High resolution scenarios of CO_2 and CO emissions

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1 Executive Summary

High resolution gridded emission inventories have significant added value for modelling at the local/city level, allowing larger concentration gradients due to emission being averaged over a smaller area. The local influence of relatively small but diffuse emission sources becomes better visible at higher resolutions and is crucial for the verification of emission inventories using in-situ or satellite observations.

This document reports on progress and current status regarding the “High resolution scenarios of CO_2 and CO emissions” developed within CHE WP4. The scope of WP4 “Coordinating Efforts on Attributing CO_2 emissions from in-situ measurements” is to explore the practical implications of distinguishing between CO_2 fluxes from fossil fuel and biofuel combustion.

This deliverable report describes the compilation of the high resolution scenarios, which are the product of combining a high resolution gridded emission inventory and a consistent assessment of associated uncertainties. The dataset covers the GHGs: CO_2 (distinguishing between fossil fuel CO_2 and biofuel CO_2), methane (CH_4) and key co-emitted species that may be used as tracers: CO (also distinguishing between fossil and biofuel), nitrogen oxides (NOx) and non-methane volatile organic compounds (NMVOC).

The features of the high resolution scenarios include:

- High resolution (1/60° x 1/120°; ~1x1km) regional gridded emission inventory for a zoom domain in Europe (-2° W – 19° E, 47° N – 56°N), with point sources (industry and power plants) at their actual location.
- Emission inventory is consistent with TNO gridded emission inventory at 1/10° x 1/20° (~6x6km).
- For CO_2 and CO emissions, a distinction is made between emissions from fossil fuel and from biofuel combustion.
- Statistically coherent assessment of associated uncertainties in activity data, emission factors, spatial and temporal distribution.

The high resolution inventory described is used in WP2 for nesting the Berlin high resolution spatially distributed emissions from the Berlin Senate (see CHE D 2.3; Denier van der Gon et al, 2019) to facilitate the WP2 modelling case study over Berlin.

2 Introduction

2.1 Background

High resolution emission inventories have significant added value in modelling at the local/city level, allowing larger concentration gradients due to emission being averaged over a much smaller area. Similarly, this is valuable when comparing modelled concentrations with local ground observations. The local influence of relatively small but diffuse emission sources becomes much better visible at higher resolutions. Especially when comparing modelled concentrations with local atmospheric measurements, emission data that is more accurately distributed in space and time allows for more reliable analysis.

To contribute to the CHE WP4 goal of attribution of CO_2 emissions, the TNO high resolution (HR) gridded inventory distinguishes between CO_2 emissions from fossil fuel and biofuel combustion.

The National Inventory Report (NIR) of countries includes an uncertainty assessment for the activity data and for the emission factors for different emission sources. What lacked was a consistent manner to translate these uncertainties to a spatial emission grid, incorporating also the uncertainty in the spatial and temporal distribution of emissions. This is especially important when comparing either ground based or satellite observations with modelled emissions. What discrepancies are within the bounds of the uncertainty range and which can only be explained by errors in the modelling or observation? Moreover, in an inversion framework the quantified uncertainties are essential to constrain the “solution space” of the framework.

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverable

This deliverable report describes the compilation of the HR gridded emission inventory and generating associated uncertainty statistics which are applied to create a set of emission scenarios. Furthermore, a short overview of the results will be presented.

2.2.2 Work performed in this deliverable

TNO has compiled a HR gridded emission inventory that includes CO_2, CO, CH_4 and NOx emissions covering anthropogenic activities over a full year (2015) for a spatial domain in Europe. This entailed creating or acquiring high resolution versions of spatial distribution maps for different sectors and fuels (chapter 3). The resolution is 36 times higher than the previous TNO gridded emission inventory for Europe. The emission inventory serves as input for some of the work in WP2, where emission data for the Berlin area, provided by the Berlin Senate, are nested in this HR emission inventory to facilitate a modelling case study over Berlin. TNO also created a set of associated uncertainty data by using uncertainty estimates listed in the National Inventory Reports (NIR) of the respective countries (chapter 4). Using this uncertainty data, a set of 10 HR emission grids has been produced that illustrate the uncertainty range of the inventory (chapter 5).

2.2.3 Deviations and counter measures

The task description notes that a high resolution (~1km x 1km) emission inventory for the EU-28 + CHE and NOR will be compiled. Due to the high data processing requirement for producing such a high resolution inventory, a smaller spatial domain (lon – lat, -2° W – 19° E, 47° N – 56°N) was chosen for the emission inventory (see Figure 1). The modellers/intended users of the emission inventory have been consulted to verify that HR inventory for the proposed domain would be fit for purpose. The domain completely covers several EU-28 countries (DEU, NLD, BEL, LUX, CZE) and also covers large parts of GBR, FRA, DNK, AUT and POL, and covers a small area of CHE, ITA, SVK and HUN. It was ensured that the domain also covers all areas that are of specific interest to other work packages in CHE and VERIFY projects (i.e. Berlin area and Rhine valley).

Following this change in the domain, the associated uncertainties have been assembled only for the countries in this domain, so as to create a complete set corresponding to the emission inventory.

Figure 1. Spatial domain of the high resolution (~1km x km) emission inventory

3 Regional high resolution inventory for CO_2 and CO

3.1 Main characteristics

This chapter describes the first version of the TNO greenhouse gas and co-emitted species HR gridded emission inventory (GHGco high resolution v.1.0) at the resolution of 1/60º x 1/120º (~ 1 km x 1 km) for the year 2015. The dataset covers a limited spatial domain in Europe (-2° W – 19° E, 47° N – 56°N; see Figure 1) for the GHGs: CO_2 (distinguishing between fossil fuel CO_2 and biofuel CO_2), methane (CH_4) and key co-emitted species that may be used as tracers: CO (also distinguishing between fossil and biofuel) and nitrogen oxides (NO_x). This chapter briefly describes the methodology followed and presents the resulting emission inventory for the domain.

The TNO GHGco v1.1 emission inventory, created in WP2 (Denier van der Gon et al., 2019), is used as a basis for the HR inventory. The GHGco v.1.1 gridded emission inventory (1/10° x 1/20° - ~6x6 km) is further processed by applying a number of sector-specific high resolution spatial distribution maps. The resulting emission grid is fully consistent[1] with the TNO GHGco v.1.1 emission grid at 1/10° x 1/20° resolution.

The TNO GHGco high resolution v.1.0 emission inventory will be made available to project partners through the project FTP site and/or a TNO link.

Table 1. Characteristics of the TNO GHGco v.1.0 high resolution emission inventory

TNO GHGco v.1.0 high resolution emission inventory	
Air pollutants	CO_ff, CO_bf, NOx
Greenhouse gases	CO_2_ff, CO_2_bf, CH_4
Resolution	1/60° x 1/120° (longitude latitude, ~ 1x1 km over central Europe)
Period covered	2015 (annual emissions)
Domain	-2° W – 19° E 47° N – 56°N
Sector aggregation	GNFR (A to L), with GNFR F (Road Transport) split in F1 to F4 (total 16 sectors)
Emission unit	kg (both in CSV and NetCDF files
Countries	Complete: DEU, NLD, BEL, LUX, CZE Partially: GBR, FRA, DNK, AUT, POL, CHE, ITA, SVK and HUN

3.2 Emission data

The emission data input for the HR inventory were taken from the TNO GHGco v.1.1 gridded emission inventory, created in WP2.2 and described in detail in CHE deliverable 2.3. The emission input data distinguishes different emission sources, each assigned a specific high resolution spatial distribution grid.

Default temporal and emission height profiles matching the GNFR[2] sectors are available from TNO through the CAMS81 project.

[1] Meaning that adding together 36 smaller 1/60º x 1/120º grid cells will add to the same emission value as the larger 1/10° x 1/20 grid cell at the same location

[2] Aggregated Nomenclature For Reporting, aggregated sector description for emission reporting

3.3 Spatial distribution

3.3.1 Overview

Table 2 gives an overview of the high resolution distribution maps that were used to make the emission inventory. These maps were compiled or acquired at the required resolution for WP4.

