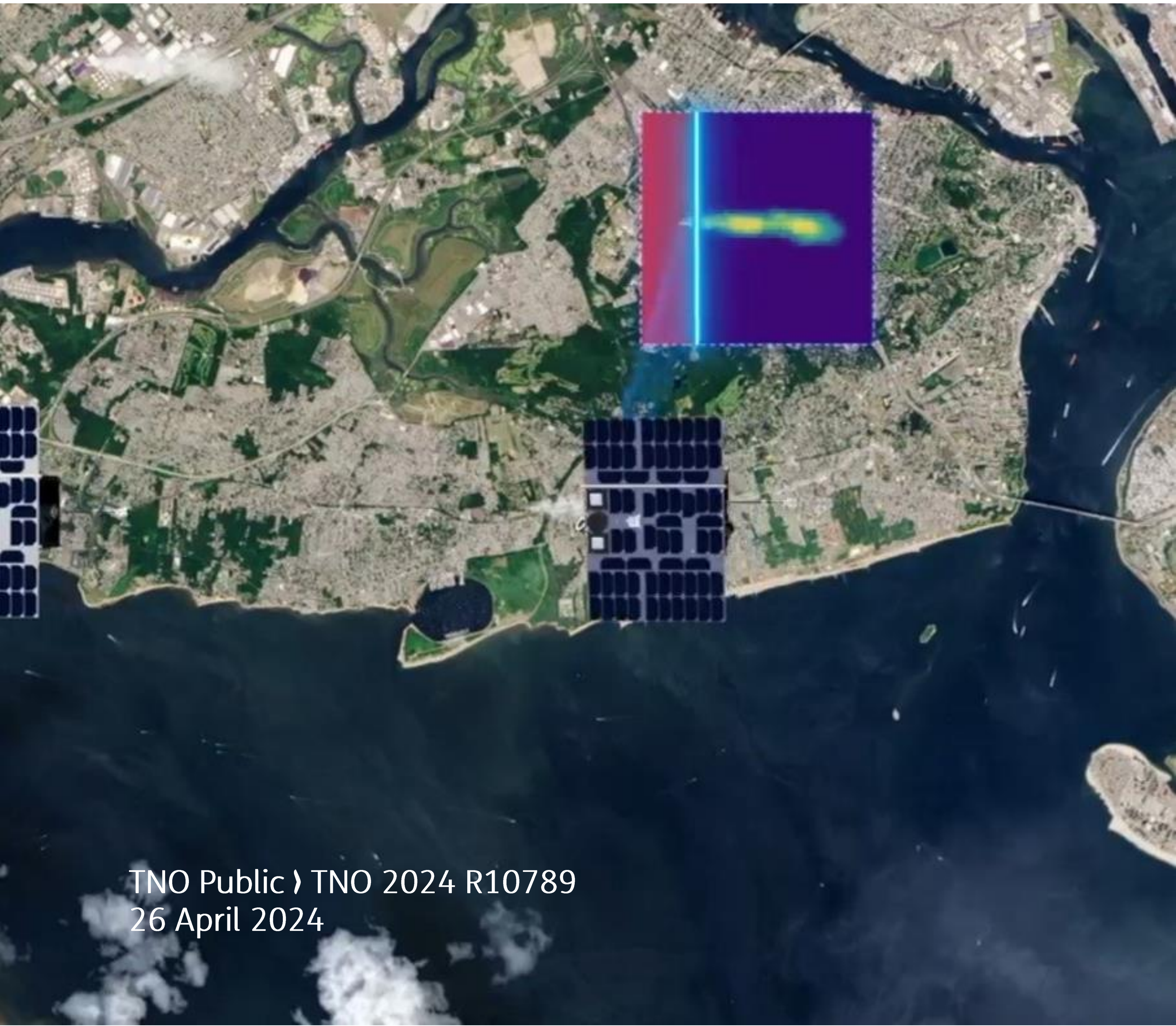
TNO GPS Emission Inventory

Global inventory of greenhouse gas emissions to support the design of the TANGO satellite mission



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TNO GPS Emission Inventory

Global inventory of greenhouse gas emissions to support the design of the TANGO satellite mission

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Executive summary

To strengthen the global response to the threat of climate change an agreement was reached at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015. The so-called Paris Agreement (PA)[1] is a legally binding international treaty which entered into force in 2016. The overarching goal is to hold “the increase in the global average temperature to well below 2°C above pre-industrial levels” and pursue efforts “to limit the temperature increase to 1.5°C above pre-industrial levels.” Despite the efforts since the PA, the world is not on track to reach its goals. According to the UNEP (2023) report, emissions must be cut by at least 28% compared to current scenarios to get back on track for the 2°C temperature rise above pre-industrial levels. Bringing it to within the 1.5°C limit will require a 42% cut.

Earth observation data, like the Tropomi methane data, can play a key role in monitoring emissions and identifying targets for mitigation actions. To further strengthen the supporting role of earth observation data to abate climate change, the recently approved ESA Scout Mission TANGO (Twin Anthropogenic Greenhouse Gas Observers) aims to monitor greenhouse gases including carbon dioxide (CO_2), shorter-lived methane (CH_4), and nitrogen oxides (NO_X) at the facility-level. Due to its higher spatial resolution, and unlike Tropomi, TANGO will not be able to cover the whole globe daily. It will have to make choices where and what to monitor. To understand the potential capabilities and added value of the TANGO missions, up-to-date and precise knowledge of the locations of CO_2 and CH_4 emitting facilities is crucial.

A proof-of-concept point source inventory, described in this report, was built in 2023 based on TNO's expertise and previous research in various Horizon Europe projects. The immediate aim is to support the TANGO mission science case and in the near future, play a major role in the direction of the satellite applications and target selection. To support the mission, TNO compiled a state-of-the-art **Global Point and gridded Sources emission inventory** (**TNO GPS**) containing more than 108,000 precise locations on the planet that emit greenhouse gases at facility level. Leveraging open-source datasets, earth observation data and TNO expert knowledge, TNO GPS is among the most complete and accurate inventories of point sources at facility level globally. The current report gives an overview of the methodology followed to construct TNO GPS and summarizes its results. To keep completeness of all anthropogenic emissions the point sources are complemented in the TNO GPS by the area sources such as livestock or rice fields taken from the CAMS-REG inventory for Europe or EDGAR for other regions. In terms of coverage, the point sources in the dataset cover 23% of total CH_4, 47% of total CO_2 and 24% of the total global anthropogenic NO_X emissions. Implying that for example 23% of the global CH_4 emissions have been assigned to individual locations. The point source data can easily be grouped in emission size bins, for example to identify super emitters, or by sector to support policy objectives.

The report describes version 0.4, version 1.0 of TNO GPS is currently under development and aims to increase the coverage of emissions in underrepresented sectors as well as improving the confidence of locations and emission estimates. As such, TNO GPS is expected to play an important role in the operationalization of the TANGO mission, placing itself as the linking chain between science and policy and supporting the global push for climate mitigation.

[1] https://unfccc.int/process-and-meetings/the-paris-agreement

Contents

Glossary

Abbreviation	Meaning
BF	Blast Furnace
CH_4	Methane
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CO_2	Carbon dioxide
DRI	Direct Reduced Iron
GHG	Greenhouse gases
GHG-co	GHG and co-emitted species
GPS (D)	Global Point Source (Database)
LTO	Landing and take-off
NO_X	Nitrogen oxides
SRON	Netherlands Institute for Space Research
TANGO	Twin Anthropogenic Greenhouse Gas Observers
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

There is an urgent need for global and high-resolution monitoring of greenhouse gas emissions, especially of so called 'super-emitters': very large and concentrated sources of greenhouse gas emissions because these represent clear mitigation targets. (e.g., Sadavarte et al., 2021). Detailed emission monitoring at the facility level will be an important tool in the implementation and monitoring of mitigation measures to meet the 2015 Paris Agreement.
Satellite mission Sentinel-5p[2], launched in October 2017 and mounted with the Dutch-engineered TROPOMI spectrometer, measures key atmospheric constituents, including ozone, nitrogen dioxide, carbon monoxide, sulphur dioxide, methane, formaldehyde, aerosols and clouds with daily global coverage (SRON, 2016). Following the lead of TROPOMI, the Twin Anthropogenic Greenhouse Gas Observers (TANGO[3]) mission is a pioneering satellite mission that will exist of two satellites: TANGO-Carbon and TANGO-Nitro. The TANGO mission will aim to monitor and quantify emissions of the greenhouse gases methane (CH_4), carbon dioxide (CO_2) and of co-emitted nitrogen oxides (NO_X) at a much higher spatial resolution, and with a higher sensitivity. This will allow emission monitoring at the level of individual emission sources such as industrial facilities and power plants. At the time of writing, TANGO has an expected launch date in 2026/2027 (SRON, 2022[4]) and has been formally selected for implementation in the European Space Agency (ESA) as part of its ESA-Scout cohort since February 21st, 2024.

To allow for higher spatial resolution and sensitivity, the TANGO satellites do not have daily global coverage and need to be targeted at locations of interest. Optimization of the monitoring capacity requires reliable information on the known or expected locations of large emission sources. To prepare for the TANGO mission, a 'fast-track' global emission inventory has been compiled combining the most accurate, comprehensive and up-to-date global point source[5] datasets for carbon dioxide (CO_2) and methane (CH_4), as well as the co-emitted nitrogen oxides (NO_X). The resulting inventory covers many emission sources across various sectors with their exact coordinates and expected annual emission rate. This global emission inventory has been named the **TNO Global Point and gridded Sources emission inventory**, or **TNO GPS emission inventory**. This inventory builds on work done by TNO and other partners in the framework of CAMS and Horizon Europe projects such as $CoCO_2$ and CORSO. The current broadening of the scope to methane and all source sectors to support target selection for the TANGO science case was done in 2023 and 2024. The resulting preliminary version 0.4, to be further completed and validated in 2024, illustrates the potential of TNO GPS to be implemented as a core product of the TANGO mission. Next to supporting the targeting of locations of interest based on specific criteria such as location, emission size, uncertainty, it may facilitate communication of future TANGO results by asset name from the database to asset owners and other stakeholders. Moreover, TANGO results could improve the quality of the TNO GPS which can again lead to better target selection.

