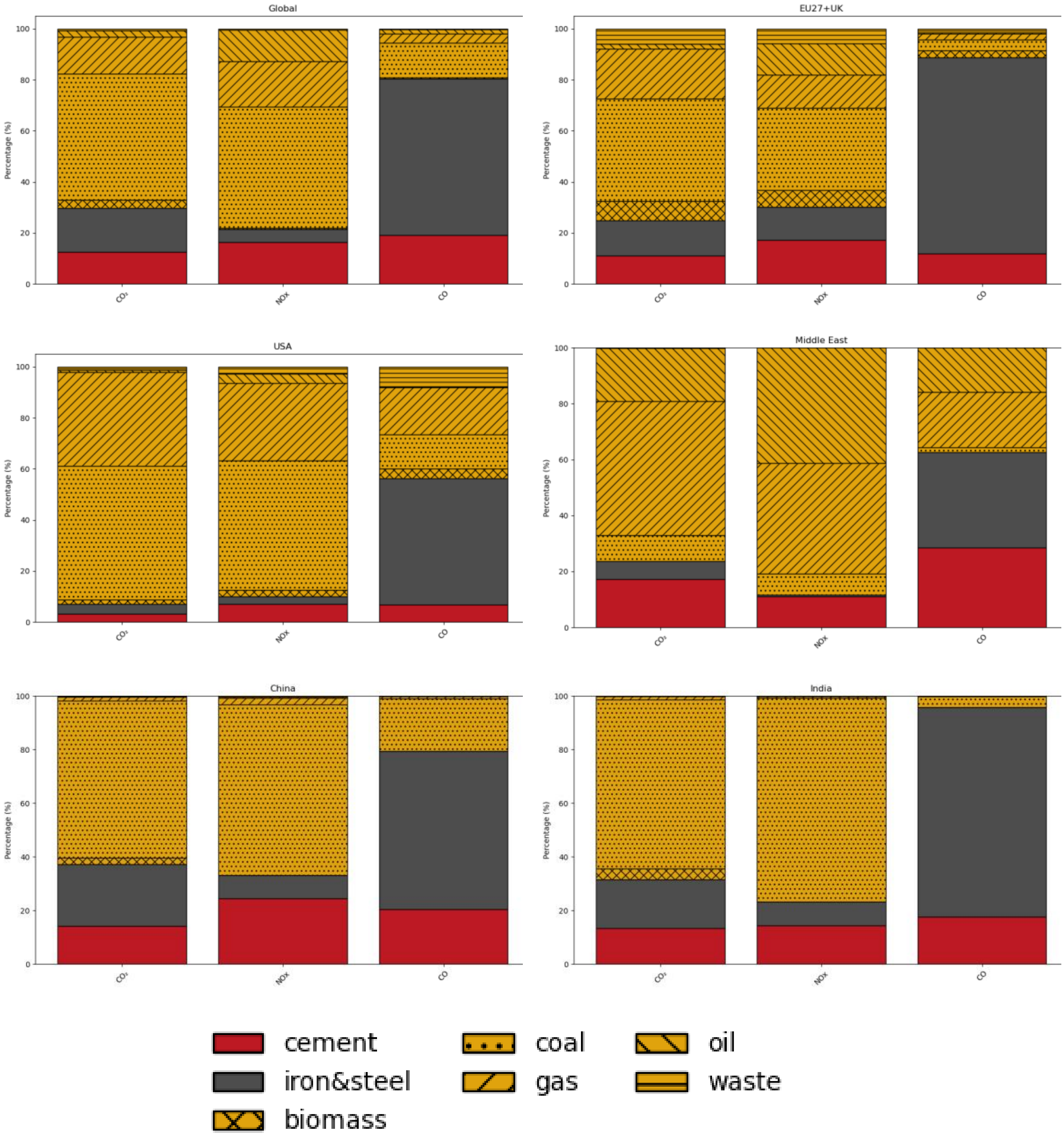

Figure 8 Relative contribution of each industrial sector (including fuel types for the power sector) to total CO_2, NO_x and CO annual emissions at the global scale and for specific regions and countries (i.e., EU27+UK, USA, Middle East, China and India).

3.4.1 Comparisons with independent emission estimates

3.4.1.1 National level

The resulting annual emissions for CO_2 and co-emitted species obtained for each of the industrial sectors were compared against independent bottom-up global, regional, national and plant-level emission inventories, as well as estimates derived from satellite observations.

Figure 9 shows a comparison between CORSO CO_2 country-level emissions estimated for the power plant sector in the top 10 non-European emitting countries against information reported by the EDGARv8 greenhouse gas inventory (Crippa et al., 2023), the MEIC-Global-CO_2 inventory (Xu et al., 2023) and the GIDv2 (Tong et al., 2018).

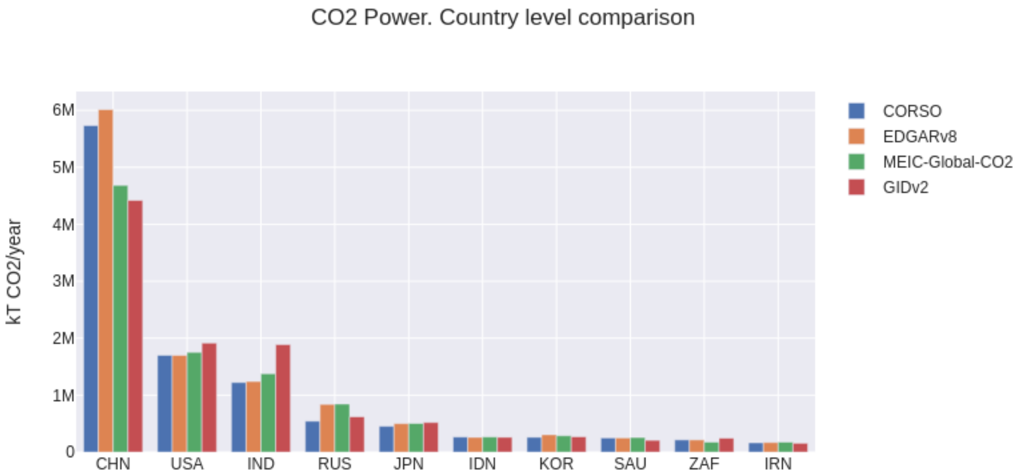

Figure 9 Comparison between CO_2 emissions estimated by CORSO and reported by EDGARv8, MEIC-Global-CO_2 and GIDv2 for the power industry in the top10 non-EU emitting countries

Figure 10 shows a comparison between CORSO NO_x country-level emissions estimated for the power plant sector against estimates reported by independent national inventories, including the National Emission Inventory for the US (US EPA, 2024), MEICv1.4 for China (Li et al., 2017; Geng et al., 2024), the Clean Air Policy Support System for South Korea (CAPSS; Choi et al., 2020), the Air Pollutant Discharge Inventory for Taiwan (TEDS; EPA Taiwan, 2023) and the EMEP Center for Emission Inventories and Projections for Canada, Turkey and Kazakhstan (CEIP, 2024). For all the cases the reference year is 2021, except for the national estimates reported by MEICv1.4 for China (2019). The results are in general in line, except in the case of USA, where CORSO reports much larger emissions. This is because the NEI inventory only reports emissions from public power plants in the power sector, while CORSO includes the emissions from public plus autoproducers. The same situation occurs for Canada and Turkey.

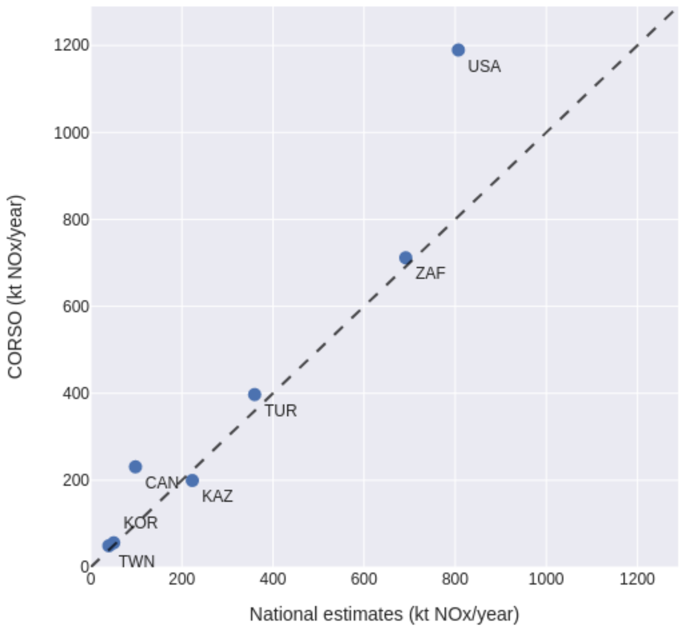

Figure 10 Comparison between NO_x emissions estimated by CORSO and reported by independent national estimates for the power sector in selected countries

Figure 11 shows a comparison between CORSO CO_2 country-level emissions estimated for cement plants for the top 10 non-EU emitters against information reported by the EDGARv8 greenhouse gas global inventory (Crippa et al., 2023) as well as national estimates reported by MEIC-Global-CO_2 inventory (Xu et al., 2023) and the GIDv2 (Tong et al., 2018). The results reported by CORSO are in general consistent with the ones reported by MEIC-Global-CO_2 and GIDv2, especially in China, the largest emitter by far. Results from EDGARv8 are generally lower since only process-related emissions are included (combustion-related emissions are reported within the combustion from non-metallic mineral industries sector and cannot be included in this comparison).