Table 2. High resolution spatial distribution maps

Distribution grid	Source type	Sources	Original resolution	Processing for CHE WP4
Airports	Point	Eurostat	N/A	-
Waste water treatment	Point	Waterbase UWWTP dataset	N/A	-
Power plants	Point	EPRTR, LCP and CARMA datasets	N/A	-
Large industrial plants	Point	EPRTR	N/A	-
Industrial sources	Point	TNO Point Source map	N/A	-
Industrial areas	Area	CORINE land cover database v. 2012	100 x 100 m	Re-gridding to 1/60º x 1/120º
Arable land	Area	CORINE land cover database v. 2012	100 x 100 m	Re-gridding to 1/60º x 1/120º
Rice fields	Area	CORINE land cover database v. 2012	100 x 100 m	Re-gridding to 1/60º x 1/120º
Gas lines	Area	TNO	1/8º x 1/16º	Re-gridding to 1/60º x 1/120º
Inland shipping	Area	FMI AIS based dataset	Received as 1/60º x 1/120º	Assign some additional areas to inland shipping
International shipping	Area	FMI AIS based dataset	Received as 1/60º x 1/120º	Assign some additional areas to international shipping
Livestock	Area	FAO	Received as 1/120º x 1/120º	Re-gridding to 1/60º x 1/120º
Population	Area	LandScan population density map 2015	Received as 1/120º x 1/120º	Re-gridding to 1/60º x 1/120º and
Rail	Area	Transtools	1/8º x 1/16º	Re-gridding to 1/60º x 1/120º
Road transport	Area	Open transport map & Open street map	N/A	Creating spatial distribution map
Wood use	Area	TNO wood use map	1/8º x 1/16º	Re-gridding to 1/60º x 1/120º

3.3.2 Processing

In the following paragraph, the specific processing that was performed to create or adapt the spatial distribution maps is explained in detail. In addition to the processing steps described in Table 2 and in the following paragraphs, each spatial distribution map was normalised to the spatial domain. That means that the shares of grid cells or point sources in each distribution map were made to add up to 1 within each country. This ensures that, for countries that are only partially covered by the HR spatial domain, the emission totals in the covered area are fully consistent between the normal- and HR emission inventories.

Since the spatial distribution maps containing point sources at their exact location required no further processing beyond the normalization mentioned earlier, these are not discussed in further detail.

3.3.2.1 Industrial areas, arable lands and rice fields

These three spatial distribution maps were created by adapting the 2012 version of the CORINE land cover database[3]. The CORINE database has a native resolution of 100 x 100 meters, which is higher than the target resolution. These three maps (arable land, industrial areas and rice cultivation) were gridded to the target resolution by adding together, for each HR grid cell, the shares of all CORINE grid cells that fall within this HR grid cell (based on the coordinates of the centre of the CORINE grid cells).

3.3.2.2 Gas lines

The original map is based on the locations of high pressure natural gas transmission pipelines according to Remme et al. (2008). Leakage emissions are distributed uniformly across pipeline trajectories. The original map has a resolution of 1/8º x 1/16º. It was decided to re-grid this original map rather than to create a new HR map. To re-grid this map to the target resolution, each grid cell and its value was divided in 225 (=15*15), creating a temporary grid with 1/120º x 1/240º resolution, which was then merged to a 1/60º x 1/120º grid.

3.3.2.3 Inland shipping and international shipping

For international and inland shipping, the distribution is based on AIS data and developed by FMI using their STEAM model (Jalkanen et al., 2016). The product is made available partly under the FMI-TNO collaboration under the CAMS81 project. The STEAM emissions are separated in sea shipping and inland shipping, by application of a land-sea mask. We labelled all sea emission as international shipping. In addition to this, a selection of the inland shipping was labelled international too. This was the emission over the Rotterdam, Antwerp and London harbour areas, the Western Scheldt, the North-East sea canal and Elbe river. The remainder of the inland emission was further processed as is.

The current shipping distribution is based on a consistent AIS-based map for the year 2016, which is used as the best approximation for 2015.

3.3.2.4 Livestock

The FAO livestock density maps[4] were acquired at a resolution of 1/120º x 1/120º. The grids were merged to 1/60º x 1/120º grids.

3.3.2.5 Population

For population density, which is used as the default distribution for many sectors the population map for 2015 is used and further processed. Urban and rural population maps have been created from the population density map by comparing the population density in each cell, with > 250 inhabitants/km^2 categorized as urban and =< 250 inhabitants as rural. This map was acquired at a resolution of 1/120º x 1/120º and merged to a 1/60º x 1/120º grid.

3.3.2.6 Rail

Railway location and traffic intensities have been taken from the Transtools model (JRC, 2008). This map was originally in a resolution of 1/8º x 1/16º. It was decided to re-grid this

[3] https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012
[4] http://www.fao.org/livestock-systems/global-distributions/en/

original map rather than to create a new HR map. To re-grid this map to the target resolution, this map was re-gridded in the same way as the gas lines gridded map.

3.3.2.7 Road transport

The emission from road transport is estimated bottom-up by the product of traffic intensity and emission factors. For the traffic data, we used Open Transport Map (OTM) and -where no OTM data is available - Open Street Map (OSM). Both datasets specify road geometries per road type (e.g. motorway or urban). For many road sections, OTM provides traffic intensities as well. For all road sections where no road data is available, a regression function was applied, which gives a relation between traffic emission and population density (from Landscan). The vehicle emission factors are specified per road type, vehicle type and country. These emission factors resulted from the weighted sum of the fleet composition (Copert/Emisia, 2018[5]) and emission factors per fuel type, technology and capacity (Samaras, 2012).

3.3.2.8 Wood use

For emissions from residential wood combustion TNO has developed a dedicated distribution map (see e.g. Kuenen et al., 2014). This map is based on the premise that fuel wood is often sourced locally and that the presence and use of wood combustion appliances is not uniform across various types of houses (e.g. free standing single family vs. high rise apartments). Based on population density classes a wood demand function is assumed, which is overlaid by a wood supply function that is based on sustainable local wood production rates. As a result, wood use is often limited by supply in more densely populated areas while in other regions it is limited by demand.

This map was originally in a resolution of 1/8^o x 1/16^o. It was decided to re-grid this original map rather than to create a new HR map. This map was re-gridded in the same way as the gas lines gridded map.

3.4 Results

The emission inventory contains the 2015 emissions by GNFR sector. For CO_2 and CO a distinction is made between emissions from fossil fuel and biofuel combustion. The figures below show the results for a number of sector-pollutant combinations.

[5] https://www.emisia.com/utilities/copert-data/

Table 3. GNFR Sector explanation.

GNFR_Category	GNFR_Category_Name
A	A_PublicPower
B	B_Industry
C	C_OtherStationaryComb
D	D_Fugitives
E	E_Solvents
F	F_RoadTransport
G	G_Shipping
H	H_Aviation
I	I_OffRoad
J	J_Waste
K	K_AgriLivestock
L	L_AgriOther
F1	F_RoadTransport_exhaust_gasoline
F2	F_RoadTransport_exhaust_diesel
F3	F_RoadTransport_exhaust_LPG_gas
F4	F_RoadTransport_non-exhaust