[2] Sentinel-5p - Missions (2016) Sentinel. Available at: https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-5p (Accessed: March 15, 2023).
[3] TNO, Tango Satellite: Monitoring Greenhouse Gas Emissions (2022) tno.nl/en. Available at: https://www.tno.nl/en/sustainable/space-scientific-instrumentation/earth-observation-monitoring-our-planet/tango-satellite-monitoring-greenhouse/ (Accessed: March 15, 2023).
[4] SRON - TANGO. Available at: https://www.sron.nl/missions-earth/tango (Accessed: March 15, 2023).
[5] Industrial facilities, power plants and other anthropogenic sources with concentrated emissions (e.g. landfills) are referred to as emission point sources.

2 TNO GPS emission inventory

The TNO GPS emission inventory that has been compiled in preparation of the TANGO satellite mission is comprised of two parts:

- The **point sources** emission inventory, with the annual emission rate at facility/location level, linked to exact source coordinates (latitude, longitude).
- The **gridded emission** inventory, with annual emission rates per sector and grid cell (0.1 x 0.1 degree grid), for sources that are more diffuse, or for which the exact coordinate is not (yet) known.

The characteristics of both inventories are shown in Table 2.1 and Table 2.2. The data files themselves also include the relevant metadata. In addition to the emission files, there are associated temporal profiles available, which can be used to derive hourly emissions by grid cell or source, and which are discussed in section 3.7.

Table 2.1: TNO GPS point source emission inventory overview

Parameters	Description
Spatial scope	Global (sources in 170 countries)
Temporal resolution	Annual – Based on 2018 data
Spatial resolution	Exact source coordinates (latitude/longitude)
Number of sectors	7 (14 for EU+ region)
Pollutants	CH_4, CO_2, NO_x
Unit	Tonnes / source / year
Version	Version 0.4 (October 2023)
Format	NetCDF or CSV

Table 2.2: TNO GPS gridded emission inventory overview

Parameters	Description
Spatial scope	Global – Gridded sources
Temporal resolution	Annual – Based on 2018 data
Spatial resolution	Gridded 0.1 x 0.1 degree
Number of sectors	18
Pollutants	CH_4, CO_2, NO_x
Unit	Kilotonnes / grid cell / year
Version	Version 0.4 (October 2023)
Format	NetCDF

3 Methodology

3.1 Workflow

The following steps were followed to compile a detailed and comprehensive emission inventory, with a focus on including emission rates and exact coordinates for point sources:

1. Searching and collecting existing emission inventories at point source level for relevant sectors. They preferably include information on:
   a. Exact source coordinates
   b. Emissions of selected pollutants at (point) source level
2. Choosing a global and complete 'base' emission inventory that covers:
   a. The required pollutants
   b. Year 2018
   c. Detailed sector disaggregation
   d. High spatial resolution
3. Comparing emission rates between available inventories:
   a. At country level
   b. At facility level (between different point source datasets)
4. Combining point source datasets into one comprehensive dataset.
5. Combining gridded emission datasets into one dataset, covering only those emissions that are not covered by the point sources dataset (avoiding both the omission and double counting of emissions).
6. Compiling the associated temporal profiles to redistribute annual emissions to hourly emissions.

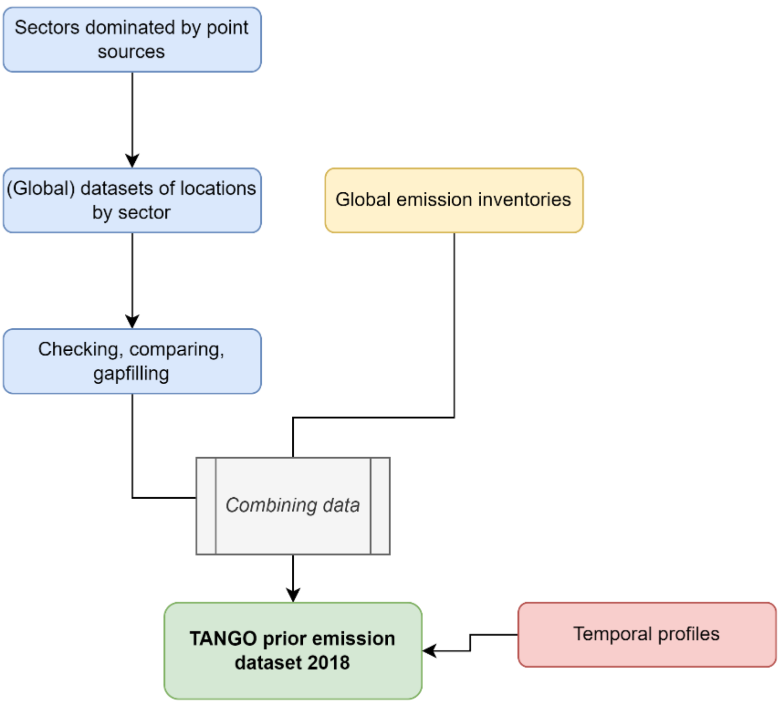

Figure 3.1: Simplified TNO GPS methodology workflow

3.2 Sector Disaggregation

In the emission inventory data files, several main economic/industrial sectors are distinguished, shown in Table 3.1 and Table 3.2below. The original data source used for the emission and location data in the layer is shown as well.

Table 3.1 Point source sector disaggregation

Sector code	Description	Pollutants	Data sources (excl. EU-27+)	Coverage
CHE	Chemical industry	CH_4, CO_2, NO_x	TNO GHG-co v.5 (only EU-27+)	EU-27+
ENE	Energy generation	CH_4, CO_2, NO_x	CoCO$_2$ GPSDB (Guevara et al., 2023).	Global
FEF_COAL	Fossil fuel exploration, coal mining	CH_4	ClimateTRACE coal mines dataset	Global
FEF_OIL_GAS	Fossil fuel oil and gas production, processing and distribution	CH_4	GFEI v2 (Scarpelli et al. 2022) GOGI v.10.3.1 (Rose et al., 2018) OGIM v1.1 (Omara et al., 2023)	Global
IND	(Other) Industry	CH_4, CO_2, NO_x	TNO GHG-co v.5 (only EU-27+)	EU-27+
IRO	Iron and steel production	CO_2, NO_x	Combination of GEM and ClimateTRACE datasets, with gap filling by TNO	Global
NFE	Non-ferrous metals production	CH_4, CO_2, NO_x	TNO GHG-co v.5 (only EU-27+)	EU-27+
NMM	Non-metallic minerals production (here only cement production)	CO_2, NO_x	ClimateTRACE cement plants dataset	Global
REF	Refineries and fuel transformation (here only oil refineries)	CO_2, NO_x	ClimateTRACE refineries dataset	Global
SLV	Solvents and product use	CH_4, CO_2, NO_x	TNO GHG-co v.5 (only EU-27+)	EU-27+
SWD_INC	Waste incineration	CH_4, CO_2, NO_x	TNO GHG-co v.5 (only EU-27+)	EU-27+
SWD_LDF	Landfills	CH_4	ClimateTRACE landfills dataset	Global
TNR	Non-road transport (here: aviation LTO)	CH_4, CO_2, NO_x	TNO GHG-co v.5 (only EU-27+)	EU-27+
WWT	Wastewater treatment	CH_4	TNO GHG-co v.5 (only EU-27+)	EU-27+

Table 3.2 Gridded source sector disaggregation

Sector code	Description	Pollutants	Data source (excl. EU-27+)
AGL	Agricultural livestock	CH_4, NO_X	CAMS-GLOB-ANT v5.3 2018
AGS	Agricultural soils	CH_4, CO_2, NO_X	CAMS-GLOB-ANT v5.3 2018
AWB	Agricultural waste burning	CH_4, CO_2, NO_X	CAMS-GLOB-ANT v5.3 2018
CHE	Chemical industry	CH_4, CO_2, NO_X	EDGAR v.7/v6.1 (NO_X)
FEF_OIL_GAS	Fossil fuel oil and gas production, processing and distribution	CH_4, CO_2, NO_X	GFEI v.2 (Scarpelli et al. 2022)
FFF	Fossil fuel fires	CH_4, CO_2, NO_X	EDGAR v.7/v6.1 (NO_X)
IND	(Other) Industry	CH_4, CO_2, NO_X	EDGAR v.7/v6.1 (NO_X)[6]
NEU	Non-energy use of fuels	CO_2	EDGAR v.7/v6.1 (NO_X)
NFE	Non-ferrous metal production	CO_2, NO_X	EDGAR v.7/v6.1 (NO_X)
REF	Refineries and fuel transformation	CH_4	GFEI v.2 (Scarpelli et al. 2022)
RES	Residential combustion	CH_4, CO_2, NO_X	CAMS-GLOB-ANT v5.3 2018
SHP	Shipping	CH_4, CO_2, NO_X	CAMS-GLOB-ANT v5.3 2018
SLV	Solvents and product use	CO_2	CAMS-GLOB-ANT v5.3 2018
SWD_INC	Waste incineration	CH_4, CO_2, NO_X	EDGAR v.7/v6.1 (NO_X)
SWD_LDF	Landfills	CH_4	EDGAR v.7/v6.1 (NO_X)[7]
TNR	Non-road transport	CH_4, CO_2, NO_X	CAMS-GLOB-ANT v5.3 2018
TRO	Road transport	CH_4, CO_2, NO_X	CAMS-GLOB-ANT v5.3 2018
WWT	Wastewater treatment	CH_4	EDGAR v.7/v6.1 (NO_X)

3.3 Datasets Descriptions – Point Sources

First, existing emission datasets were identified and investigated for those sectors where point sources represent a large share of emissions. For CO_2 and NO_X, the energy sector, iron and steel production, cement production, and refineries are examples of sectors where a large share of emissions are emitted through a stack and can thus be very precisely localised. For CH_4, landfills, coal mines, and oil and gas production locations may represent locations of high and concentrated emissions.

After collecting many potentially relevant datasets for these sectors, their completeness and quality were investigated through comparisons against (reported) country totals and between point source emission estimates across datasets. The year 2018 was chosen as a base year for the product to promote consistency within the inventory compilation. In the $CoCO_2$ project

[6] *A custom data layer version was supplied by the EDGAR team in which combustion emissions from the iron/steel and cement sectors had been removed, to avoid double-counting with the point source data.*

[7] *The methane gridded emissions in the landfills data layer have been scaled at the country level to avoid double counting with the point source layer for landfills*

the first prior emission dataset made was also for 2018[8] . Indeed, 2018 was found to be the year with most data overlaps in all datasets used as mentioned in Table 3.1. The baseline year is expected to be subject to change in the coming years, particularly as new data is integrated from recent developments from Carbon Mapper and later on, TANGO. Note that by definition a global point source register will not be static as facilities may be opened and /or closed over time.