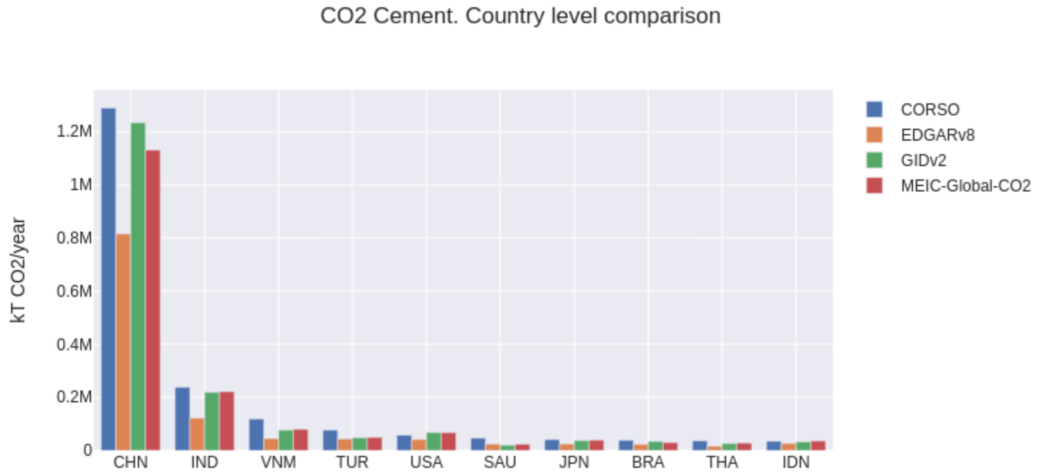

Figure 11 Comparison between CO_2 emissions estimated by CORSO and reported by EDGARv8, MEIC-Global-CO_2 and GIDv2 for the cement industry in the top10 non-EU emitting countries

Figure 12 shows a comparison between CORSO CO_2 country-level emissions estimated for iron and steel plants against information reported by the UNFCCC official inventories (UNFCCC, 2023) for the top 10 emitters plus the MEIC-Global-CO_2 emissions reported for China and India (Xu et al., 2023).

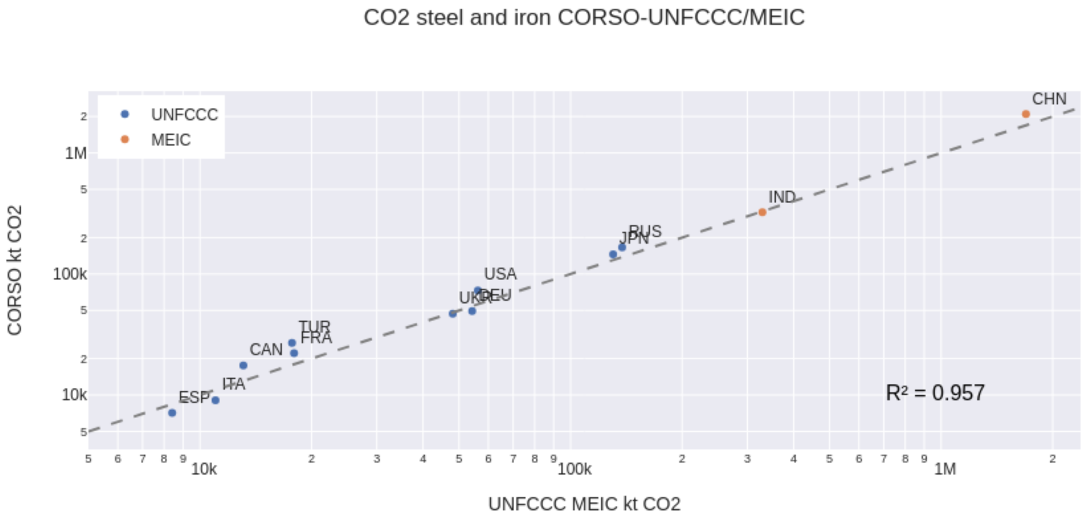

Figure 12 Comparison between CO_2 emissions estimated by CORSO and reported by UNFCCC official inventories and the MEIC inventory for the iron and steel industry

Emissions of co-emitted species for cement and iron and steel plants are very challenging to compare against independent estimates as these emissions are typically included into more general industrial sector categories, such as combustion in non-metallic mineral industries (which includes the production of glass, ceramics and others, besides cement). However, for China we were able to compare the results computed for cement NO_x, SO_x and CO emissions against the MEICv1.4 2019 inventory (Geng et al., 2024), the results showing a very good agreement (Figure 13). Although the conclusions obtained for this country cannot be extrapolated to other regions, they are still relevant considering that China is the top one emitting country for this industrial sector.

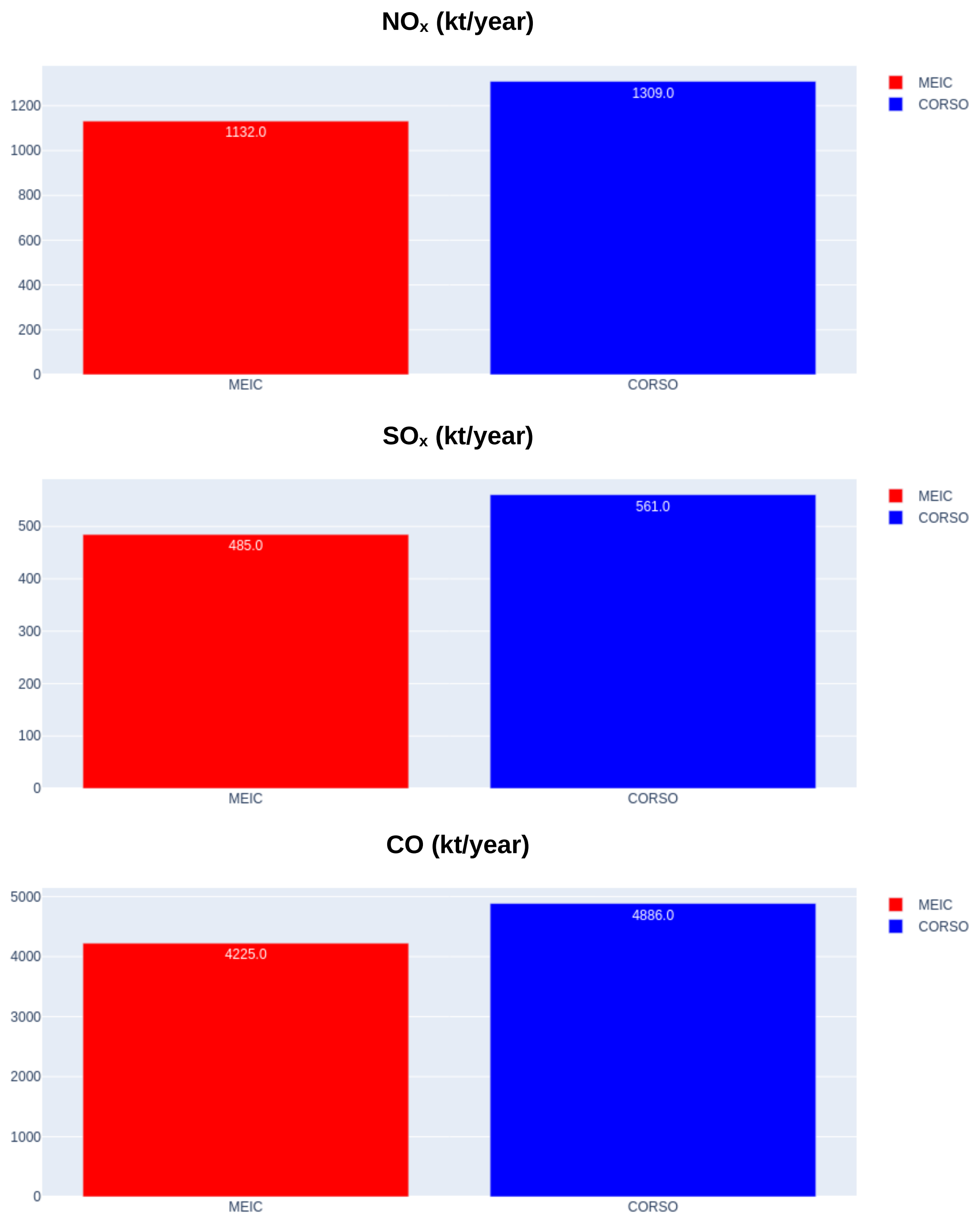

Figure 13 Comparison between CORSO and MEIC NO_x, SO_x and CO emissions reported for the cement sector

Figure 14 shows a comparison between country-total CO_2 emissions from the power and heat sector in European countries in the CORSO inventory versus the national inventory (CEIP, 2024) and the CEDS inventory (Hoesly et al., 2024). Note that there is in general good agreement between the datasets. In many cases, the national inventory is not independent of the E-PRTR/LCP reported data, as these facility-level data are often used for compiling the national inventory. As coverage of the facility-level emission data is typically not complete due to reporting thresholds, countries may use their own methods to estimate missing emissions, leading to differences between the CORSO inventory and national inventories. In some countries, national reporting does not integrate facility-level emissions, which may lead to larger differences between the datasets, especially for co-emitted species, which are less constrained by national fuel statistics. The most substantial discrepancy exists for Germany, where the CORSO dataset includes ~25 Mton lower CO_2 emissions than the national inventory, a difference that lies mostly with biomass-based energy generation. This may be because smaller biogas and biomass plants are not included in the facility-level reporting, and due to differences in fuel allocation and definitions. The difference is even larger for NO_x (see Figure 15 and Figure 16), which is not easily explained as for both pollutants, more than 96% of emissions in the CORSO inventory for Germany are from direct reporting, not gap filling.