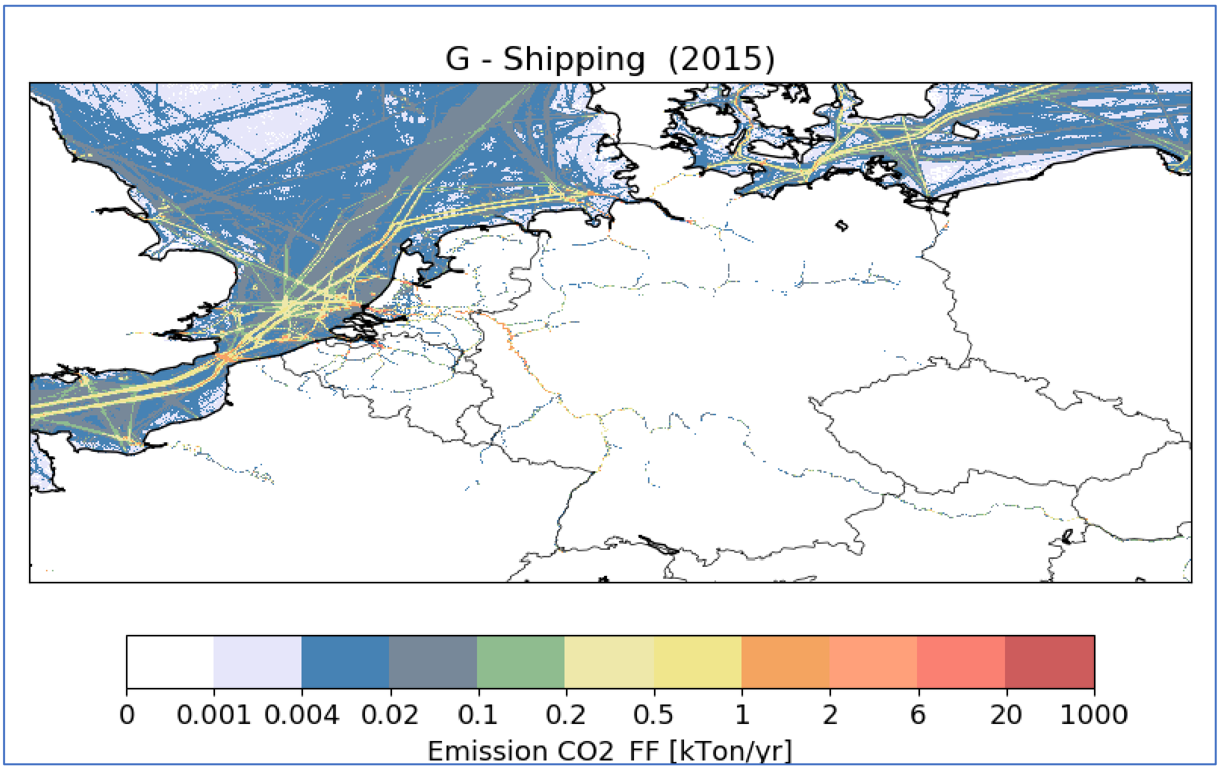

Figure 2. CO_2 Emission from fossil fuel combustion in shipping

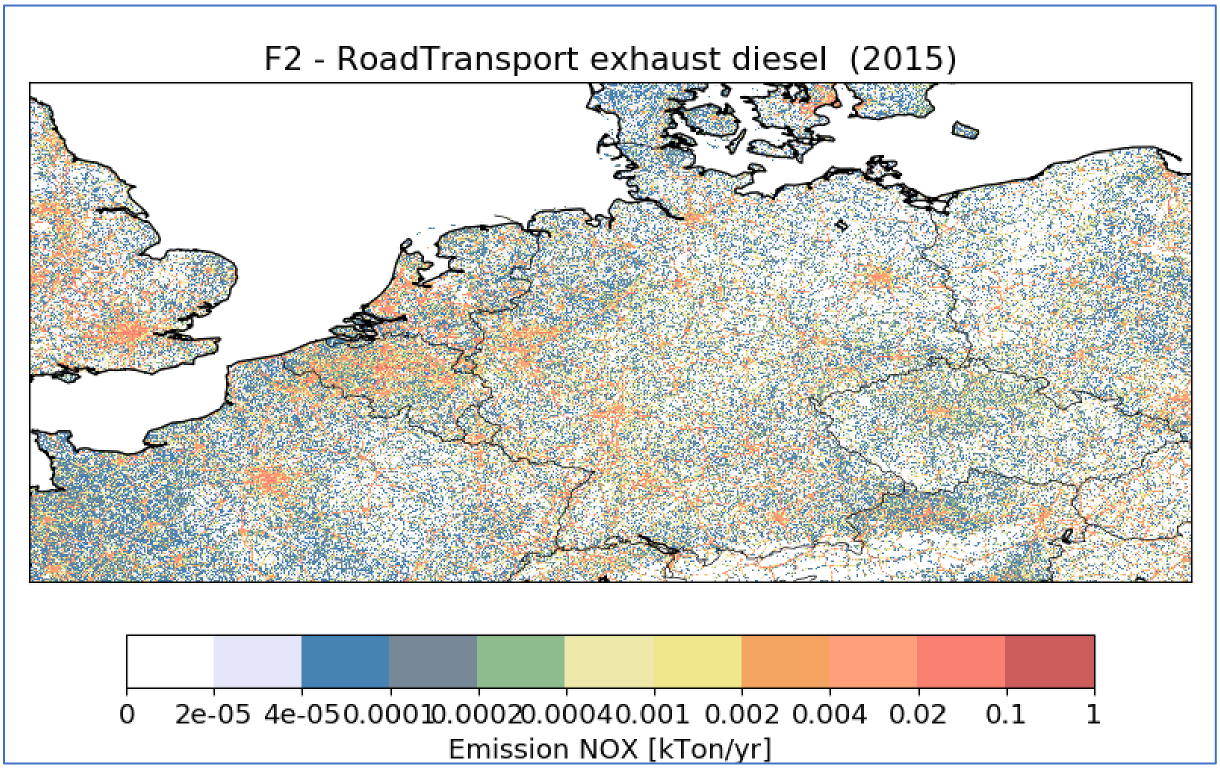

Figure 3. NOx emissions from diesel fuelled road transport

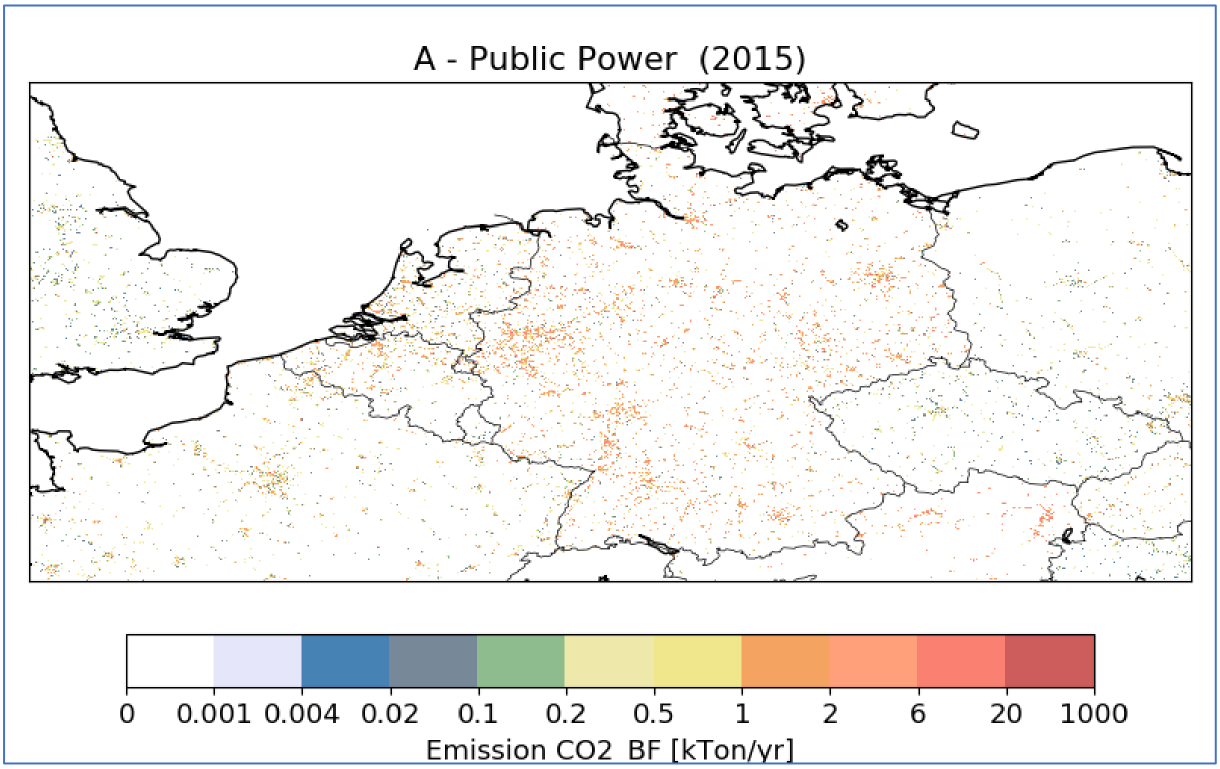

Figure 4. CO_2 emissions from biofuel combustion in the public heat and power sector