The datasets used to compile the TNO GPS emission inventory are listed and discussed below.

3.3.1 TNO GHG-co

For the EU-27 countries + GBR, CHE, NOR and ISL, the in-house TNO GHG-co v.5 emission inventory was used both for point and gridded emission sources (Denier van der Gon et al., 2023). A custom output was generated for 2018 with sector (dis)aggregations lined up with the other available datasets. The emission inventory follows the methodology described in Kuenen et al. (2022). The starting point is the officially reported emission data from the countries under the UNFCCC (for greenhouse gases) and CLRTAP (for air pollutants). These are combined, checked, and supplemented with data from the IIASA GAINS model. A consistent spatial disaggregation is applied across the domain to distribute emissions to individual grid cells and point source locations. The final inventory contains the greenhouse gases CO_2 and CH_4 and the co-emitted air pollutants CO, NO_X and NMVOC. Known point source locations are included at their exact coordinates. This dataset therefore aligns well with the design of the TNO GPS point source emission inventory.

3.3.2 $CoCO_2$ Global Point Source Database

The global point source database from $CoCO_2$ (Guevara et al., 2023) for the energy sector is used to represent all emissions from the public power and heat sector. While the database is not fully complete in its coverage of small power plants, auto-producer plants, and heat plants for some countries, comparisons with global estimates show that it covers a substantial share (>90%) of global fuel input and CO_2 emissions from the energy sector. Therefore, it was decided to have this dataset represent all energy sector emissions globally.

The $CoCO_2$ database was compiled by combining data from the Global Power Plant Database (2021), the IndustryAbout database (2021) and the Open Infrastructure Map (2022), as well as various national and regional power plant databases such as the Geocomunes Mexican power plant database (2020), the Japan electrical power station database from Electrical Japan (2022), the E-PRTR/LCP database for the EU, and Emissions and Generation Resource Integrated Database for the US (eGRIDv2018; US EPA, 2020). The dataset includes annual emission rates at facility level for CO_2, CH_4, and co-emitted species including NO_X. Particular attention was put in the manual checking of power plant coordinates which resulted in corrections for some 360 facilities.

3.3.3 ClimateTRACE

Data from the ClimateTRACE[9] initiative was used as the core of the TNO GPS emission inventory, as data on multiple sectors is available at a high level of detail. This includes data from 2015-2021, at facility or source level, and includes the pollutants of interest. Furthermore, the data includes additional information such as facility ownership, location, and production capacity information (ClimateTRACE, 2022). Where available, data for the year

[8] D2.1 Prior Emission Dataset (PED) 2018 (https://coco2-project.eu/node/327).
[9] https://climatetrace.org/

2018 was used as baseline, as it doesn't suffer from the effects of the Covid-19 pandemic and was the most commonly available year for the majority of datasets at the time. For some sectors where 2018 data was not available, data for later years was used such as 2021 data for coal mines.

ClimateTRACE datasets were used for representing the point source emissions for the following sectors: coal mines, landfills, iron and steel, cement, and refineries. For landfills, the coverage was rather incomplete for a significant number of countries, so this data was used where available, and replaced with gridded data from the EDGAR inventory were incomplete. Note that at the time of writing, an updated version of the ClimateTRACE data has become available, including additional points for the landfill sector which will be updated in a future version, as discussed in section 5.5.

3.3.4 Global Energy Monitor (GEM)

The Global Energy Monitor (GEM[10]) is an open, annually updated database with emission data for individual sources in several sectors. The GEM Global Steel Plant Tracker (GSPT) provides facility-level data on location, ownership, capacity, and technology for all iron/steel plants globally over a threshold of 0.5 million metric tonne of crude steel per year. As of March 2023, this covers more than 1000 steel plants in the world and includes data on their start date and/or closure status, as well as information on ownership.

For the TANGO point source dataset, the GEM Global Steel Plant Tracker (GSPT) data was combined with ClimateTRACE data on the iron and steel sector, facilitated by the fact that ClimateTRACE uses GSPT as a basis for the plant locations. The GEM GSPT covered a small number of iron/steel plants that were not included in the ClimateTRACE dataset. For these, TNO estimated the CO_2 emission based on capacity data and technology information as available in the GSPT in combination with emission factors from Bosch et al. (2011).

3.3.5 Oil and Gas Infrastructure Mapping (OGIM)

The Environmental Defense Fund (EDF) OGIM dataset compiles global, spatially explicit databases of oil and gas infrastructure for the year 2022 that are relevant for methane emissions including those from oil and gas production wells, offshore production platforms, natural gas compressor stations, processing facilities, pipelines, and crude oil refineries. This compilation includes 450 publicly available geospatial datasets including inventory and satellite data from 202 data sources. For countries with significant oil and gas infrastructure such as the US, Australia, Norway and Brazil, data from governmental open-source public sources was included. In total, 6 million locations are present in the dataset, the majority of which are oil wells and minority liquefied natural gas facilities. It is anticipated that this work will be updated regularly. The inventory does not include emission values and therefore was used only to localize gridded methane emissions from the GFEI dataset (see sections 3.4.3 and 3.6.1.2).

3.3.6 Global Oil and Gas Infrastructure Inventory (GOGI v10.3.1)

The Global Oil and Gas Infrastructure (GOGI) inventory was developed by Rose et al. (2018) and integrates a large number of separate datasets on oil and gas infrastructure into one harmonised global dataset. The dataset contains locations of refineries, processing plants,

[10] https://globalenergymonitor.org/

compressor stations, underground storage, wells, platforms, and other infrastructure. The inventory does not include emission values and therefore was used only to localize gridded methane emissions from the GFEI dataset (see sections 3.4.3 and 3.6.1.2).

3.4 Datasets Descriptions – Gridded Inventory

For sectors where point sources are less dominant or where data on point source emissions or locations was not available, the emissions are spatially distributed to grid cells in a 0.1 x 0.1 degree global grid. The following datasets are used to complete the points source emissions in TNO-GPS.

3.4.1 CAMS-GLOB-ANT

For most gridded emission sources, the CAMS-GLOB-ANT v5.3 dataset is used (Granier et al., 2019; Soulie et al. 2023). This dataset is based on EDGAR v5 data with a 0.1 x 0.1 degree spatial resolution (Crippa et al., 2018; 2022) and CEDS v2021 data in 0.5 x 0.5 degree resolution (Hoesly et al., 2018; McDuffie et al., 2020). These datasets were harmonised to facilitate sector disaggregation to 11 sectors.

While being mostly based on the EDGAR data, CAMS-GLOB-ANT includes updated shipping sector emissions from the CAMS-GLOB-SHIP dataset, that is based on the STEAM model from FMI (Johansson et al., 2017; Jalkanen et al., 2016) and which uses time and weather-dependent, high-resolution dynamic shipping traffic data. The CAMS-GLOB-ANT inventory can be directly linked to the CAMS-GLOB-TEMPO temporal profiles, which allows the redistribution of annual emissions to hourly emissions.

3.4.2 Emissions Database for Atmospheric Research (EDGAR)

The EDGAR v7 (v6.1 for NO_X) emission inventory (Crippa et al., 2018; 2022; Janssens-Maenhout, 2019) was used as the gridded emission inventory for the industrial and waste sectors, as it provides in some cases a more detailed sector disaggregation than does CAMS-GLOB-ANT. The EDGAR database uses international (energy) statistics to compile a bottom-up and coherent global dataset of anthropogenic emissions with a long time series (1970 – 2021). EDGAR covers a comprehensive selection of sectors/activities and includes emissions both of greenhouse gases and air pollutant species.

3.4.3 Global Fuel Exploitation Inventory (GFEI)

The Global Fuel Exploitation Inventory dataset (GFEI v2), updated in 2022 (Scarpelli et al., 2022), contains methane emissions from the production, processing, transport and distribution of coal, oil, and natural gas. The updated GFEI v.2. provides annual emissions for 2010–2019 and incorporates recent UNFCCC national reports and matches them with global infrastructure data locations. Additions from version 2 include the locations of new oil–gas wells, and improved spatial distribution of emissions for Canada, Mexico, and China in a 0.1 x 0.1 degree grid. Validation of the methane emission totals by region was done using global methane inversions from GOSAT satellite and in-situ platforms (GLOBALVIEWplus).

3.5 Dataset Descriptions: Temporal Profiles

3.5.1 CAMS-GLOB-TEMPO

The temporal profiles have been derived from CAMS-GLOB-TEMPO v3. (Guevara et al., 2021). The temporal profiles are sector specific and in some cases pollutant specific. The profiles are both available as a gridded product (0.1 x 0.1 degree resolution) or by country code. This allows differentiation in temporal patterns between regions. The temporal profiles allow the redistribution of annual emissions to estimate hourly emissions, through a combination of monthly (share month in year), weekly (share weekday in week), and diurnal/hourly (share hour in day) fractions. For some sectors, the monthly and weekly profiles are replaced by a daily (share day in year) profile.

3.6 Processing

3.6.1 Point Source Data

3.6.1.1 Gap-Filling

Several processing steps were performed to combine the different point source datasets into one consistently formatted dataset.

As some datasets such as ClimateTRACE included only CO_2 emission data and no estimate of NO_X emissions, a gap filling routine was introduced for NO_X, based on the typical average ratio between CO_2 and NO_X emissions for the specific sector, as shown below in Table 3.3. As ratios may differ substantially between actual facilities, the resulting NO_X emission estimate has a considerable uncertainty.