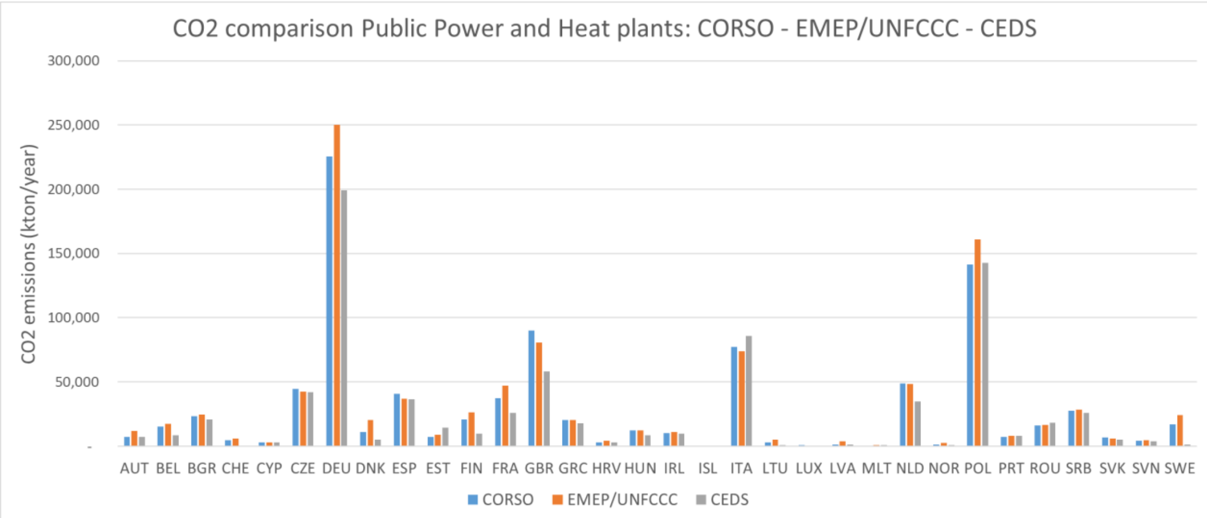

Figure 14 Comparison between national CO_2 emissions from power plants in European countries in CORSO versus the national inventory (CEIP, 2024) and CEDS (Hoesly et al., 2024).

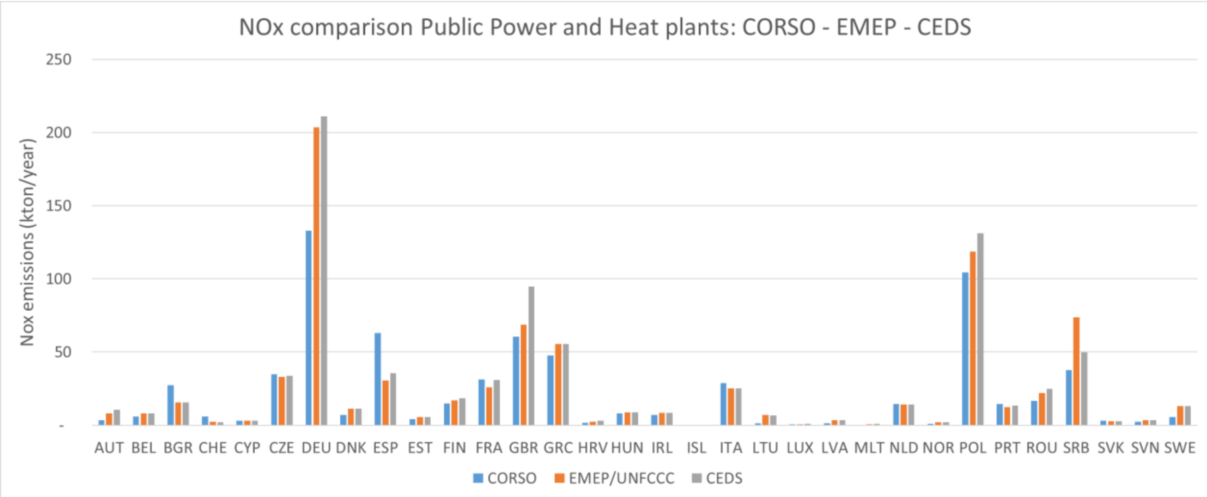

Figure 15 Comparison between national NO_x emissions from power plants in European countries in CORSO versus the national inventory (CEIP, 2024) and CEDS (Hoesly et al., 2024).

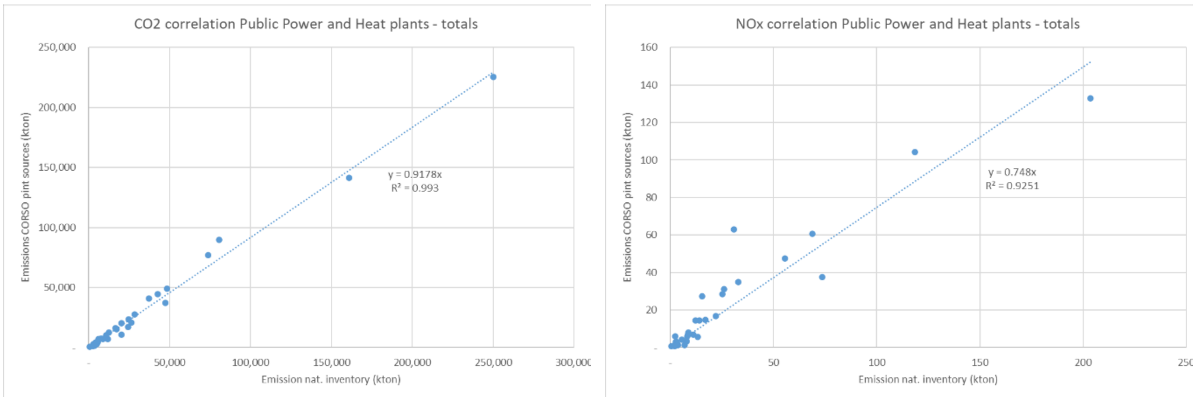

Figure 16 Intercomparison between national CO_2 (left) and NO_x (right) emissions from power plants in European countries in CORSO versus the national inventory (CEIP, 2024)

Figure 17 shows a comparison between country total CO_2 emissions for cement production for the European countries in the CORSO inventory versus the national inventory (CEIP, 2024), the CEDS inventory (Hoesly et al., 2024) and the Climate TRACE cement dataset. The Climate TRACE dataset is a source level dataset containing the largest cement plants. The CORSO dataset is not fully independent from the national inventory and the Climate TRACE dataset as it may use the Climate TRACE dataset for scaling or direct gap filling when emissions are missing in the facility reporting.

Note that both the UNFCCC and CEDS inventories only include process emissions of CO_2 separately, meaning that combustion emissions are not included in these bars, leading to substantially lower emissions. The linear regression in Figure 18 shows that the ratio between CORSO total emissions, and national inventory process emissions is very consistent between countries. For NO_x and CO, both the national inventories and CEDS inventory contain very few process emissions, making a comparison unhelpful.

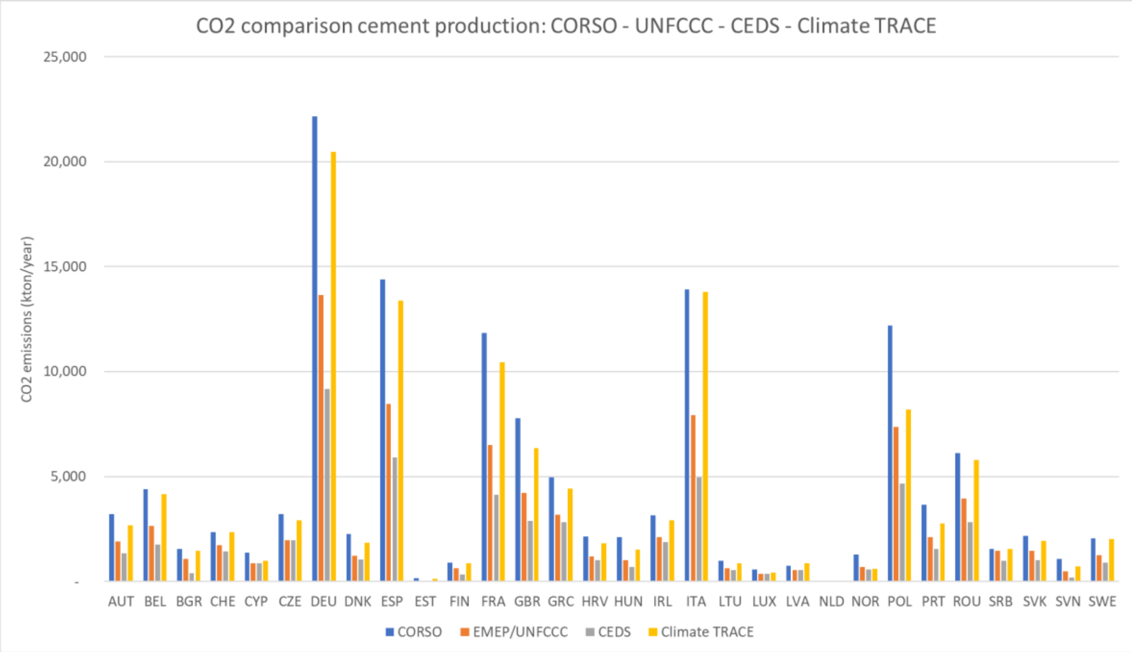

Figure 17 Comparison between national CO_2 emissions from cement plants in European countries in CORSO versus the national inventory (CEIP, 2024) and CEDS (Hoesly et al., 2024) and the Climate TRACE cement dataset.