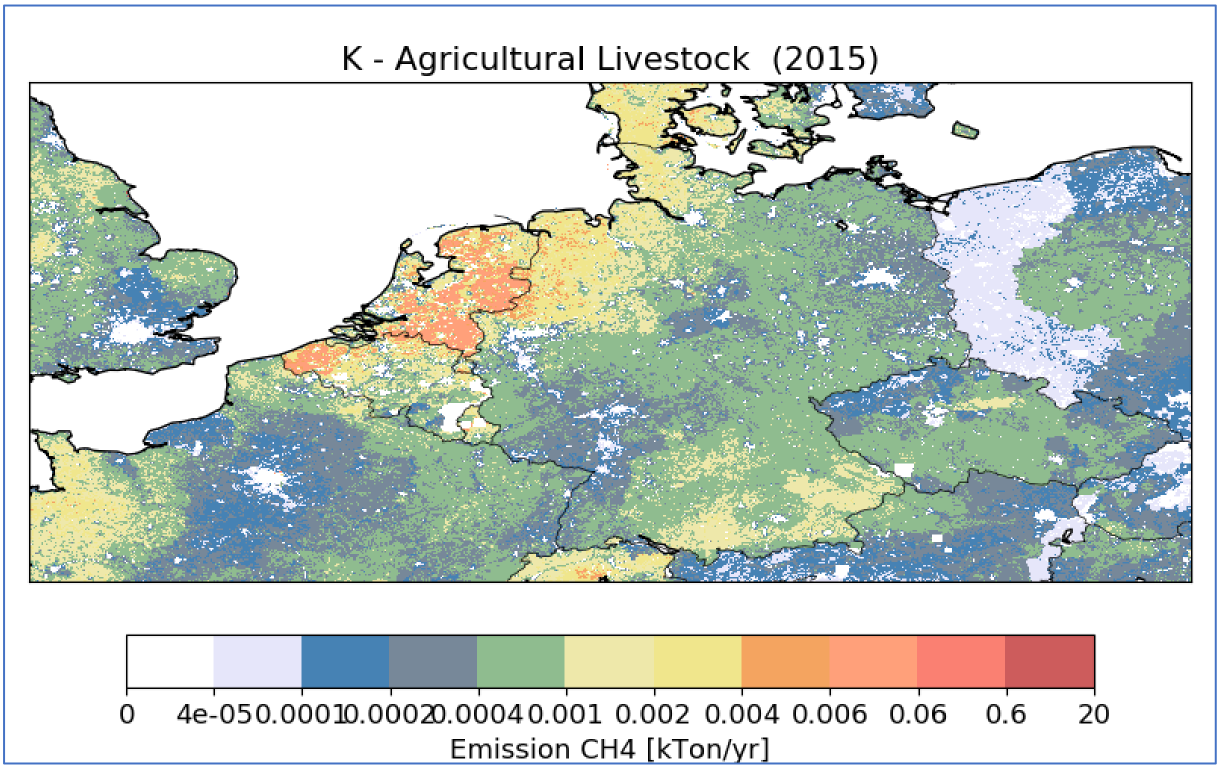

Figure 5. CH_4 emission from agricultural livestock

3.5 Access to the data

The TNO GHGco v.1.0 high resolution gridded emission inventory is made available in .CSV and NetCDF format and can be downloaded through an FTP-server. For questions regarding access to the data please contact Hugo Denier van der Gon at hugo.deniervandergon@tno.nl.

4 Uncertainty profiles

In the preparation of the HR gridded emission inventory for CO_2 and CO, the TNO gridding system distributes country-submitted emission data over a geographical grid. There is uncertainty in the original emission data as well as in the spatial and temporal distribution. The goal was to estimate and use uncertainty data in a statistically coherent manner to create a family of ten emission grids that illustrate the uncertainty space.

Available country-submitted emission data are split by sector/fuel combinations for CO_2, and sectors (no fuel disaggregation) for CO. For CO_2, most of the emissions per sector/fuel combination are directly coupled to a distribution proxy. So for CO_2 the uncertainty in the gridded hourly HR emission inventory is composed of the uncertainty in the

- Activity data used by countries
- Emission factors used by countries
- Spatial proxies in the TNO gridding
- Temporal disaggregation used by TNO

For CO, an internal disaggregation by fuel type is made in the country-submitted emission data before the emission data can be coupled to spatial proxy data, which adds for CO some uncertainty to the uncertainties already mentioned.

A Monte Carlo simulation is then used to create a set of possible solutions in the emission space, reflecting the uncertainties in these underlying parameters. The following sections describe how the key uncertainties have been estimated and processed to estimate the overall uncertainty (Chapter 4). Chapter 5 describes the compilation of the family of ten temporally disaggregated emission grids for CO_2 and CO.

4.1 Uncertainty data

4.1.1 Activity data

Activity data used by countries to estimate CO_2 and CO emission consist for the most part of fossil fuel consumption data available from national energy balances. Some fuel consumptions are better known than others and uncertainties vary across sectors. Besides fossil fuels, biofuels are also used, most importantly biofuels in power production and industry, fuel wood by households and bioliquids in transport. The National Inventory Reports for GHGs provide a table (Tier 1 or 2 uncertainty analysis) with uncertainties in activity data used for GHG emission estimation, on the level of NFR[6] sector - fuel combinations. These activity data are basically the same for all substances.

Fuel wood use by households is especially relevant for CO but disregarded for CO_2 in the NIRs because there is no reporting obligation for short cycle CO_2. NIRs do provide basic uncertainty data for biofuels, as these are relevant for other GHGs like CH_4. Biofuels are however not of key importance in the NIRs. Uncertainty for fuel wood consumption is likely higher than for fossil fuel use but this is not always reflected by the NIRs.

Appendix A lists the country-specified uncertainties in activity data, as taken from the NIRs. It also lists an average for all countries in the HR domain. Selected activities in Appendix A cover more than 90% of both the total CO_2 and CO emissions in the domain.

Based on the uncertainties reported in the NIRs, an average activity rate uncertainty is derived for the countries in the HR domain, for each sector/fuel combination.

[6] Nomenclature For Reporting, sector description for air pollutant emission reporting

4.1.2 Emission factors

Besides activity data uncertainty, the NIRs also provide uncertainties for CO_2 emission factors at the same level of detail (NFR sector - fuel combination). Uncertainty in CO_2 emission factors primarily relate to fuel carbon content and to a limited extend the oxidation fraction. Solid waste fuels and gaseous waste fuels are usually the most uncertain with regard to carbon content. Appendix B lists the country-reported uncertainties for the CO_2 emission factors, for the same set of activities as Appendix A. Uncertainties in emission factors are for CO_2 usually in the same order as the uncertainty in the activity data and all have a normal distribution.

NIRs do not include CO so the uncertainty in CO emission factors is based on other information. CO emissions are extremely dependent on highly variable combustion conditions and therefore the uncertainty in the emission factors is up to an order of magnitude higher than for CO_2. The air pollutant inventories from which CO emissions are taken usually not include any uncertainty ranges. For most sources the EEA Guidebook provides basic uncertainty ranges for CO emission factors in general, and in absence of country-specific uncertainties these are assumed to be representative for the country-submitted CO emission data. Guidebook data is supplemented by BREF reference documents from which reported emission factor ranges are taken as uncertainty range.

Uncertainty ranges of CO emission factors are generally expressed by a factor in literature, which means that the highest and lowest limit values are either the specified factor above or below the most common value. If for instance an emission factor is 3, plus or minus a factor of 3, this translates to a range of 1 to 9, with a lognormal distribution. For lognormal distributions, Appendix B lists the natural logarithm (Ln) of the uncertainty fraction representing the 95% confidence interval.