Table 3.3: Weighted average NO_X/CO_2 ratio (kg/kg) based on EPRTR reported emission data

Sector	Technology	Ratio NO_X / CO_2	Comment
refineries	all	0.00076	derived from EPRTR
cement	all	0.00111	derived from EPRTR
iron/steel	electric	0.00157	derived from EPRTR
iron/steel	electric, oxygen	0.00157	derived from EPRTR
iron/steel	integrated (BF[11])	0.00070	derived from EPRTR
iron/steel	integrated (BF and DRI[12])	0.00070	derived from EPRTR
iron/steel	integrated (DRI)	0.00157	assumed electric ratio
iron/steel	oxygen	0.00070	derived from EPRTR
iron/steel	unknown	0.00070	assumed BF ratio

[11] BF: Blast furnace
[12] DRI: Direct Reduced Iron

3.6.1.2 Oil and Gas Infrastructure Emissions

There are several datasets available on the locations of known oil and gas infrastructure, in addition to gridded emissions datasets on methane emissions from the oil and gas sector. However, to our knowledge and at the time of writing, there is currently no comprehensive dataset with methane emissions from individual locations. As this sector has a large contribution to anthropogenic methane emissions, a first attempt was made to allocate methane emissions to actual oil and gas infrastructure. To do this, three existing datasets were combined, GFEI v.2. which has gridded methane emissions by subsector, OGIM and GOGI which cover a large number of known oil and gas infrastructure location on exact coordinates. The approach followed a stepwise allocation of gridded emission values from the GFEI dataset to infrastructure locations within the same grid cell from OGIM and GOGI. Priority was given to locations from the OGIM dataset, as it is more recent. There is also a hierarchy in first allocation emissions to processing locations, compressor stations, platforms, and terminals, and then to well sites. Locations in grid cell where there are no gridded emissions in the GFEI dataset receive no emissions. Furthermore, grid cells with methane emissions where there are no known infrastructure locations are retained in the gridded emission layer for the fugitives from oil and gas (fef_oil_gas) sector. When there are multiple infrastructure locations of the same type in one grid cell, the emissions for that grid cell are distributed evenly over the locations.

3.6.1.3 Combination of Global and EU 27+ Data

In order to have a consistent dataset across sectors and spatial domain, emissions from all datasets were converted to tonnes/year. For the energy sector, the CoCO_2 global point source inventory was used for all countries, as it already uses the same EPRTR based emission data as does the TNO GHG-co dataset. For the other sectors, data for all countries is taken from the available global inventories, except for the EU-27+ countries, where the point source data from the TNO GHG-co dataset is used. Note that the TNO GHG-co data contains several additional sectors, such as chemical industry, for which no global point source dataset was found, and where point source locations are thus limited to the EU-27+ area.

The point source data is exported as CSV file and as NetCDF file. As the point sources are not spatially located on a regular grid, the NetCDF file contains all sources into one long array, with the pollutant type as the second dimension. Relevant metadata has been included in the NetCDF file.

3.6.2 Gridded Data

3.6.2.1 Reformatting and Unit Conversion

To correctly align all gridded datasets, the coordinates were snapped to the centre of the grid cells, rounded to 2 decimals, and regridded from -180 – 180 degrees longitude and -90 – 90 degrees latitude, with 0 longitude being the prime meridian at Greenwich, and 0 latitude being the equator. The TNO-GHG-co dataset was aggregated from 0.1 x 0.05 degree to 0.1 x 0.1 degree spatial resolution.

Where needed, emission values were converted to kilotonnes (Gg) per grid cell per year (e.g. for the GFEI v.2 database, the original emission unit in Mg/year/km^2 was converted to kt/year/grid cell by multiplying by the area of the grid cell.).

For datasets that differentiated between CO_2 emissions from fossil and biogenic sources, these emission values were added together as total CO_2 emissions.

3.6.2.2 Geographical Differentiation

The area of Europe (EU-27 + 4 countries inc. Norway, Great Britain, Iceland, and Switzerland) was masked out in the other gridded datasets in order to allow the use of the TNO GHG-co dataset that was specifically designed for Europe. This was done for all sectors except shipping, agricultural soils, and oil/gas exploration. The Gridded Population of the World (GPW[13] v3) gridded country mask was used as the country mask for gridded data.

The country mask was also used to scale back landfill CH_4 emissions from the EDGAR database (swd_ldf layer) proportionally to the amount of CH_4 emissions covered by the landfills point source layer from ClimateTRACE for each country.

The gridded dataset is exported as NetCDF file with 3 dimensions: lon, lat, pollutant. The different sectors are included as data variables, as well as an additional data layer holding the summed emissions of all sectors.

3.7 Temporal Profiles

While the emission inventories for point sources and gridded emission give the total annual emission value by source or grid cell, the associated temporal profiles allow for an hourly emission value to be calculated. Each point source and each grid cell emission value are linked to a set of temporal profiles. For most sources there are 3 profiles that can be combined to calculate an hourly emission value:

- Monthly weight factor
- Weekday weight factor
- Hourly weight factor

For the residential sector, there is an additional daily weight factor available (for all 365 days in 2018) that was derived using temperature data, and that can be used to replace the combination of monthly and weekday weight factors for this sector.

For the point source emissions, the temporal profiles are linked through a temporal profile ID. For the gridded emissions, the temporal profiles are also gridded by sector and pollutant, which allows to calculate hourly emissions by grid cell, pollutant, and sector.

The main data sources used to compile the temporal profiles are the CAMS-GLOB-TEMPO profiles (v.3.1 and 3.2; Guevara et al., 2021), the older MACC temporal profiles (Denier van der Gon et al., 2011), the temporal profiles delivered alongside the $CoCO_2$ GPSDB (Guevara et al., 2023), and the monthly emission information from the ClimateTRACE data (ClimateTRACE, 2022). The exact data source used for a specific profile has been documented in the temporal profile files directly.

The level of detail in the temporal profiles varies; for some sectors, temporal profiles are defined at the country, pollutant, or even at the individual point source level, while for other sectors there is only one generic profiles for all sources. Note that in the gridded temporal profiles, the profiles for the different pollutants are in most cases identical. Also, several sectors are presented with the same, more generically defined, temporal profiles.

[13] https://sedac.ciesin.columbia.edu/data/collection/gpw-v3

The associated temporal profiles are separated into 7 files, listed in Table 3.4 and Table 3.5.

Table 3.4: Point source temporal profiles

Parameters	Monthly	Weekday	Hourly
Time steps	12	7	24
Number of sectors	8	6	6
Pollutants	Not specific	Not specific	Not specific
Unit	Weight factor (compared to average value)	Weight factor (compared to average value)	Weight factor (compared to average value)
Format	CSV	CSV	CSV
Main data sources	CAMS-TEMPO, CoCO$_2$ GPSDB, ClimateTRACE	CAMS-TEMPO, CoCO$_2$ GPSDB, MACC	CAMS-TEMPO, CoCO$_2$ GPSDB, MACC

Table 3.5: Gridded temporal profiles

Parameters	Monthly	Weekday	Hourly	Day in a year
Time steps	12	7	24	365
Number of sectors	19	19	19	1 (residential)
Pollutants	Not specific	Not specific	Not specific	Not specific
Unit	Weight factor (compared to average value)	Weight factor (compared to average value)	Weight factor (compared to average value)	Weight factor (compared to average value)
Spatial resolution	Gridded 0.1 x 0.1 degree	Gridded 0.1 x 0.1 degree	Gridded 0.1 x 0.1 degree	Gridded 0.1 x 0.1 degree
Format	NetCDF (4 dimensions: time, lat, lon, pollutant)	NetCDF (time, lat, lon)	NetCDF (time, lat, lon)	NetCDF (time, lat, lon)
Main data sources	CAMS-TEMPO, CoCO$_2$ GPSDB, ClimateTRACE	CAMS-TEMPO, CoCO$_2$ GPSDB, MACC	CAMS-TEMPO, CoCO$_2$ GPSDB, MACC	CAMS-TEMPO

4 Results

4.1 Point Source Database

In the point source database v.0.4, there are 105,208 emission locations included across 14 sectors and 170 countries (Figure 4.1). A large share of the locations are associated with the oil and gas sector. In terms of methane emissions, the biggest point source emitters (often referred to as 'super-emitters') are in the coal and oil and gas sectors (Figure 4.2). For CO_2 (Figure 4.3) and NO_X (Figure 4.4) the energy sector and iron/steel production are dominant in terms of locations and total emissions.

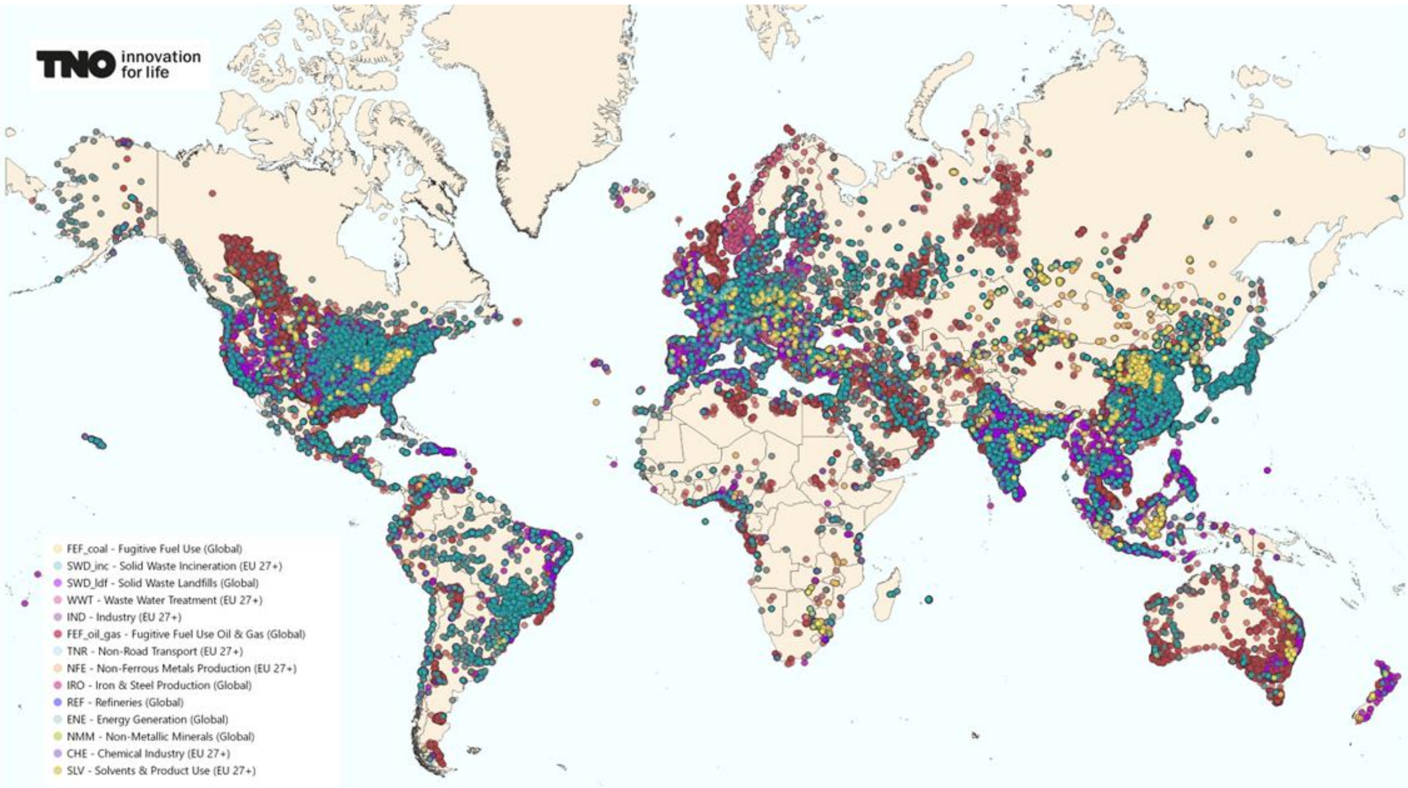

Figure 4.1: TNO GPS global coverage overview. v.0.4. Each point represents an exact set of coordinates with emissions data.