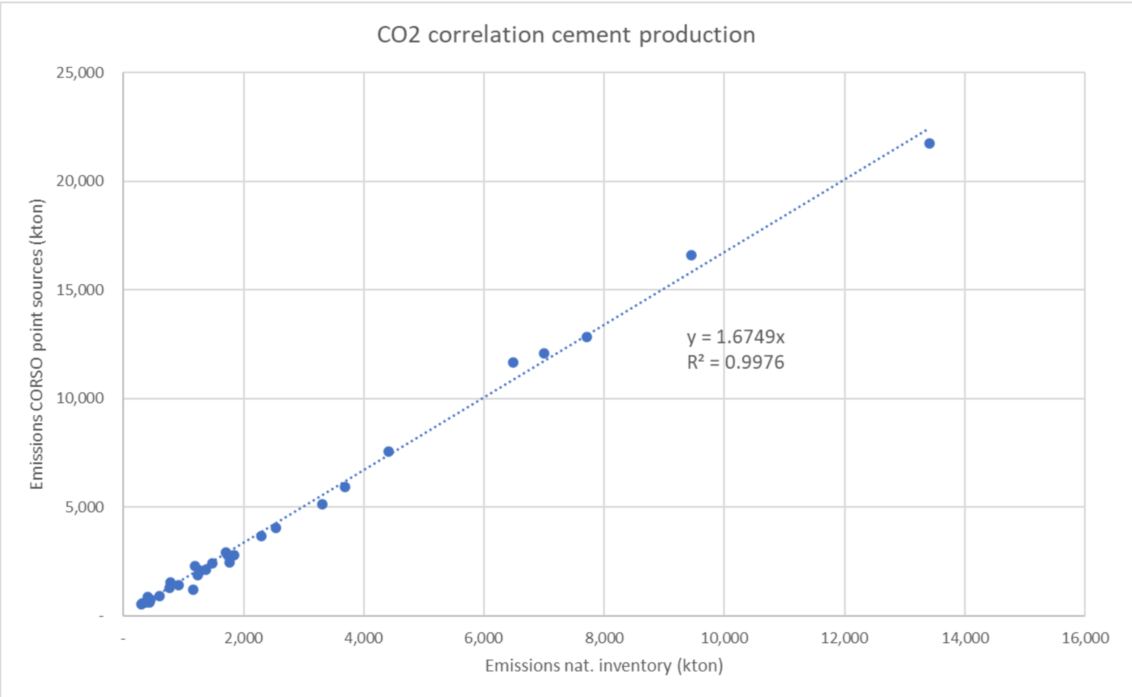

Figure 18 Intercomparison between national CO_2 emissions from cement plants in European countries in CORSO versus the national inventory (CEIP, 2024)

Figure 19 shows a comparison between country total CO_2 emissions for iron and steel production for the European countries in the CORSO inventory versus the national inventory (CEIP, 2024), the CEDS inventory (Hoesly et al., 2024) and the Climate TRACE steel production dataset. The Climate TRACE steel production dataset is also a source level dataset containing the largest steel plants. The CORSO dataset is not fully independent as it may use the Climate TRACE dataset for scaling or direct gap filling when emissions are missing in the facility reporting. While for many countries, the agreement is quite good, there are clearly substantial differences for countries like Germany, Czech Republic, Spain and Poland. This can be due an omission of smaller installations in the facility-level data, or due to different choices in sector allocation (e.g. sector allocation of power plants that produce electricity for smelting, or power plants that combust gases from steelworks, as is the case in the Netherlands).

The differences are typically larger for CO (Figure 20), where are larger share of the emissions are being gap filled using emission ratios. A very substantial difference can be seen for France, where CO_2 emissions are similar in all inventories, but CO emissions are much lower in the CORSO inventory. With only 166 kton CO reported by French iron/steel production facilities, it is not clear why the national reporting is so much higher.

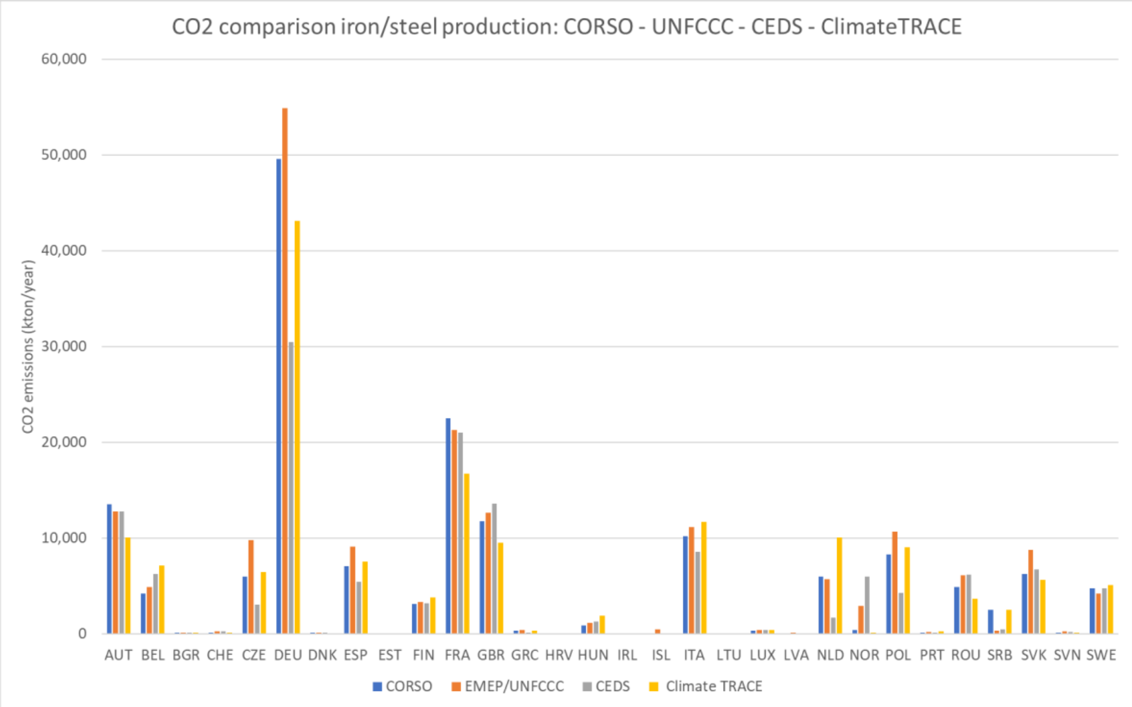

Figure 19 Comparison between national CO_2 emissions from iron&steel plants in European countries in CORSO versus the national inventory (CEIP, 2024) and CEDS (Hoesly et al., 2024) and the Climate TRACE iron&steel dataset.

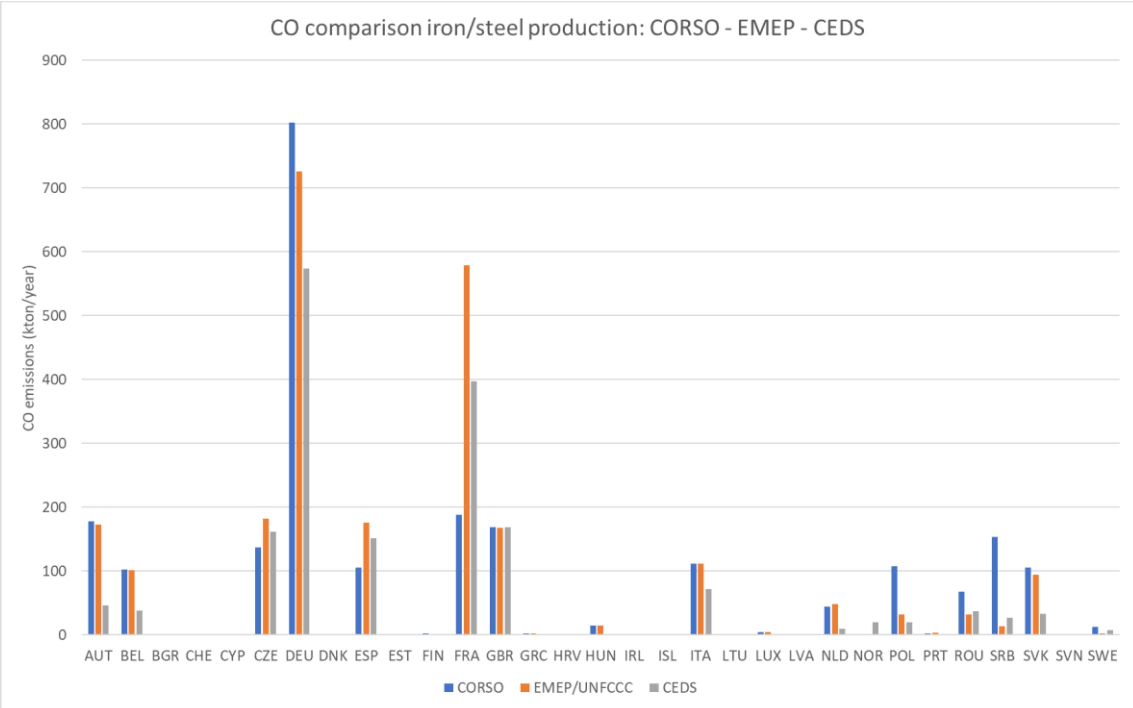

Figure 20 Comparison between national CO emissions from iron&steel plants in European countries in CORSO versus the national inventory (CEIP, 2024) and CEDS (Hoesly et al., 2024)

Table 7 shows the total emissions and number of locations in the EU-27+ UK for the different industrial sectors considered in CORSO. For most pollutants, the power and heat production sector has the largest contribution to total emissions of all sectors where large concentrated point sources are dominant. For CH_4 most emissions (>90%) result from gap filling estimates, while for CO_2, NO_x and SO2, most emissions are from direct facility-level reporting.