4.1.3 Spatial distribution

Earlier in this report the most important data used for the spatial distribution has been discussed and the available set of spatial proxies has been presented. In the TNO gridding system, the emission data is split by pollutant, country, sector and fuel, and is at this level individually linked to one or more proxies out of this set of spatial proxies. The spatial information includes for instance EPRTR (covering a large part of the power plants and industrial emissions), the TNO point source database (that includes type, location and capacity where no EPRTR is available), CORINE general industrial areas, LandScan population (total, urban and rural), TNO residential wood use distribution, TNO road transport maps (cars, trucks etc.), other transport/mobile sources maps (inland waterways, FMI AIS sea shipping tracks/port extends, rail lines, pipelines, airports etc.), FAO livestock distributions and CORINE arable land distribution.

The modelling of the uncertainty in gridded emissions, introduced by the use of spatial proxies can be complicated and difficult to oversee. Andres et al. (2016) have previously tried to quantify uncertainties related to the use of proxies for emission gridding, taking into account the discrete nature of the grid and the difficulty to exactly pinpoint sources, the uncertain relationship between a proxy and the emissions, and the uncertainty in the proxy map itself. Here, we identified the same sources of uncertainty:

1. How well does the proxy represent the actual real-world location of what it is supposed to represent (are the roads, population centers, point sources etc. in the right spots (in accordance with reality), or are there many cells included in which in reality none of the intended activity takes place, or vice versa, are there cells missing?)
2. To what degree is the selected proxy representative for the activity it is assumed to represent and linked to (e.g. are the locations of general industrial areas indeed

representative for a specific industrial activity, even though the location of the industrial area is correct?)

3. What is the error/uncertainty in the cell values themselves (e.g. cell traffic intensities, number of inhabitants or animals etc.)

Due to time constraints only the second and the third of the above-mentioned aspects have been considered at this stage. For those proxies that are used to distribute the largest fraction of the emissions it has been attempted to capture these two aspects in a single numerical indicator for the uncertainty at cell level. Appendix C describes in detail how the uncertainties introduced by the spatial distribution have been quantified. This appendix also includes a table with the relative uncertainty of that activity's emission per cell (i.e. the likelihood of the allocated cell emission being equal to the actual emission of that activity in that cell), solely as a result of the spatial distribution. All values in the table are based on expert quantification of the issues mentioned above and inevitably include a considerable amount of subjectivity. The data should therefore be considered as a first order indication only.

4.1.4 Temporal distribution

The time profiles currently consist of fixed monthly, daily and hourly fractions that are based on long-term average activity data and/or socio-economic characteristics. These profiles are applied for each year and for the entire domain, taking into account only time zone differences. In reality, the time profiles can differ enormously between countries, and also from year to year. For example, residential emissions are strongly correlated with the outside temperature and therefore show a strong seasonal cycle. However, one winter can be very cold, whereas the next can show above-average temperatures. This is shown in Figure 6, where January-April show above-average activity (blue line) due to low temperatures. The orange line is a typical example of a fixed time profile.

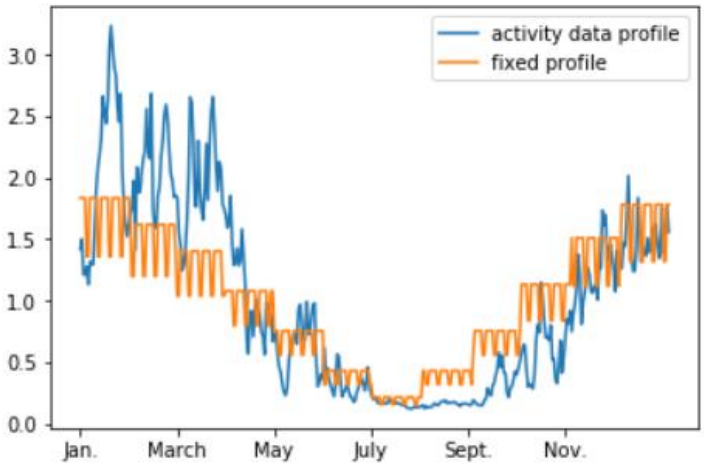

Figure 6. Time profiles (daily averages) for residential combustion in the Netherlands based on activity data (from smart meters in 2013) and the fixed profile.

To quantify the uncertainty in time profiles, a range of time profiles (for a full year, hourly resolution) was created for each source sector based on activity data (such as traffic counts). These are compared to the fixed time profiles, similar as the comparison in Figure 6. The profiles based on activity data can be from different years and countries, so that the full range of possibilities is included. The uncertainties are summarized in Table 4. All these uncertainties are normally distributed.

Table 4. Uncertainties (in %) in hourly time profiles.

Sector	Uncertainty (%)
A_Public Power	16.0
B_Industry	5.7
C_Other Stationary Combustion	29.2
F_RoadTransport	23.3
G_Shipping	30.3
H_Aviation	35.6
I_OffRoad	40.4

4.2 Processing of uncertainties

Before further processing, the uncertainties in the activity rate and the emission factor are combined to estimate the total uncertainty of the emission, per sector – fuel combination. When both uncertainties are of the same order and relatively small, as well as both having a normal distribution, the overall emission uncertainty is calculated with the standard formula for error propagation for non-correlated normally distributed variables: $(\sqrt(uncertainty\ activity\ data^2 + uncertainty\ emission\ factor^2)$).

For most CO emission factors, as well as the activity data for uncontrolled open burning of waste, uncertainties are much higher and have a lognormal distribution instead of normal. In case either the emission factor or activity is lognormally distributed, the uncertainty of the variable with the highest uncertainty is assumed to be indicative for the overall uncertainty of the emission, which in general means the uncertainty of the CO emission factor determines the overall uncertainty of the CO emission, with the distribution remaining lognormal.

Most countries estimate CO emission based on an activity rate and a fuel and sector or technology-specific CO emission factor. Before reporting of the estimated CO emissions on NFR level, an aggregation over fuel type takes place (contrary to CO_2 for which the emissions are reported by fuel type). For power plants and Residential, Commercial and Other sector combustion sources, fuel disaggregation is required to link to the proper spatial proxy. The TNO gridding system therefore makes a disaggregation by fuel again for these sectors, based on the ratio between the fuel contributions to CO emission as reported by the GAINS model (Amann et al., 2011). The fuel disaggregation made by the TNO gridding system introduces some additional uncertainty for CO, which has at this stage been disregarded.

4.3 Covariance matrices

Next, all uncertainties (emissions and spatial/temporal distribution) are gathered and combined into a covariance matrix. A covariance is a matrix containing the covariances (σ^2) on the diagonal and the cross-correlations (correlation between two variables) on the off-diagonal. These are used in the Monte Carlo simulations (see Chapter 5). Three covariance matrices are made in total. The first one contains the uncertainties of the total emissions per subsector and fuel type (based on the uncertainties in activity data and emission factors, see above). The second covariance matrix contains uncertainties in the spatial proxies and the third covariance matrix the uncertainties in the time profiles. Given the large amount of grid cells and time steps, one constant uncertainty per sector was assumed that is valid for the entire domain/year.

The covariance matrices are very large, so only the total uncertainty per aggregated sector is shown in the figures below. More detailed information on uncertainties (including underlying data) is given in the appendices. We assumed that correlations only exist between different fuel types of one sector and therefore they do not show up in the matrices below (where these fuels are aggregated per sector). Correlations between CO_2 and CO emissions are not included, although they are disaggregated using the same spatial proxies and time profiles.

To limit the amount of parameters in the simulation and covariance matrices, a selection was made of subsectors that are very important for the total emissions or that have a large uncertainty. A total of 112 subsectors (including fuel disaggregation) were included in the Monte Carlo for the total emissions. That means a covariance matrix of 224x224 given that we have two species (CO_2 and CO). These subsectors are partly aggregated before starting the Monte Carlo for the spatial proxies (mostly fuels are combined per sector, because they have the same spatial distribution), leading to a total of 59 spatial proxies in the covariance matrix. Note that with the selected subsectors we describe 96% and 92% of the total fossil fuel CO_2 and CO emissions in the domain, respectively. The remainder is added again in the final stage.