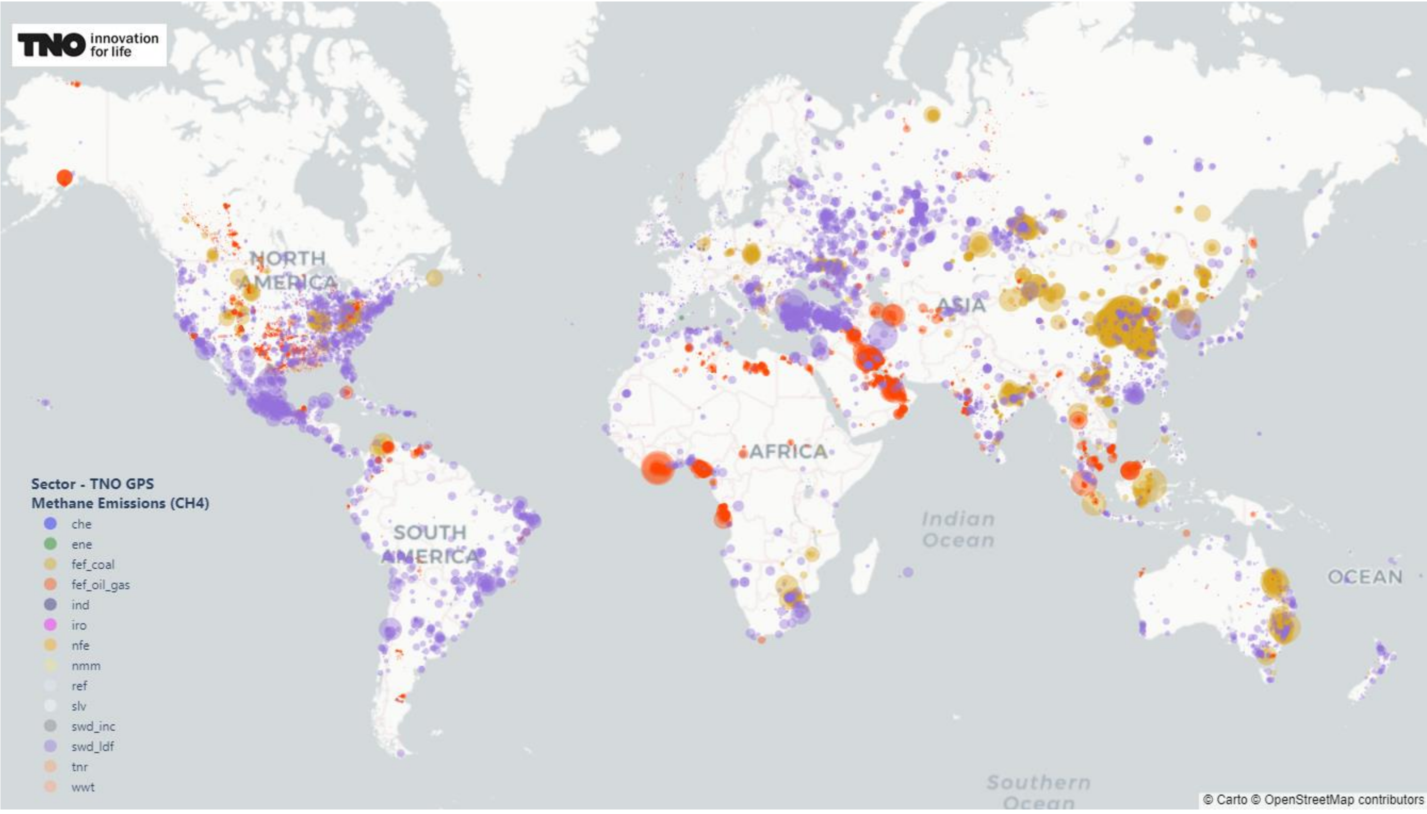

Figure 4.2: Weighted methane (CH_4) emissions for TNO GPS point source emission inventory for all sectors. Both fugitive fuel use coal and oil and gas stand out as the highest emitting sectors for methane per point source. While the majority of sources have annual emissions below 1 kt of methane per year, around two-thirds of total methane emissions are emitted by sources with >10 kt of methane emissions per year. Map from OSM, available under [Open Database License](#).

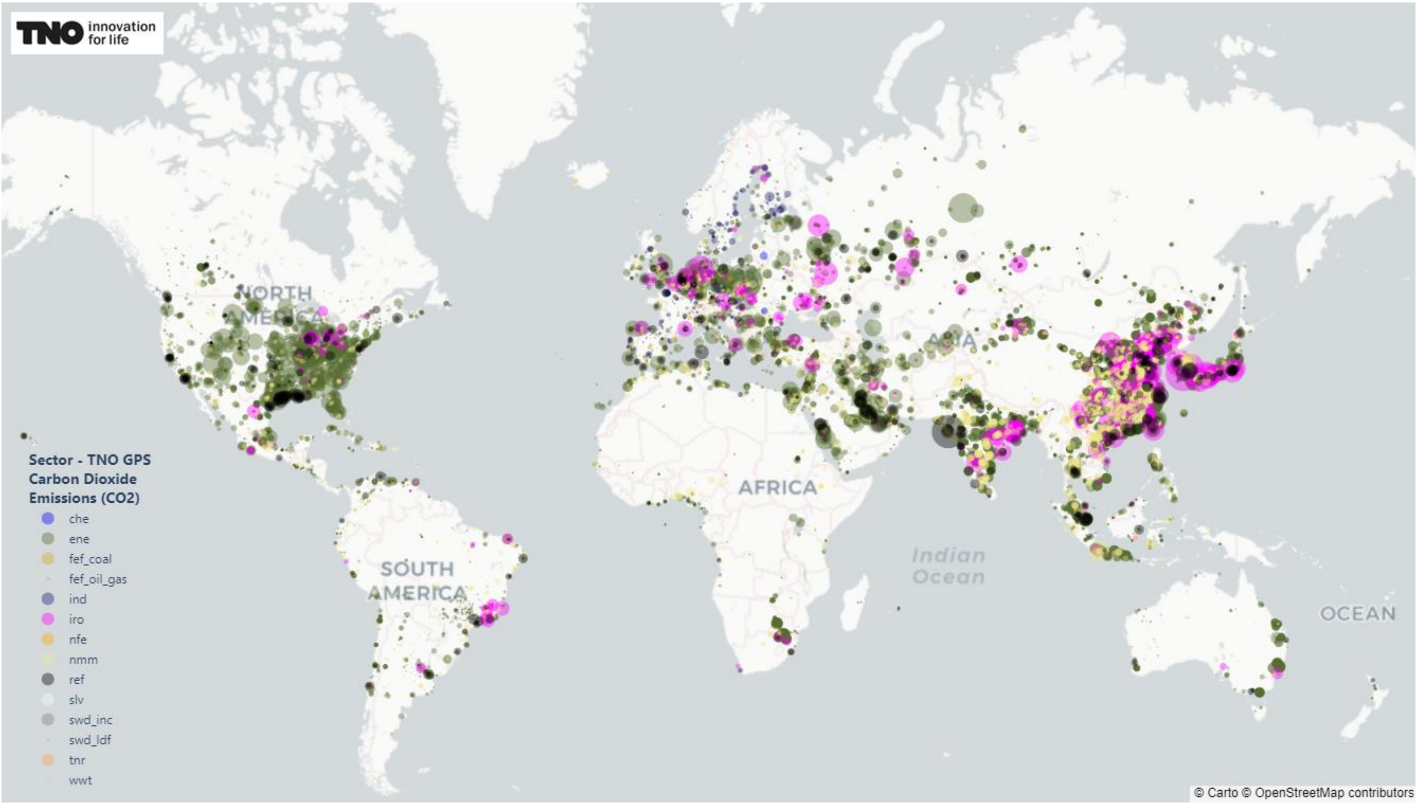

Figure 4.3: Weighted carbon dioxide (CO_2) emissions for TNO GPS point source emission inventory for all sectors. Both iron and steel production and non-metallic minerals production stand out as the highest emitting sectors globally for carbon dioxide per point source. Map from OSM, available under Open Database License.