Table 7 Summary of total annual emissions and number of facilities in the EU27+UK per pollutant and industrial sector

	Power and heat	**Iron&steel**	**Cement**
# locations	1,849	215	226
CO_2 (Mt/yr)	928	163	134
NO_x (kt/yr)	689	121	160
CO (kt/yr)	389	2,316	359
CH_4 (kt/yr)	159	19	16
SO_2 (kt/yr	701	116	75

3.4.1.1 Plant level

Figure 21 shows a comparison between the plant-level CO_2 emissions (kt yr^{-1}) estimated by this work and reported by the GIDv2.0 database (Tong et al., 2018). Results are shown for the top 20 (10) emitters reported by each inventory for power plants (cement and iron and steel plants). Overall, the total emissions are almost equal. However, some large discrepancies (up to a factor of two) are observed at the plant level. Reasons for these discrepancies can be many, including the activity and emission factors assigned to each facility.

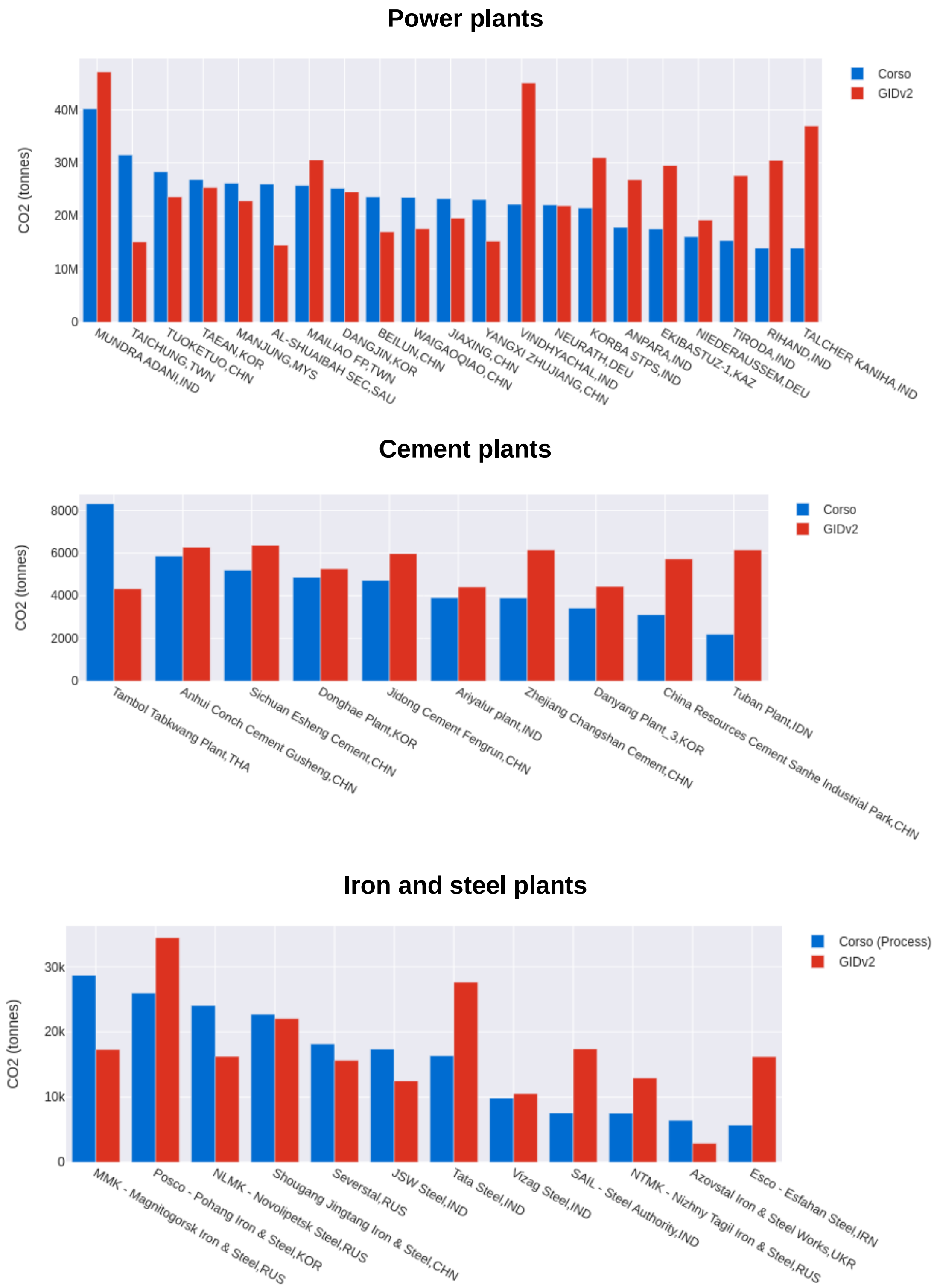

Figure 21 Comparison between plant-level CO_2 (t yr−1) estimated in CORSO and GIDv2.0 for the top 20 (power plants) and 10 emitters (cement and iron/steel) of each inventory.

Figure 22 presents a comparison of plant-level NO_x emissions reported by CORSO and top-down estimates reported by Beirle et al. (2023) in South Africa, South Korean and Iranian/Iraqi power plants. For South Africa, the comparison also includes the official estimates provided by ESKOM (2023). For South Africa, CORSO estimates are in general within the range of uncertainty reported by Beirle et al. (2023). There are three facilities where the values reported by these two datasets are significantly lower than the official ones reported by ESKOM, which are in principle based on data from continuous measurement systems. In South Korea, CORSO tend to report lower emissions than Beirle et al. (2023), although it is important to note that the levels of emissions in these facilities are between 8-10 times lower than the ones observed in South Africa. The largest discrepancies are observed in Iranian and Iraqi power plants, where satellite-based estimates can be up to 4 times larger than the ones reported by CORSO. These discrepancies will be further explored and analysed in the framework of T1.3, where other satellite-based estimates produced by WP2 will be added to these comparisons.

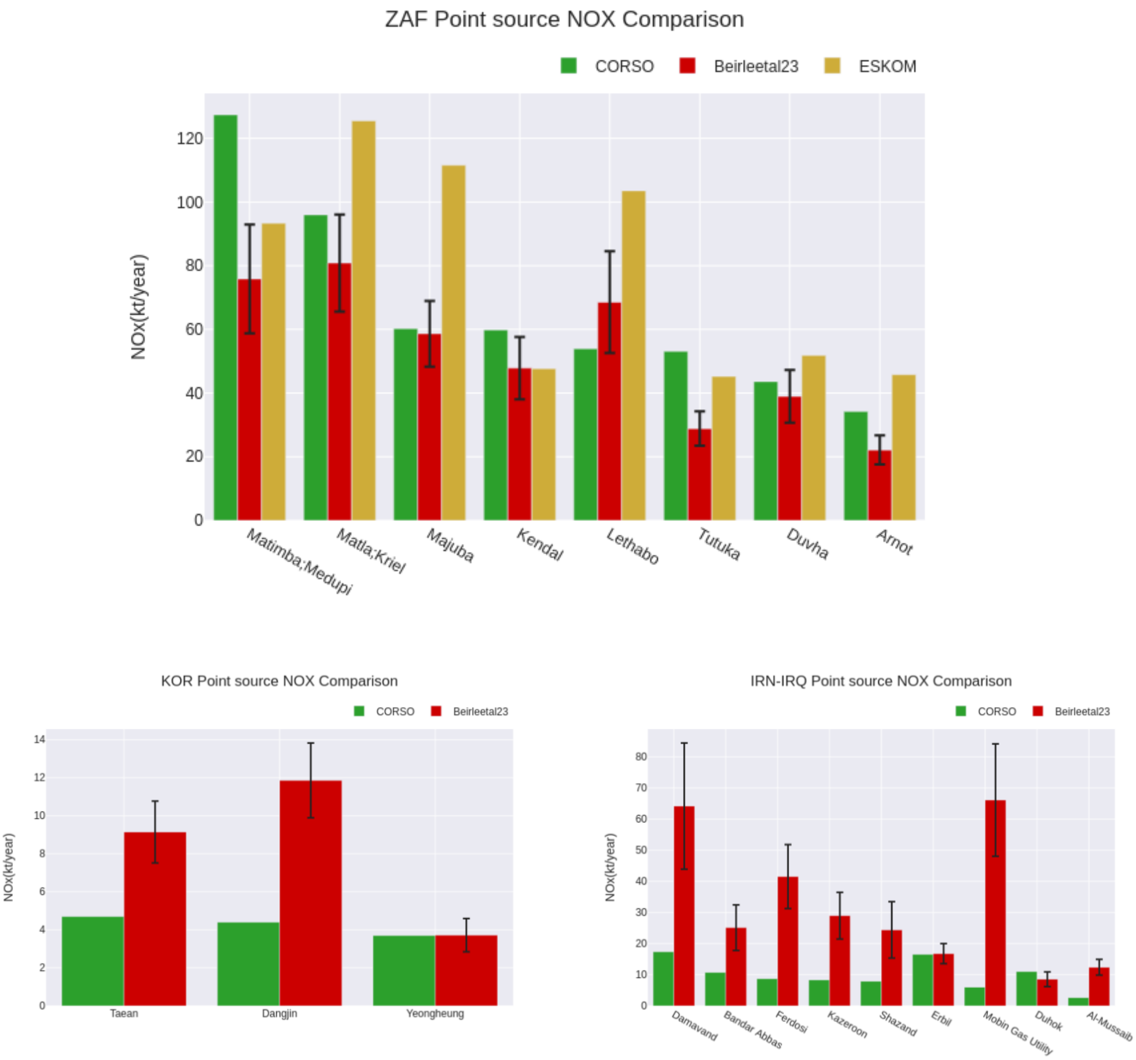

Figure 22 Comparison between plant-level NO_x emissions reported by CORSO and top-down estimates by Beirle et al. (2023) in South African, South Korean and Iranian/Iraqi power plants. For South Africa, results include also official emissions reported by ESKOM.