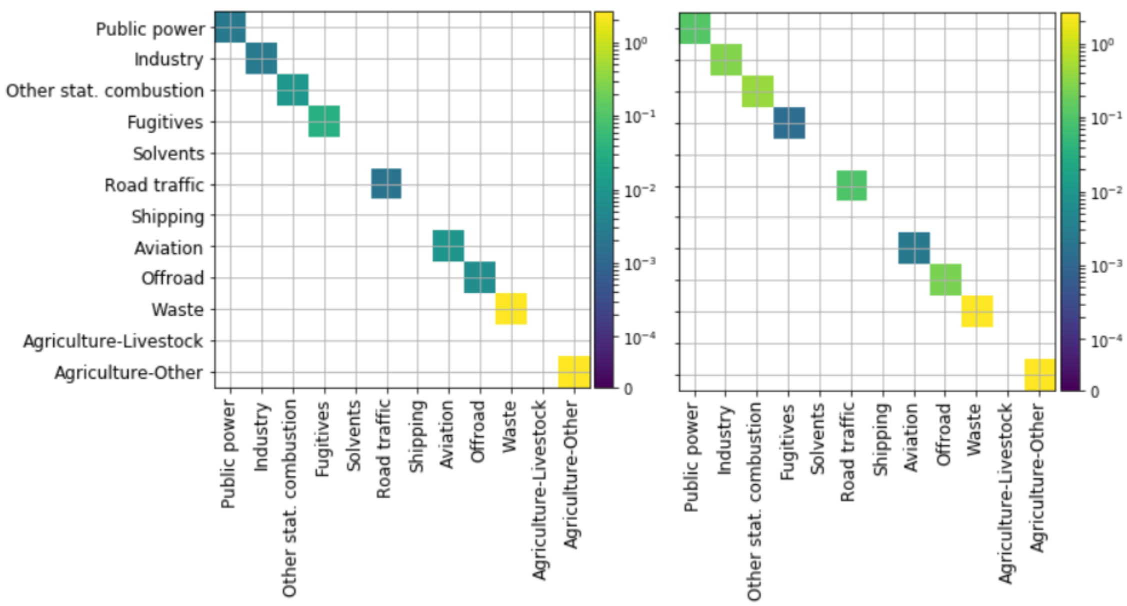

Figure 7. Covariance matrices for total emissions of CO_2 (left) and CO (right) per aggregated source sector. A white space on the diagonal indicates this sector is not included in the Monte Carlo simulation.

As can be seen the uncertainty is highest for the uncontrolled burning of waste and agricultural waste / residue. However, in absolute terms these categories contribute less than 0.1% to CO2 emission and well below 1% of CO emissions. In the Monte-Carlo analysis they are therefore excluded as is discussed in more detail in chapter 5.

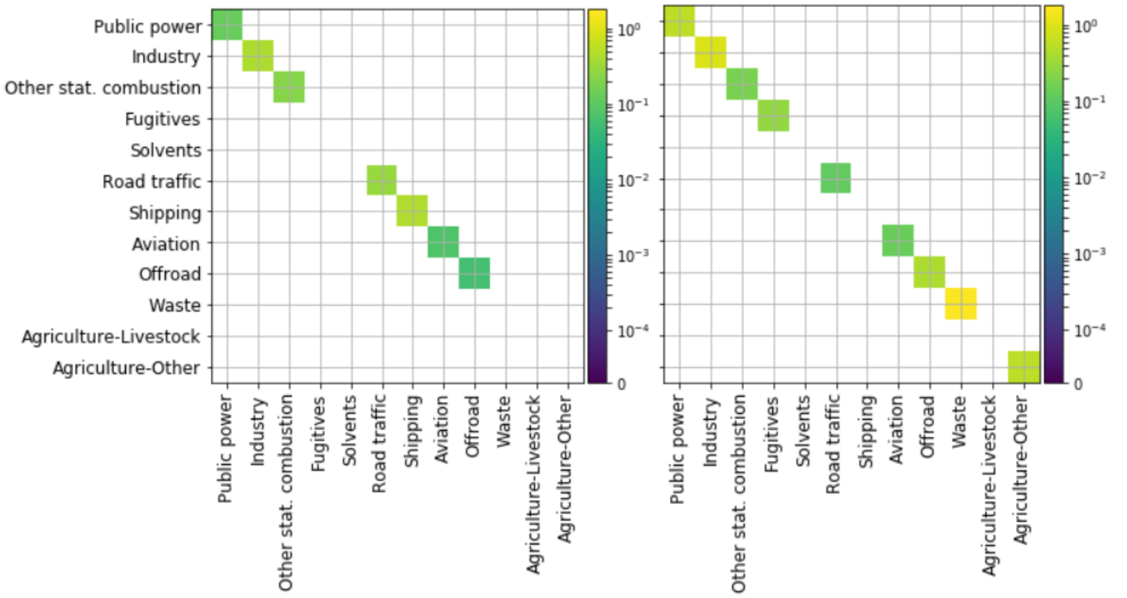

Figure 8. Covariance matrices for time profiles (left) and spatial proxies (right) per aggregated source sector. These are the same for CO_2 and CO. A white space on the diagonal indicates this sector is not included in the Monte Carlo simulation.

5 Family of 10 emission grids

5.1 The Monte Carlo simulation set-up

The goal was to create a set of 10 European emission maps that represent the full range of possible emission scenarios based on uncertainties in key parameters. These key parameters are activity data, emission factors, spatial distribution proxies and temporal distribution proxies. Within a Monte Carlo simulation we create an ensemble (N=10) by drawing random samples from the covariance matrices described before and calculate emission maps for each ensemble member. This creates a set of possible solutions in the emission space, reflecting the uncertainties in the underlying parameters. Figure 9 shows a flow diagram of the entire process. The sample of N=10 is rather small to accurately describe the shape of the emission uncertainties and therefore the 10 emission maps should not be considered as a full representation of the emission space. However, given the large amount of data and to keep the forward modelling efforts achievable within this project a series of 10 maps was deemed to be sufficient.

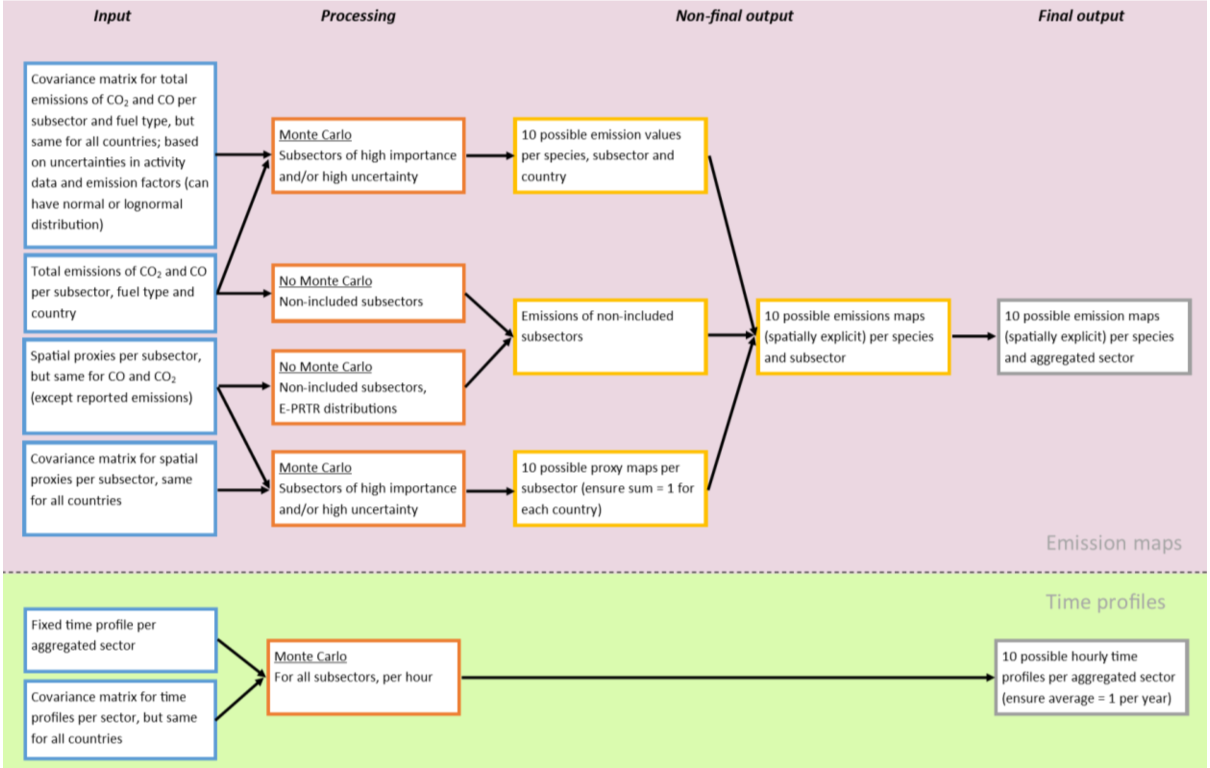

Figure 9. Flow diagram showing the input, processing and output of the Monte Carlo simulation.