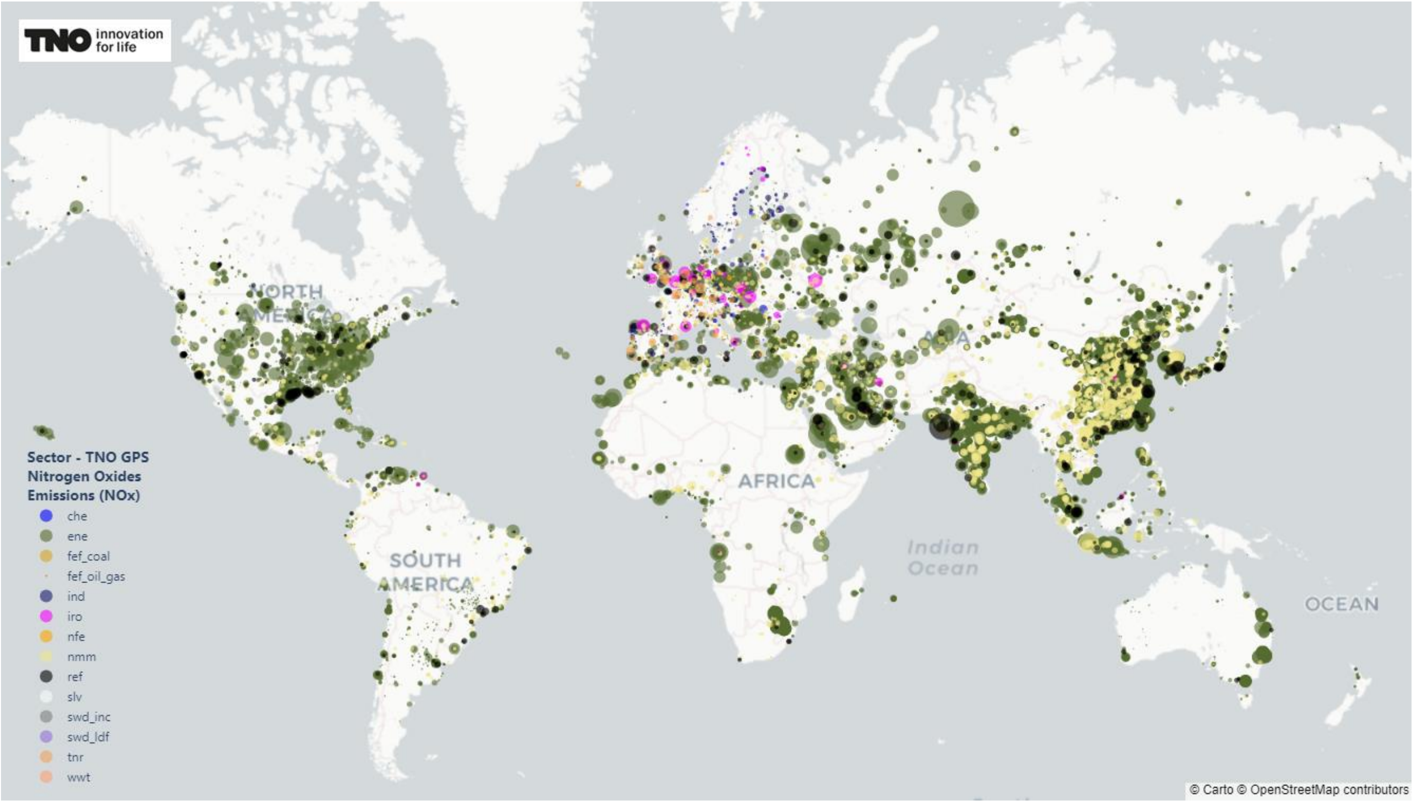

Figure 4.4: Weighted nitrogen oxides (NO_X) point source emissions in the TNO GPS point source emission inventory for all sectors. Both iron and steel production, non-metallic minerals production and the energy sector stand out as the highest emitting sectors for NO_X per point source. Map from OSM, available under [Open Database License](#).

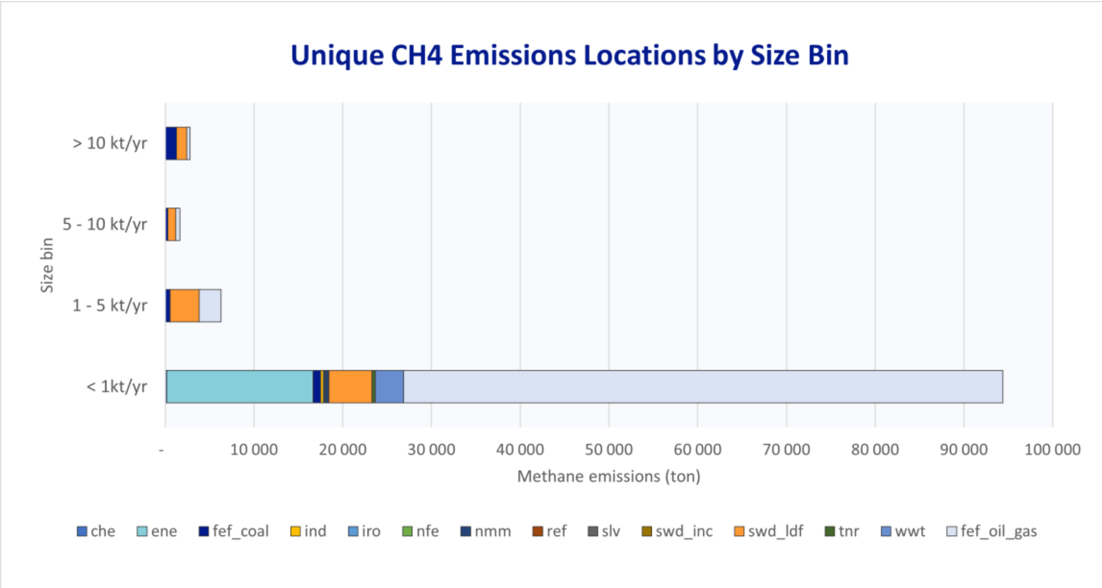

Figure 4.5: Number emission locations per emission size bin.

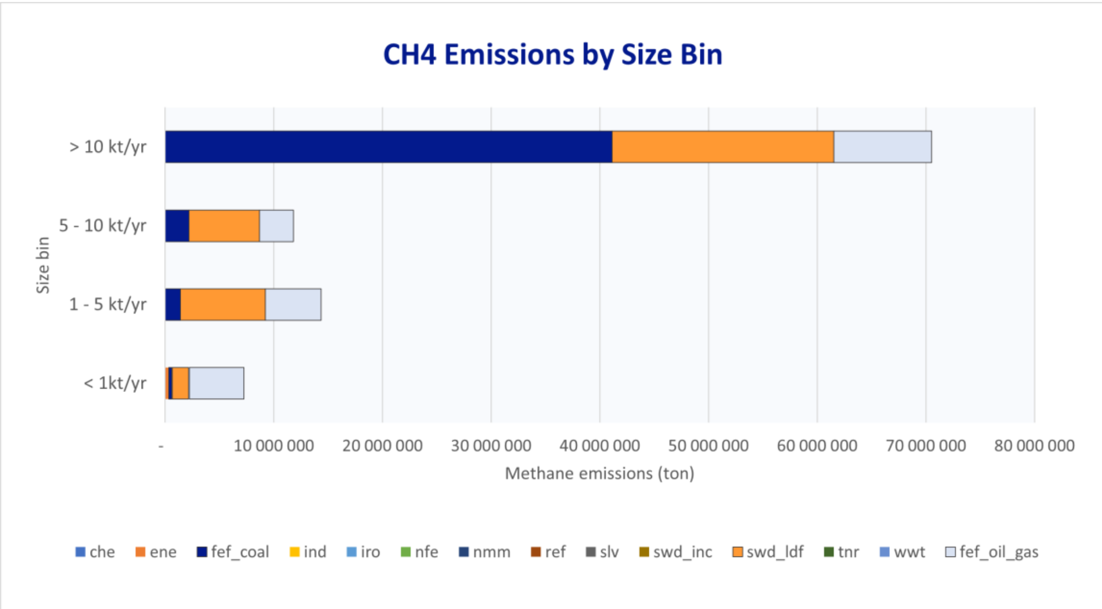

Figure 4.6: Methane emissions per emission size bin

It can be seen in Figure 4.5 and Figure 4.6 the number of point source locations is dominated by over 90,000 small sources but that the bulk of the point source emission comes from super emitters with emission above 10 kt/yr. In terms of coverage, the point source dataset includes around 23% of CH_4, 47% of CO_2 and 24% of global anthropogenic NO_X emissions assigned to individual locations (see Figure 4.7). It is expected that further improvement of the TNO GPS emission inventory could increase the coverage and allocating a larger share of emissions to individual locations. Some large emission sources, such as traffic and transport, and the residential sector, occur mostly in a diffuse manner, and are thus better represented through gridded emission data rather than point locations.

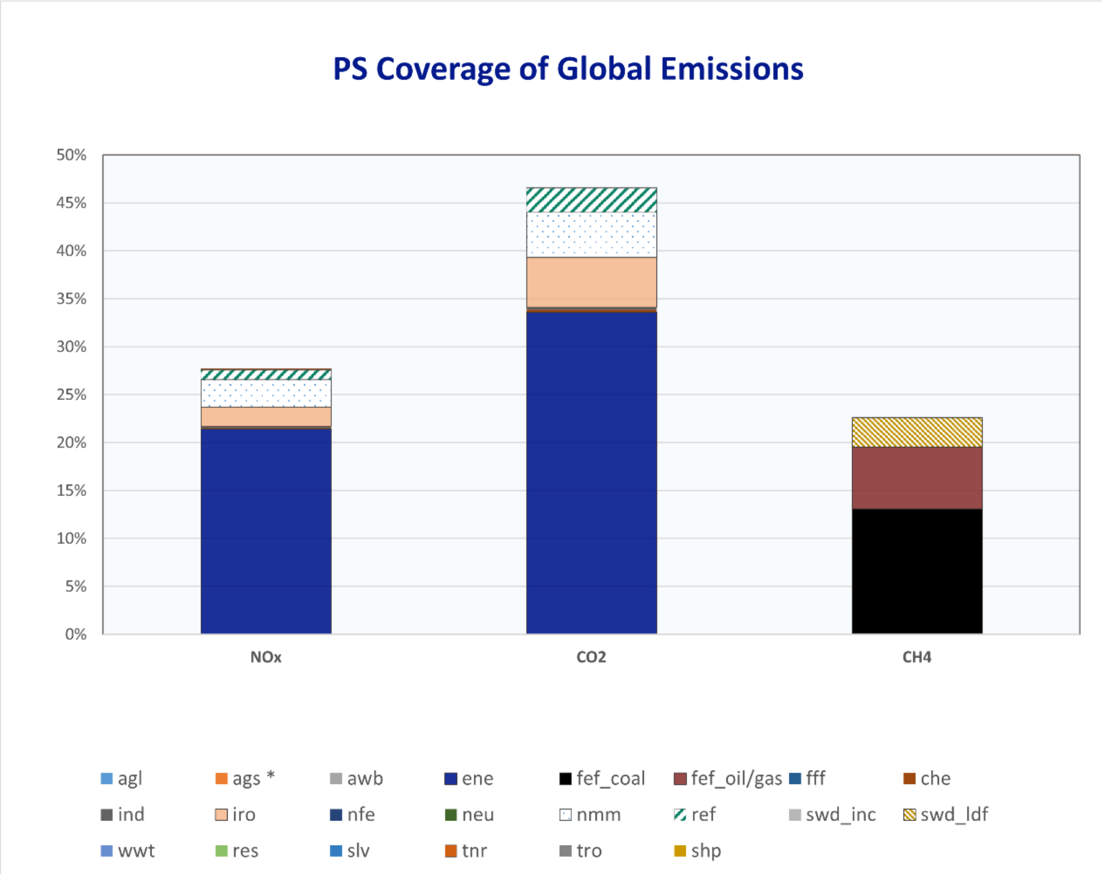

Figure 4.7 : Point source emissions by sector, relative to the global total anthropogenic emissions as reported in the EDGAR dataset. See Table 3.1 for source sector abbreviations.