3.5 Temporal profiles

3.5.1 Power plants

Country- (state- for the US) and fuel-dependent monthly, weekly and hourly temporal profiles were constructed homogeneously for all power plants (i.e., European and non-European datasets) using the electricity production statistics summarised in Table 8. 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 EDGAR emission inventory (Crippa et al., 2018). The resulting profiles were assigned to each facility as a function of the country and fuel type information. For countries with no electricity generation information for the year 2021, we considered the data reported for 2018 and that was used to develop the CoCO2 profiles.

Table 8 Sources of electricity production statistics and corresponding characteristics

Country/Region	Source of information	Temporal resolution	Information per fuel	Reference year
Uruguay	ADME (2021)	Hourly	yes	2018
Australia	AEMO (2021)	Hourly	yes	2021
Guatemala	AMM (2021)	Daily	yes	2018
Indonesia	BPS (2021)	Monthly	no	2018
Argentina	CAMMESA (2021)	Daily	yes	2021
Mexico	CENACE (2021)	Hourly	yes	2018
Algeria, Botswana, Lebanon, Malawi, Sri Lanka, Qatar	CEIC Data (2021)	Monthly	no	2018
Chile	CNE (2021)	Hourly	yes	2021
Peru	COES (2021)	Daily	thermal/renewable	2018
United Arab Emirate	DEWA (2021)	Monthly	yes	2018
EU27	ENTSO-E (2021)	Hourly	yes	2021
Thailand	EPPO (2021)	Monthly	yes	2021
South Africa	ESKOM (2021)	Hourly	yes	2021
UK	ESO (2023)	Hourly	yes	2021
Malaysia	GSO (2021)	Monthly	yes	2018
China, Canada, Colombia, South Korea, New Zealand, Mexico, Japan	IEA (2021)	Monthly	yes	2021
Kazakhstan	KOREM (2021)	Monthly	thermal/renewable	2018
Kuwait	MEW (2021)	Monthly	no	2018
Moldova	MOLDELECTRICA (2021)	Hourly	no	2018
Oman	NCSI (2021)	Monthly	yes	2018
India	NPP (2021)	Daily	yes	2021
Japan (*)	OCCTO (2021)	Hourly	thermal/biomass/renewable	2018
Brazil	ONS (2021)	Hourly	yes	2021
Bangladesh	PGCB (2021)	Hourly	yes	2018

Russia	SO-UPS (2021)	Monthly	thermal/renewable	2018
Switzerland (*)	SWISSGRID (2021)	Hourly	no	2018
Turkey	TEIAS (2021)	Daily	yes	2018
Ukraine	UNEC (2021)	Hourly	yes	2018
US	US EPA (2021)	Hourly	yes	2021
(*) Monthly data derived from IEA as it is reported by fuel type				

Figure 23 to Figure 25 show monthly, weekly and hourly profiles constructed for selected countries and fuels for the year 2021.

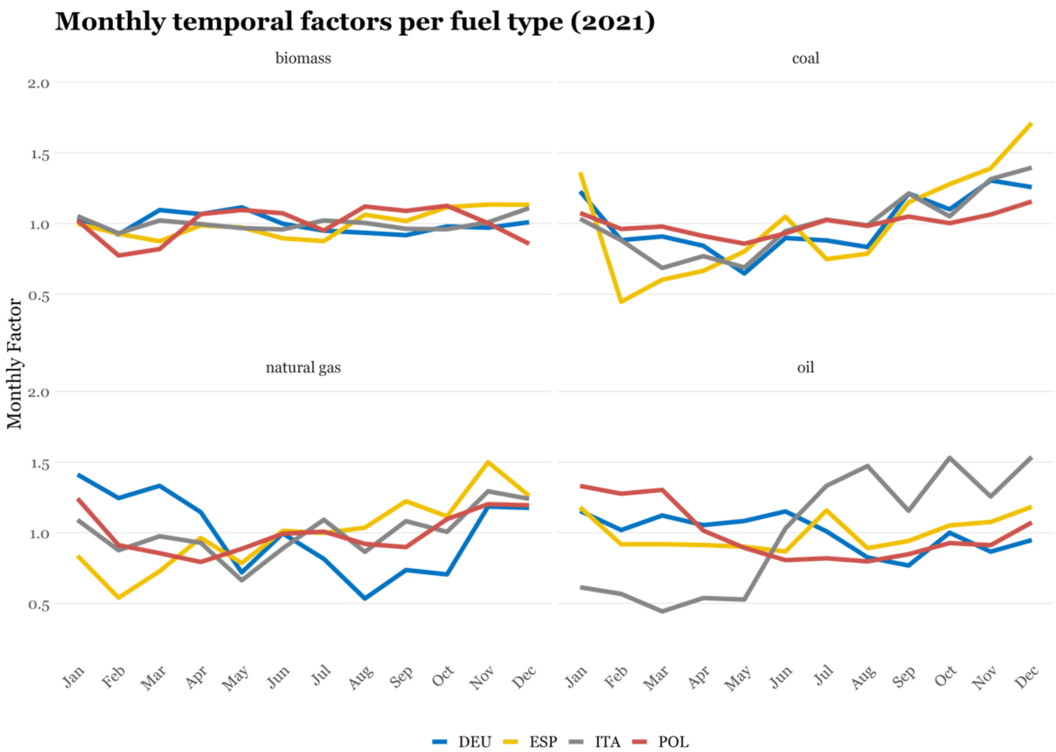

Figure 23 Monthly fuel-dependent profiles constructed for power plants for Germany (DEU), Spain (ESP), Italy (ITA) and Poland (POL)

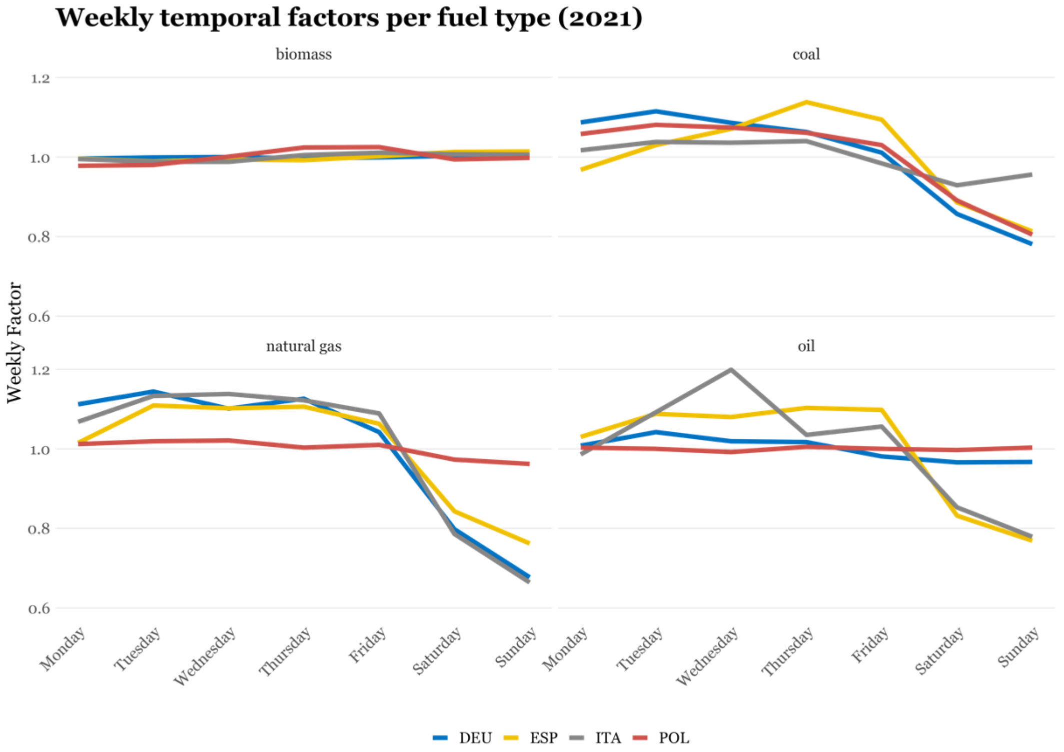

Figure 24 Weekly fuel-dependent profiles constructed for power plants for Germany (DEU), Spain (ESP), Italy (ITA) and Poland (POL)

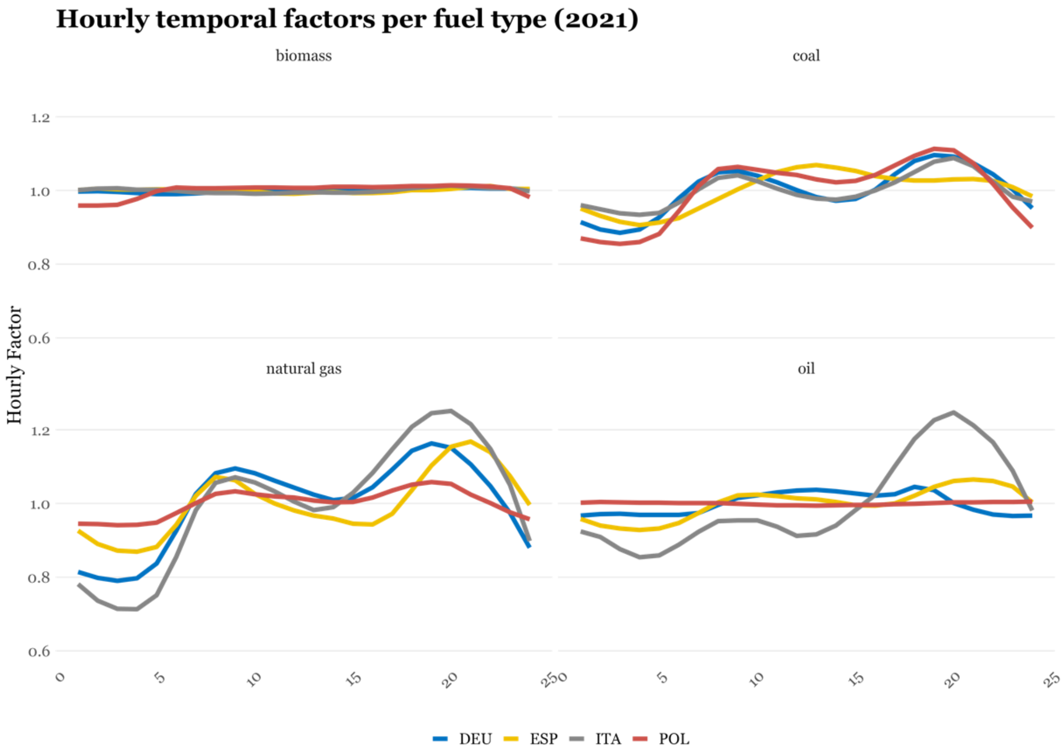

Figure 25 Hourly fuel-dependent profiles constructed for power plants for Germany (DEU), Spain (ESP), Italy (ITA) and Poland (POL)

3.5.1 Cement plants

Country-dependent monthly profiles were derived from the monthly cement and clinker production database reported by Andrew (2023b), which compiles information from national sources and the (now discontinued) UN Monthly Bulletin of Statistics. Monthly clinker production statistics for the year 2021 were considered for the development of the profiles. A climatology was used when data for the year 2021 was not available. For countries with no information on production, an average global profile is used considering the sum of the statistics provided for all countries.