Total yearly emissions are disaggregated in space and time using proxies. The proxy itself can be uncertain (e.g. the location of specific sites can be unknown), but also the representativeness of that proxy for the spatial or temporal distribution of the emissions can be uncertain. The main difficulty with these proxies is that they should not affect the total emissions. Therefore, after the Monte Carlo and before applying the spatial or temporal disaggregation, these proxies are corrected such that the spatial proxies add up to 1 for each country and the time profiles are on average 1 over a full year. In this way the total emissions per subsector do vary per member (due to the Monte Carlo simulation with the emissions per subsector), but this is not affected by the spatial proxies and temporal profiles.

For the spatial proxies we give each pixel the freedom to take any value within the uncertainty function of a proxy. In reality, pixels with similar characteristics (e.g. urban pixels) or pixels that are close together might have correlated errors. However, this is currently not taken into account as it would require a large effort to implement this correctly. Time profiles are treated similarly to spatial proxies and each time step can take any value within the uncertainty function.

5.2 Results

The Monte Carlo produces a family of 10 emission grids and 10 sets of time profiles. The spread in total CO_2 and CO emissions per source sector is shown in Figure 10. For most sectors the range for CO_2 is only a few % with the fugitives showing the largest range. For CO the spread is much larger and there are some high outliers due to the lognormal shape of the uncertainties in CO emission factors. Note that the uncertainty in the spatial proxies does not affect the total emissions, only the spatial distribution. The mean/median emissions per source sector and the upper and lower limits are also shown in Table 5.

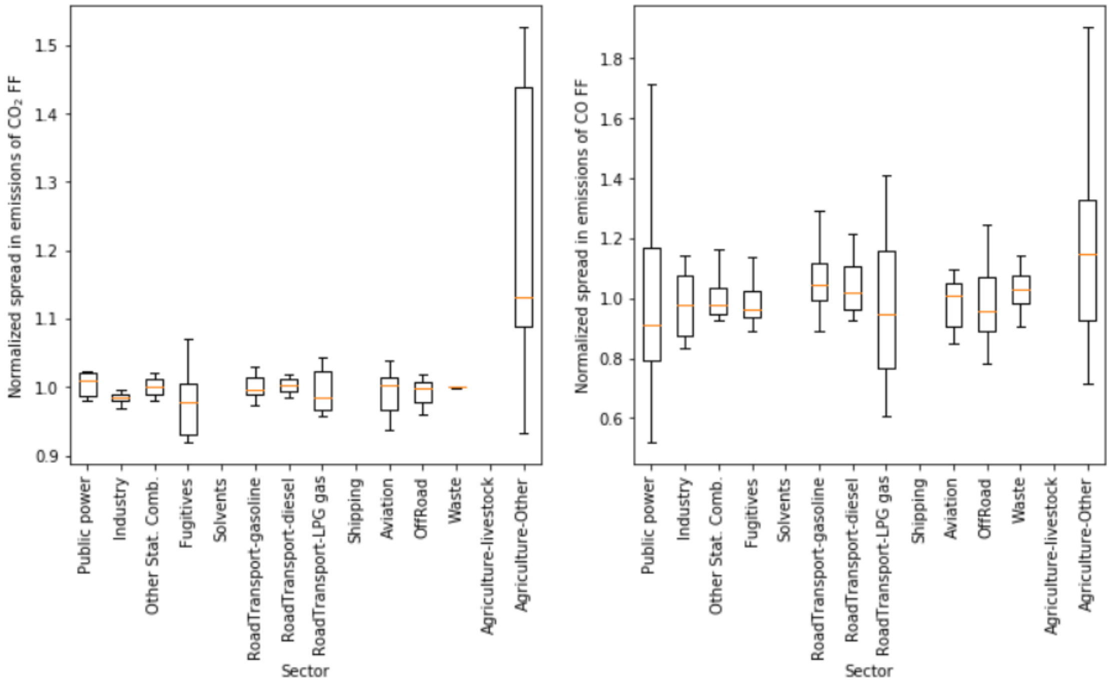

Figure 10. Normalized spread in emissions per source sector for CO_2 (left) and CO (right); Note the different scales of the Y-axis in both figures

Table 5. Mean (CO_2) or median (CO) and upper/lower limits of emissions per source sector, in the family of 10 emission grids.

GNFR sector	CO_2 emissions (kg/yr)	CO emissions (kg/yr)
Public power	5.88E11 (5.74E11 – 5.99E11)	2.11E8 (2.05E8 – 2.16E8)
Industry	4.01E11 (3.98E11 – 4.05E11)	4.17E9 (3.43E9 – 5.26E9)
Other stat. combustion	3.17E11 (3.10E11 – 3.27E11)	7.95E8 (7.34E8 – 9.22E8)
Fugitives	2.48E10 (2.32E10 – 2.70E10)	2.14E7 (1.97E7 – 2.57E7)
RoadTransport-gasoline	1.24E11 (1.21E11 – 1.28E11)	6.12E8 (5.22E8 – 7.57E8)
RoadTransport-diesel	2.95E11 (2.989E11 – 3.06E11)	1.37E8 (1.24E8 – 1.63E8)
RoadTransport-LPG gas	5.31E9 (5.312E9 – 5.58E9)	2.73E7 (1.75E7 – 4.06E7)
Aviation	8.34E9 (7.88E9 – 8.73E9)	4.24E7 (3.57E7 – 4.61E7)
OffRoad	2.81E10 (2.72E10 – 2.88E10)	7.56E8 (6.19E8 – 9.82E8)

The time profiles have a relatively large uncertainty. Figure 11 shows some ensemble members for several sectors. The spread is much larger than in the fixed time profile, because of the large freedom each hourly emission factor has.

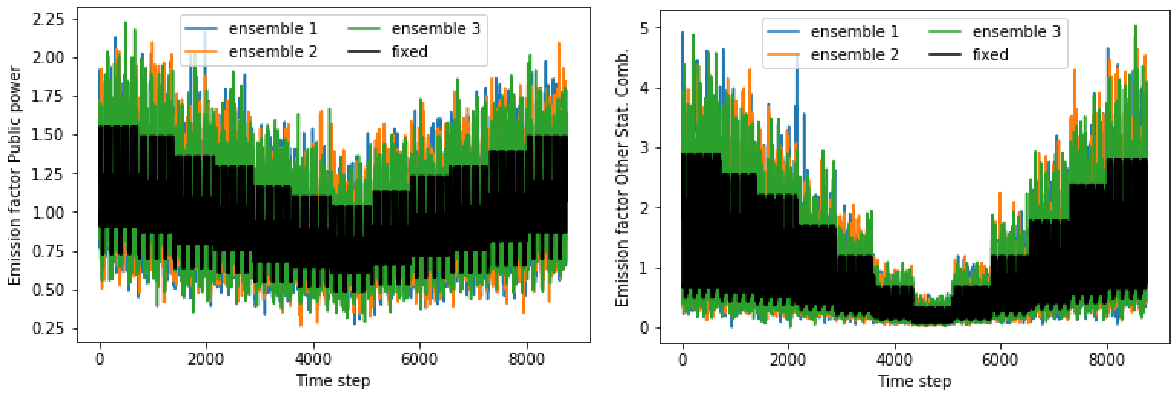

Figure 11. Examples of time profiles for the sectors Public power (left) and Other stationary combustion (right). The fixed profile is the base profile.