4.2 Gridded Emissions

The maps below show the gridded emissions of CH_4, CO_2 and NO_X and thus represent the global anthropogenic totals minus the point source emissions.

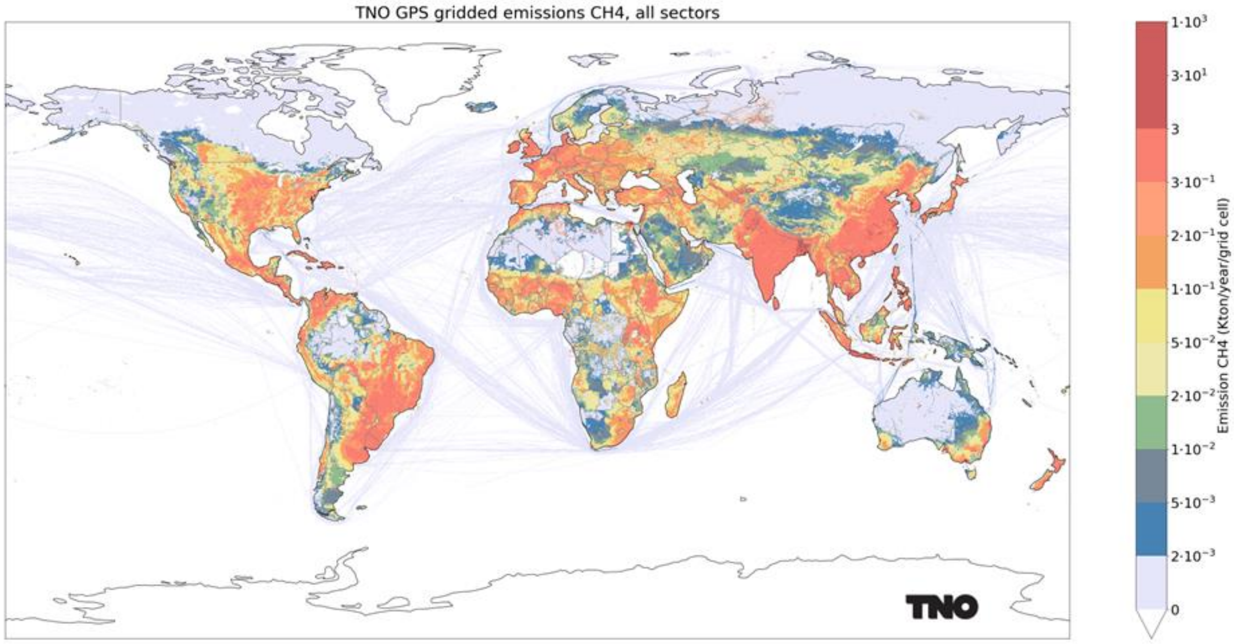

Figure 4.8: Sum of gridded CH4 emissions for all sectors in the TNO GPS gridded emission inventory v.0.4

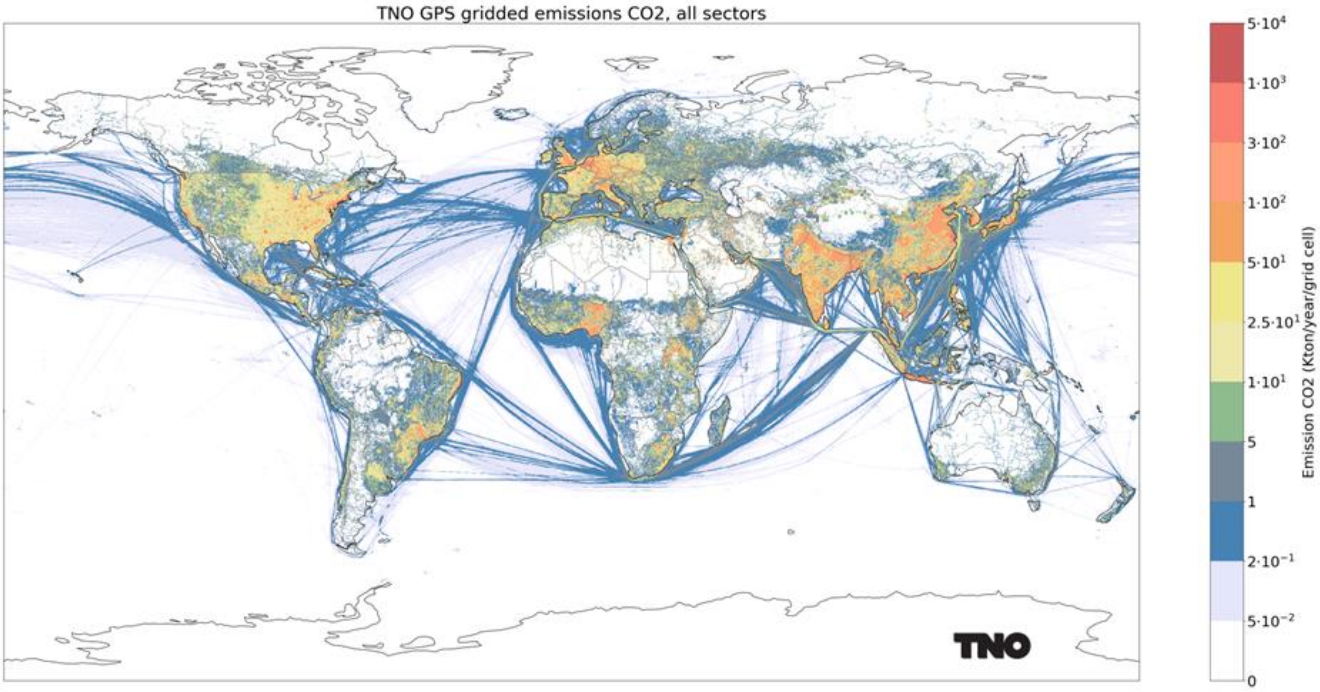

Figure 4.9: Sum of gridded CO2 emissions for all sectors in the TNO GPS gridded emission inventory v.0.4.

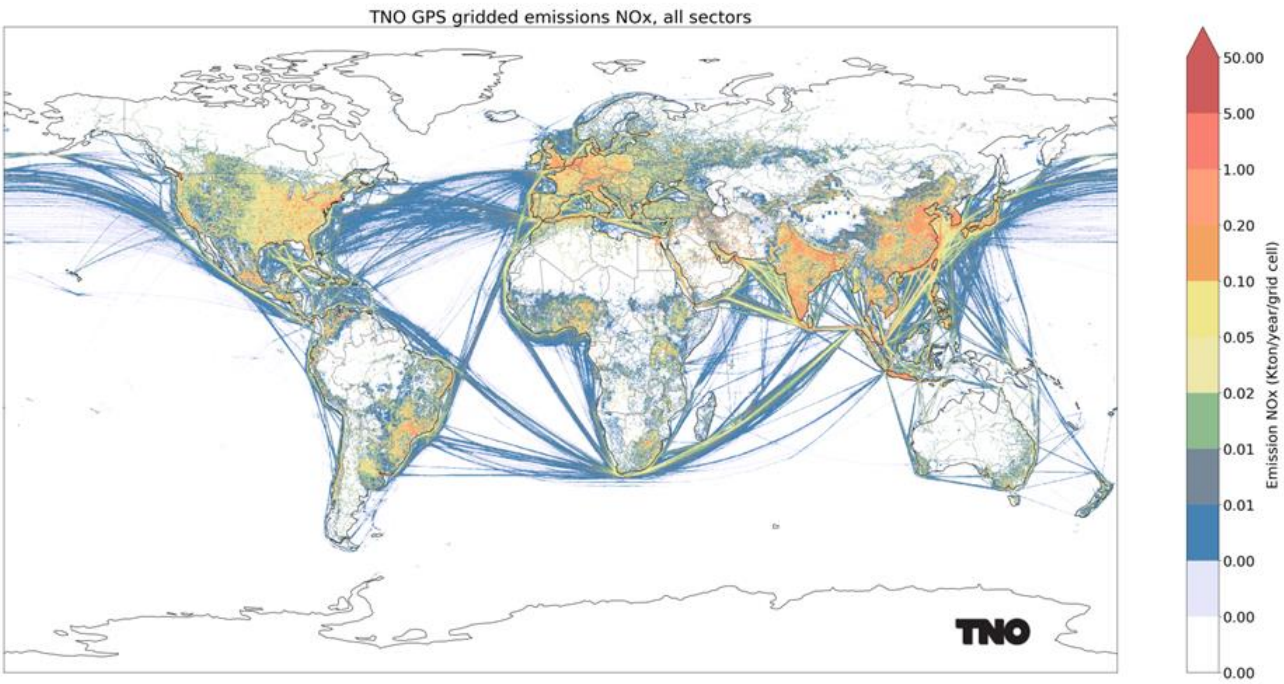

Figure 4.10: Sum of gridded NOX emissions for all sectors in the TNO GPS gridded emission inventory v.0.4.

Especially for CO_2 and NO_X the maps are very similar with the same regions being highlighted for high emissions, which can be explained by the fact that both pollutants are mostly emitted during the same combustion processes. For CH_4, the patterns are still similar, but some regions such as in the Middle East, the west of Canada, and the north-west side of South America, appear to have a more substantial contribution to CH_4 emissions, than for CO_2 and NO_X.