Figure 26 shows the resulting profiles obtained for a selection of countries. In general, profiles are rather flat, with important drops occurring in certain countries mostly related to summer or Christmas holidays.

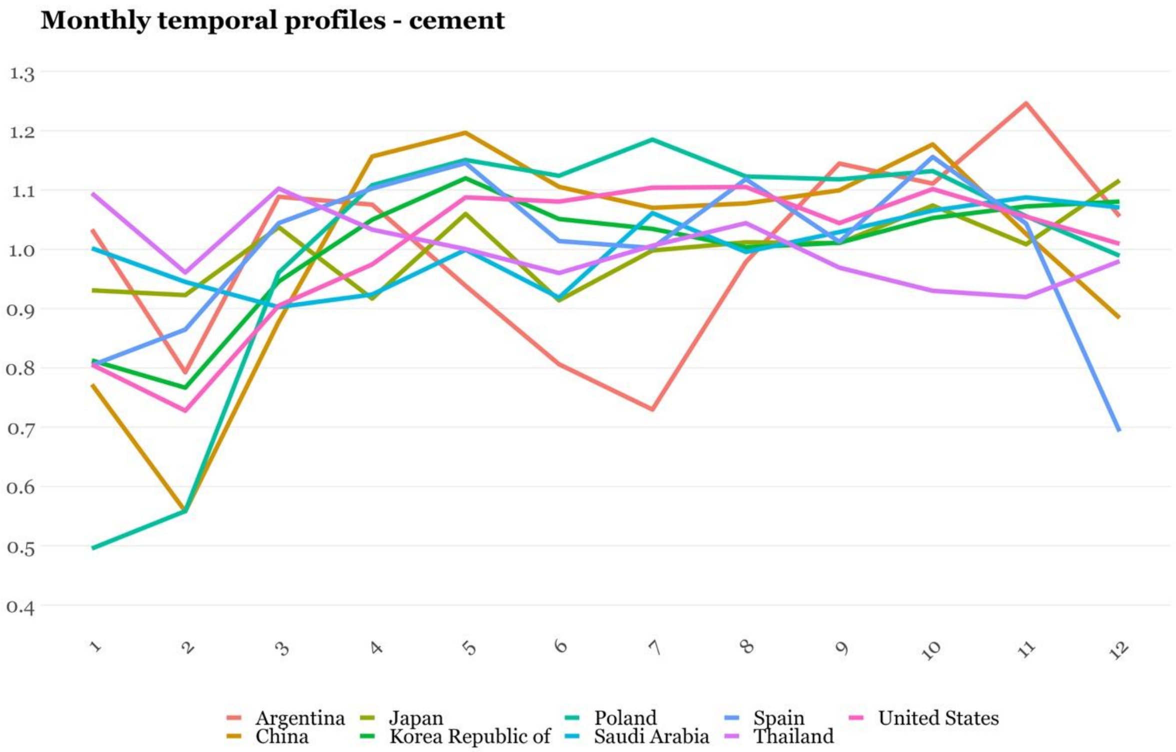

Figure 26 Monthly temporal profiles constructed for cement plants in selected countries

Weekly and hourly flat profiles are proposed for this industrial sector, as no detailed information on production or emissions at these temporal resolutions is available. We investigated the use of the satellite-based VIIRS Nightfire product (VNS; Elvidge et al., 2013) to assess the temporal variability of thermal activity in individual facilities and potentially derive more detailed temporal profiles. We considered the VNF temporal profiles product that VNS provides for individual multiyear infrared emitter sites, which includes daily information on radiant heat and temperature estimated from VNF detections for more than 20000 industrial sites worldwide (including 83 cement plants). However, the temporal coverage of the dataset is quite limited for most of the sources, the number of days with information per year being limited to less than 100 in the majority of the cases, which make its usage very limited for the construction of high-resolution temporal profiles.

3.5.2 Iron and steel plants

Country-dependent monthly profiles were derived from the crude steel monthly statistics provided by the World Steel Association (Worldsteel, 2023). For countries with no information on production, an average global profile is considered taking into account the sum of the production statistics provided for all countries.

Figure 27 shows the resulting profiles obtained for a selection of countries. In general, profiles are rather flat, with important drops occurring in certain countries during summertime (e.g., Italy).

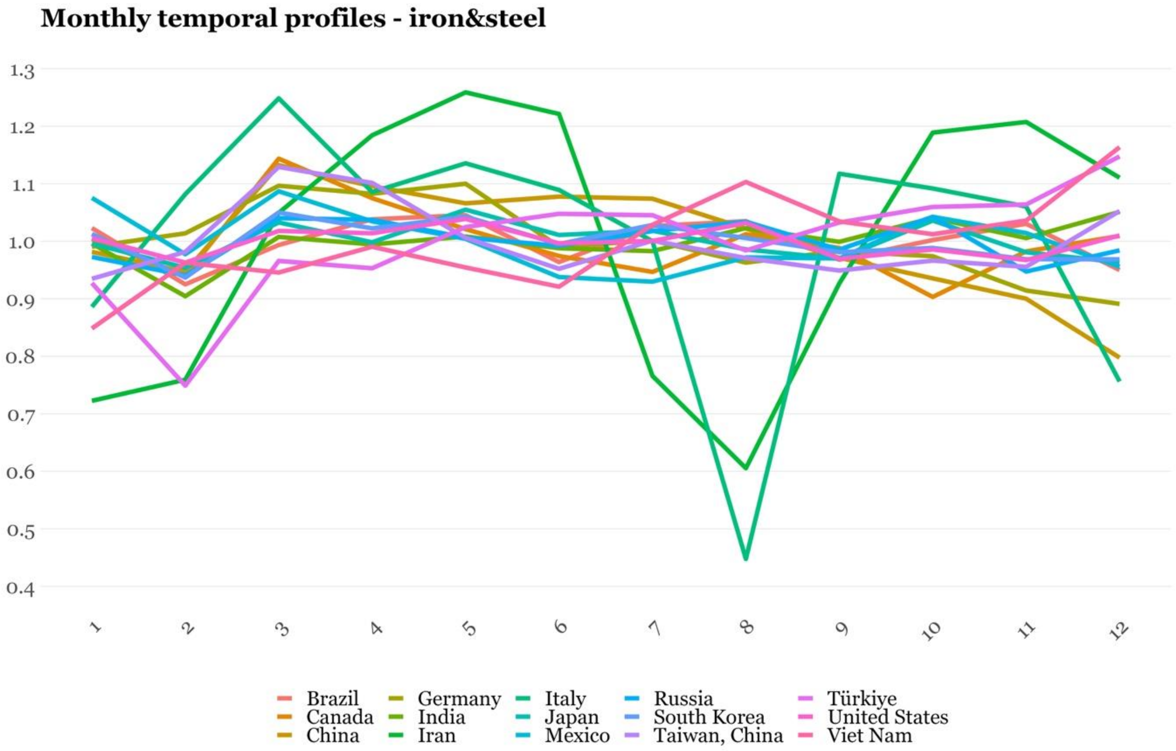

Figure 27 Monthly temporal profiles constructed for iron and steel plants in selected countries

Weekly and hourly flat profiles are also proposed for this industrial sector due to the lack of production data at a higher temporal resolution.

3.6 Vertical profiles

The plant-level vertical profiles computed in the framework of CoCO2 considering stack parameters (e.g., stack height, stack diameter) and meteorological-dependent plume rise calculations (Guevara et al., 2023) are used to describe the vertical distribution of power plant emissions. The resulting profiles provide vertical weight factors associated to a total of 16 vertical layers (from 0m up to 1500m with breaks every 100m, and above 1500m). For the power plants that have been incorporated to the CORSO point source database and that cannot be assigned to a specific CoCO2 vertical profile (around 15% of total facilities), we assign generic fuel-dependent vertical profiles derived from the available catalogue of vertical profiles (Figure 28). To model the vertical distribution of cement and iron and steel plants, we propose to use averaged profiles derived from the collection of vertical profile clusters reported by Bieser et al., (2011). For cement plants, we averaged the collection of vertical profiles reported for NO_x emissions related to the combustion of fuels in the manufacturing industry, while for iron and steel plant we make use of the vertical profiles reported for CO emissions related to processes in the manufacturing industry.