5 Discussion

5.1 State-of-the-art Point Source Atlas

In order to support the TANGO ESA Scout mission, prior knowledge of locations, emissions, sectors of importance as well as uncertainty is key to mission development. As such, TNO GPS, provides a state of the art global point-source emissions inventory. This allows the TANGO science team to make a quantitative assessment of the added value TANGO will bring in terms of point sources it can monitor and what share of global emissions these will represent. By providing, more than 108,000 data points on the globe, covering points from Brazil to Senegal, the USA, China, or the Netherlands, we ambition to showcase the most up-to-date point source inventory for the globe whilst progressing towards continuously integrating the latest science such as satellite-derived plume retrievals for both new points and data validation.
The strength of the TNO-GPS dataset also lies in the use of expert knowledge at TNO and a track record of constructing regional emissions inventory such as under the Copernicus programme (CAMS-REG (Kuenen et al., 2022)) or the TNO-GHG co dataset used in Horizon Europe projects such as VERIFY, CoCO_2, CORSO and now TNO GPS. As mentioned in 3.3.1, this dataset stands out with its sector and location specific greenhouse gas information for Europe and includes sectors such as the chemical industry or solid waste incineration which are not present in many global datasets at the moment. Therefore, this leads to a high coverage of point sources in the European domain and confidence in the accuracy.

5.1.1 Supporting TANGO

With its point and stare infrastructure, the TANGO satellite will be able to precisely target locations of interest. In order to know where to look, the provision and constant updating of the GPS data product in support of the mission can play role in quickly determining where, how, when, how often, and what to look for in emissions. By bridging the gap between inventory producers, open data platforms and plume satellite data, the latest science has and will be incorporated to provide up-to-date and state of the art information. The TANGO mission team can choose to give e.g. CO_2 priority over CH_4 and/or give super emitters priority over large numbers of small point sources.

5.2 Limitations

As the TNO GPS emission inventory represents a preliminary version working towards a comprehensive inventory of global emission sources for CO_2, CH_4 and NO_X, there are limitations with regards to the data and methodology, which result in uncertainties in both locations and emission rates. The main limitations are discussed below.

5.2.1 Coverage of Point Source Sectors

Several sectors which are known to be dominated by point source emissions have not yet been included in the point source inventory for lack of appropriate data. There is currently limited global coverage for landfills, although this will be further updated in a future version, as the latest ClimateTRACE update on global landfill coverage as of December 2023 has more data points. A concern and challenge, however, is how to validate the associated reported emissions. Other industrial facilities such as aluminium production, chemical industry and paper/pulp production are also missing due to lack of data on exact locations and emission rates for these sectors.

5.2.2 Point Source Emission Rates

Point source emission data has been derived using various methodologies and relying on multiple assumptions or generalizations, and thus may have a larger degree of uncertainty. Missing NO_X emission data for the iron/steel, cement and refinery sectors have been estimated through average emission ratios for known European plants. Also, the third-party datasets used may rely on numerous assumptions and generalizations. For example, emission rates for power plants in the $CoCO_2$ dataset have been estimated based on country-level energy statistics and power plant capacities. Non-CO_2 emissions are derived through emission ratios from the IIASA GAINS model, which may differ between individual power plants. The sector with possibly the largest uncertainties in locations and emission rates is the oil and gas sector, where an experimental methodology was applied to combine three existing datasets that each have their own limitations. An important point is that CH_4 emission from the oil and gas sector is associated with leakage and/or accidents. These emission causes are not necessarily proportional to production. Thus, (statistical) activity data may not be a good predictor for total emissions.

5.2.3 Temporal Representativeness

While data for 2018 was used where available, in some cases emission data for a different year than 2018 was used. For example, the GFEI dataset for 2019 was used for the oil/gas production sector in the gridded dataset. Depending on the sector, smaller or larger variations between years are expected. Temporal profiles are an important intermediate step when there is a need for comparing modelled pollutant concentrations with observations. The temporal profiles which can be used to break down annual emissions to hourly emission rates have obvious and considerable uncertainties, as generalizations may be made between regions and sectors.

5.2.4 Completeness of Global Emission Total

With regard to completeness of the global emission total there are also several limitations. To avoid double counting, some gridded sector layers were completely replaced by a point source layer, even though the point source layer was known to be incomplete. This is most notably the case for the non-metallic minerals (replaced by cement) and the energy sector (where small power plants, some auto producer plants, and heat-only plants may be missing from the point source data).

While the sector definition and aggregation differ between different datasets used, building on our in-house knowledge of emission inventories, these were made as uniform as possible. However, there may not always be a direct 1:1 match.

5.2.5 Spatial Representativeness

The use of a country mask to uniformly scale back or remove emissions from the global grid may lead to some inaccuracies and artefacts. For example, as the spatial distribution underlying the landfill layer in the EDGAR dataset will be different from the landfill data from ClimateTRACE, uniformly scaling back the EDGAR landfill layer may leave substantial emissions at known landfill sites, with the addition of the ClimateTRACE data then leading to an overestimate of local emissions.

The majority of datasets used are based on global inventories, often with emission estimates determined by proxies and lacking regional specificity. For example, it was found that EDGAR data showed energy sector emissions in Central Africa, especially Chad and DRC, which were spatially scarce in $CoCO_2$ data point sources. This was then reflected in the countries' emission totals for the energy sector where EDGAR displayed higher emissions than the point sources emission total.

5.3 Validation and Future Improvements

As a proof of concept, the current TNO GPS emission inventory has not been directly validated through emission measurements or observations. Future efforts will focus on validation of locations and associated emission rates through the use of currently available measurement data, both in-situ, ground campaigns, flights and satellite data (e.g. CarbonMapper, SENTINEL, TROPOMI, NASA VIIRS). Even without accurate quantification of emission rates, such a validation will help confirm if the sources that are included are indeed facilities that are likely to have substantial emissions that can be targets for future monitoring through the TANGO mission.

In addition to the efforts in data validation, the TNO GPS emission inventory should be further improved and expanded. This requires a more complete coverage of locations both within currently included sectors, and for sectors which are not currently included in the point source data, such as wastewater treatment and paper production. Data may be gathered from additional or updated data sources, such as CarbonMonitor-GRACED, E-PRTR, ClimateTRACE, the Global Carbon Project and others.

For regions that are under-represented in our datasets, local inventories may provide more accurate emission data than the currently used datasets. For example, the DACCIWA dataset for the African continent (Keita et al., 2021) may provide more reliable data than EDGAR or CAMS-GLOB for this region and can be integrated in further developments.

6 Conclusion

With continuous advances in the use of earth observation techniques, bridging the gap between emission inventories and satellite observations is of the utmost importance to improve our understanding of large emission sources and support effective emission mitigation. Through the combining, cross-checking, comparing and gap filling of a selection of comprehensive and up-to-data emission datasets, as well as TNO's own data, the TNO GPS emission inventory version 0.4 has been compiled as a step towards this goal.

The TNO GPS emission inventory combines more than 10 datasets across 14 sectors at exact facility locations for more than 108,000 substantial emission sources in 170 countries for CO_2, NO_X and CH_4. In this version 0.4, the point source dataset inventory includes between 23% and 47% of the total reported global anthropogenic emissions, with the highest coverage for CO_2. The biggest contributing sectors include the power generation sector for NO_X and CO_2, and fossil fuel production including oil and gas, as well as coal mining and solid waste landfill for CH_4.

The current version of the TNO GPS emission inventory is still lacking coverage of point source emission locations in several sectors such as the chemical and paper industries, as well as having limited coverage of landfills. There are also significant uncertainties related to the emission rates reported for individual sources, which is precisely why highly sensitive satellite observations such as those provided by the TANGO mission are needed.

The current push towards increased methane source attribution and facility-level detection has recently led to the publication of new open source emission datasets which will be included in future work to achieve better coverage of sectors such as landfills and wastewater treatment.

6.1 Outlook

The TNO GPS emission inventory initiative was started to support the TANGO satellite mission. A first role is to provide a prior emission dataset that can be used to assess what TANGO may be capable of detecting, both in terms of number of sources as well as share of global emission per GHG. It will also support future targeting strategies and allows prioritization by gas and/or by expected emission strength. TNO-GPS is expected to evolve and integrate the feedback from (satellite) observations in the near-future to further improve the completeness, accuracy and reliability of this version's point source and gridded emissions inventory. The TNO GPS emission inventory lays the foundation for more integration of satellite data into emission inventories through a feedback loop for uptake of new satellite-based results into the dataset. It is envisaged that an improved and partially validated version 1.0 will be produced in 2024.

Moving forward, integration into the TANGO operational pipeline would allow for continuous integration of new plume retrieval data from TANGO into GPS in order to reduce uncertainty and increase accuracy and precision of emission data whilst putting (super) emitters back on the map.

7 Documentation & Licenses

7.1 Licenses

The datasets used to compile the TNO GPS emission inventory list the following licenses:

- All ClimateTRACE data is freely available under the Creative Commons Attribution 4.0 International Public License, unless otherwise noted. All potential changes made to ClimateTRACE data have been mentioned in the above document.
- All Global Energy Monitor data is freely available under the Creative Commons Attribution 4.0 International Public License, unless otherwise noted. All potential changes made to GEM data have been mentioned in the above document.
- All GFEI data is freely available under the Creative Commons Attribution 4.0 International Public License, unless otherwise noted. All potential changes made to GFEI data have been mentioned in the above document.
- All GPW data is freely available under the Creative Commons Attribution 4.0 International Public License, unless otherwise noted. All potential changes made to GPW data have been mentioned in the above document.
- All OGIM data is freely available under the Creative Commons Attribution 4.0 International Public License, unless otherwise noted. All potential changes made to GFEI data have been mentioned in the above document.
- All GOGI data is freely available under the Creative Commons Attribution 4.0 International Public License, unless otherwise noted. All potential changes made to GFEI data have been mentioned in the above document.
- All Open Street Map data is available under the Open Database License.
- All other datasets used have no mentioned license and will be used as such.

7.2 Dataset Documentation

Documentation for the datasets used to compile the TNO GPS emission inventory can be found with the following links:

- CAMS-GLOB-ANT
- EDGAR
- TNO-GHG-co
- $CoCO_2$ GPSD
- GEM
- Scarpelli et al. (2022)
- ClimateTRACE
- OGIM
- GOGI
- Open Street Map

7.3 Data Access

Data in NetCDF and CSV format are available from the TNO FTP server using specified credentials available upon request and following conditions of data use. For further questions, comments, requests or recommendations, and access to TNO GPS emission inventory please contact the following:

- Stijn Dellaert – stijn.dellaert@tno.nl
- Emma Schoenmakers – emma.schoenmakers@tno.nl
- Hugo Denier Van der Gon - hugo.deniervandergon@tno.nl

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