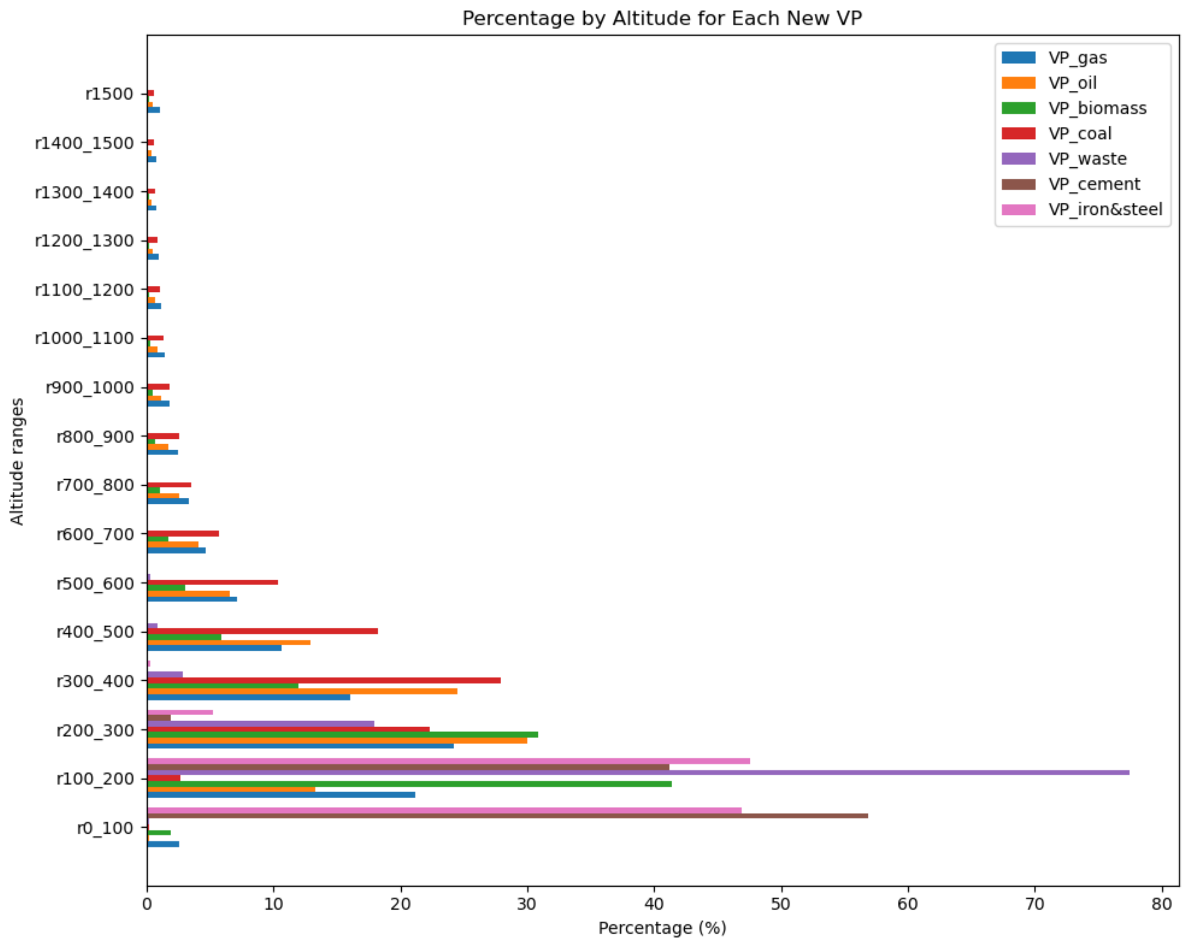

Figure 28 Generic vertical profiles estimated for power plants (by fuel type), cement plants and iron and steel plants based on the CoCO2 catalogue of vertical profiles and Bieser et al. (2011)

3.7 Description of the final dataset

The global point source database (corso_ps_database_v1.zip) is composed of five CSV files:

1. Catalogue of point sources and associated profiles (corso_ps_catalogue_v1.csv)

Field of information	Description
ID	Unique identifier assigned to each unit
ISO3	Country where the unit is located (identified with the three-letter country code defined in ISO 3166-1)
plant_name	Name of the plant, as originally reported in the databases used as input (i.e., E-PRTR/LPS, GEMS, ClimateTrace, eGRID)
sector	Industrial sector (i.e., power, cement, iron&steel)
fuel	Main fuel category associated to each facility (coal, gas, oil, biomass, waste and gas/oil) – only for power plants
latitude	Latitude (in degrees)
longitude	Longitude (in degrees)
co2_kty	Total CO_2 annual emissions associated to each plant (in kt/year)
nox_kty	Total NO_x annual emissions associated to each plant (in kt/year), expressed as NO_2
co_kty	Total CO annual emissions associated to each plant (in kt/year)
sox_kty	Total SO_x annual emissions associated to each plant (in kt/year) expressed as SO_2
ch4_kty	Total CH_4 annual emissions associated to each plant (in kt/year)
ID_MonthFact	Monthly temporal profile unique identifier (FM_xxx). The identifiers are cross-referenced with the monthly temporal CSV file where the numeric profiles are stored
ID_WeekFact	Weekly temporal profile unique identifier (FW_xxx). The identifiers are cross-referenced with the weekly temporal CSV file where the numeric profiles are stored
ID_HourFact	Hourly temporal profile unique identifier (FH_xxx). The identifiers are cross-referenced with the hourly temporal CSV file where the numeric profiles are stored
ID_VertProf	Vertical profile unique identifier (VP_xxxxx). The identifiers are cross-referenced with the vertical CSV file where the numeric profiles are stored. The generic profiles proposed for power plants (fuel-dependent) and cement and iron&steel plants are identified as follows: VP_coal, VP_gas, VP_oil, VP_waste, VP_biomass, VP_cement, VP_iron&steel.

2. Monthly temporal profiles database (corso_ps_monthly_profiles_v1.0.csv)

Field of information	Description
ID_MonthFact	Monthly temporal profile unique identifier (FM_xxx). The identifiers are cross-referenced with the catalogue of point sources.
Jan - Dec	Monthly weight factor associated to each month [0-12]
tot	Total sum of the monthly weight factors [12 for all cases]

3. Weekly temporal profiles database (corso_ps_weekly_profiles_v1.0.csv)

Field of information	Description
ID_WeekFact	Weekly temporal profile unique identifier (FW_xxx). The identifiers are cross-referenced with the catalogue of point sources.
Monday-Sunday	Weekly weight factor associated to each day of the week [0-7]
tot	Total sum of the weekly weight factors [7 for all cases]

4. Hourly temporal profiles database (corso_ps_hourly_profiles_v1.0.csv)

Field of information	Description
ID_HourFact	Hourly temporal profile unique identifier (FH_xxx). The identifiers are cross-referenced with the catalogue of point sources.
H0 – H23	Hourly weight factor associated to each hour of the day [0-24]. Expressed in local time.
tot	Total sum of the hourly weight factors [24 for all cases]

5. Vertical profiles database (corso_ps_vertical_profiles_v1.0.csv)

Field of information	Description
ID_VertProf	Vertical profile unique identifier (VP_xxxxx). The identifiers are cross-referenced with the catalogue of point sources.
r0_100 – r1500	Weight factor associated to each vertical layer [0-1]. Distribution is defined across 16 vertical layers (from 0m up to 1500m with breaks every 100m, and above 1500m)
tot	Total sum of the vertical profiles [1 for all cases]

The dataset can be downloaded from the following public FTP:

Server: es-ftp.bsc.es

Username: mguevara

Password: p5SEEZDU/i8niLLG

Port: 8021

And the files are stored in the following path: mguevara/ corso/corso_ps_v10

Note that in the final point source dataset, there are some power plants for which zero emissions are reported for all pollutants. These plants are in countries for which the IEA energy statistics do not provide information on fuel consumption (e.g., Aruba, Afghanistan), and therefore no emissions could be estimated. However, we decided to keep them in the catalogue and report their location, as it may be relevant for inverse modelling exercises.

4 Conclusion

Under this task we improved the global bottom-up point source dataset that was constructed in CoCO2,. The improvements performed under CORSO include updating the reference year of emissions from 2018 to 2021, reviewing and updating the databases and methods considered for the estimation of power plant emissions, the addition of emissions from energy-intensive industries not previously not considered, including cement and iron/steel plants, and the updating of the temporal and vertical profiles associated to the point sources.

The resulting annual emissions for CO_2 and co-emitted species (NO_x, SO_x, CO and CH_4) obtained for each of the industrial sectors (power, cement and iron and steel) were compared against independent bottom-up global, regional, national and plant-level emission inventories, finding in general a good agreement. A preliminary comparison against existing top-down emission estimates indicated large discrepancies in Iranian and Iraqi oil and gas-fired power plants. Further investigation of these discrepancies and validations works against satellite-based emission estimates will be performed in the framework of CORSO T1.3, making use of the top-down emission products that are being produced as part of WP2.

Overall, the global point source catalogue developed in CoCO2, and further improved in CORSO, holds promise for implementation into the CAMS CO2MVS in the coming years. It should be noted, however, that for other sectors than Energy (power plants) it will be more complicated to develop a merged dataset combining the point source emissions and diffuse and/or area source emissions. The underlying reason is that for sector energy the entire sector can be replaced which avoids complications on double counting and/or underreporting. In parallel to this work, and in the framework of the CAMS2_61 emission service, BSC and TNO have started to work on the adaptation of the point source catalogue so that it can also support the global air quality modelling activities performed under CAMS. This implies addition of species not addressed in CoCO2 and CORSO. The goal of this adaptation effort is to ensure an alignment and consistency between emission developments to support modelling efforts of both air pollutants and greenhouse gases under CAMS. The integration of the present catalogue into the CAMS services will require allocating efforts to continue the maintenance and improvement of the dataset, including, among others, the regular updating of the reference year and refinement of the estimation methods, based on the feedback received from the inverse modelling works performed under CAMS and CO2MVS

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