Since the spatial uncertainties are now applied randomly, the emission maps are not very illustrative (the difference only shows random noise) and therefore they are not included here.

5.3 Access to the data

The TNO GHGco v.1.0 high resolution gridded emission ensemble inventory is made available in .CSV and NetCDF format and can be downloaded through an FTP-server. For questions regarding access to the data please contact Hugo Denier van der Gon at hugo.deniervandergon@tno.nl.

6 Conclusion

Significant progress has been made in improving the applicability of the TNO GHGco gridded emission inventory for local and regional scale modelling by a 36- fold increase of the spatial resolution, but staying fully consistent with the TNO GHGco gridded emission inventory at 1/10° x 1/20° resolution. Since uncertainties exist at each level of the inventory compilation process (e.g. the activity data, emission factors, spatial distribution and temporal distribution), a statistical process has been developed to take into account the uncertainties at these different levels in a statistically coherent manner. Using Monte Carlo simulation, a family of 10 emission inventory grids and 10 time profiles have been compiled that illustrate the possible solutions in the emission space. This method can be used in the future to create uncertainty maps for inverse modelling purposes.

7 References

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Document History

Version	Author(s)	Date	Changes
0.1	TNO	05/03/2019	Version for internal review
1.0	TNO	04/04/2019	Processed comments from internal review

Internal Review History

Internal Reviewers	Date	Comments
Michael Vossbeck and Thomas Kaminski (iLab)	25/03/2019	Approved with comments
G. Balsamo (ECMWF)	27/03/2019	Delivered. Fig 10 addition and Table 5 Aviation correction needed

Estimated Effort Contribution per Partner

Partner	Effort
TNO	6 MM
Total	**6 MM**

Appendix A: Activity data uncertainty as reported by countries

The table below lists the country-reported uncertainties in activity data as taken from the NIRs. The quoted uncertainty ranges are assumed to be representative for a 95% confidence interval. Uncertainties in activity data are often relatively low and symmetrically distributed, i.e. the upper 95% confidence limit is equally distanced from the average as the lower limit, and normal (Gaussian) distributions are assumed for these activities. Fuel use in non-road mobile sources is often the most uncertain activity for fossil fuel use. The largest uncertainties are found for solid biofuels and open burning of waste (not covered by the NIRs). The uncertainty of the latter activity has been estimated by TNO and assumed to have a lognormal distribution. Note that, as indicated by the table footnote, the natural logarithm (Ln) of the uncertainty fraction is given in case uncertainty has a lognormal distribution.

Sector (NFR)	**Fuel type**	AUT	BEL	CHE	CZE	DEU	DNK	FRA	GBR	LUX	NLD	POL	SWE	**Average***	**Distrib.**
Sum of all power plants (1.A.1.a)	**Solid (fossil)**	0.005	0.01	0.05	0.04	0.04	0.005	0.01	0.014	0.01	0.01	0.02	0.007	**0.018**	**Norm**
	Liquid (fossil)	0.005	0.01	0.007	0.05	0.04	0.027	0.01	0.058	0.02	0.005	0.02	0.014	**0.022**	**Norm**
	Gaseous (fossil)	0.02	0.01	0.05	0.03	0.04	0.013	0.01	0.010	0.02	0.005	0.02	0.02	**0.021**	**Norm**
	Biomass	0.05	0.2	0.1	0.08	0.04	0.03	0.01	0.007	0.07	0.025	0.1	0.013	**0.060**	**Norm**
	Waste (n-ren.)	0.1	0.05	0.05	0.2	0.04	0.02	0.01	0.012	0.08	0.032	0.05	0.02	**0.055**	**Norm**
Oil and gas refining (1.A.1.b & 1.B.2.d)	**All**	0.02	0.05	0.05	0.03	0.03	0.01	0.01	0.058	0.02	0.05	0.03	0.096	**0.038**	**Norm**
Iron and steel (1.A.2.a & 2.C.1)	**All**	0.005	0.02	0.05	0.07	0.05	0.05	0.1	0.012	0.05	0.03	0.05	0.041	**0.044**	**Norm**
Non-ferrous metals (1.A.2.b & 2.C.2_3)	**All**	0.02	0.02	0.05	0.03	0.08	0.013	0.03	0.012	0.02	0.02	0.03	0.05	**0.031**	**Norm**
Chemicals (1.A.2.c & 2.B)	**All**	0.02	0.02	0.05	0.03	0.01	0.013	0.03	0.183	0.02	0.02	0.02	0.086	**0.042**	**Norm**
Pulp, paper and print (1.A.2.d)	**All**	0.02	0.02	0.05	0.03	0.05	0.013	0.03	0.010	0.02	0.02	0.03	0.035	**0.027**	**Norm**
Food processing, beverages and tobacco (1.A.2.e)	**All**	0.02	0.06	0.05	0.03	0.03	0.013	0.03	0.010	0.02	0.02	0.03	0.031	**0.029**	**Norm**
Non-metallic minerals (1.A.2.f & 2.A)	**All**	0.02	0.08	0.02	0.03	0.03	0.01	0.05	0.010	0.01	0.05	0.05	0.02	**0.032**	**Norm**
Other manufacturing industry (1.A.2.g)	**All**	0.02	0.08	0.05	0.03	0.03	0.013	0.03	0.010	0.02	0.02	0.03	0.018	**0.029**	**Norm**
Aviation (1.A.3.a)	**All**	0.03	0.075	0.01	0.04	0.08	0.1	0.03	0.196	0.1	0.3	0.03	0.082	**0.089**	**Norm**
Sum of all road transport (1.A.3.b)	**Gasol. (fossil)**	0.03	0.05	0.007	0.03	0.09	0.02	0.03	0.010	0.02	0.02	0.03	0.03	**0.031**	**Norm**
	Diesel (fossil)	0.03	0.05	0.009	0.03	0.09	0.02	0.03	0.01	0.02	0.02	0.03	0.05	**0.032**	**Norm**
	Gaseous (fossil)	0.03	0.05	0.05	0.03	0.09	0.02	0.03	0.01	0.02	0.05	0.04	0.05	**0.039**	**Norm**
	LPG	0.03	0.05	0.05	0.03	0.09	0.02	0.03	0.01	0.02	0.05	0.04	0.05	**0.039**	**Norm**
	Biofuels	0.05	0.05	0.1	0.03	0.09	0.02	0.03	0.01	0.02	0.05	0.1	0.05	**0.050**	**Norm**
Railways (1.A.3.c)	**All**	0.03	0.06	0.009	0.05	0.1	0.02	0.03	0.15	0.02	0.05	0.03	0.05	**0.050**	**Norm**

Navigation (1.A.3.d)	**All**	0.03	0.1	0.007	0.05	0.18	0.11	0.03	0.179	0.02	0.05	0.03	0.027	**0.068**	**Norm**
Other transport (1.A.3.e & 1.A.4 mobile)	**All**	0.02	0.05	0.05	0.04	0.01	0.35	0.03	0.15	0.02	0.005	0.03	0.05	**0.067**	**Norm**
Other mobile (1.A.5.b)	**All**	0.01	0.2	0.007	0.05	0.03	0.41	0.03	0.15	0.02	0.2	0.03	0.036	**0.098**	**Norm**
Residential (1.A.4.b)	**Gaseous (fossil)**	0.02	0.04	0.05	0.03	0.06	0.013	0.05	0.010	0.02	0.05	0.04	0.092	**0.040**	**Norm**
	Liquid (fossil)	0.005	0.1	0.007	0.05	0.06	0.027	0.05	0.058	0.02	0.1	0.04	0.061	**0.048**	**Norm**
	Solid (fossil)	0.005	0.15	0.05	0.04	0.06	0.016	0.05	0.014	0.01	0.5	0.04	-	**0.085**	**Norm**
	Other (fossil)	0.1	0.2	-	-	0.06	0.05	-	0.012	0.08	-	0.04	-	**0.077**	**Norm**
	Biomass	0.05	0.65	0.1	0.08	0.11	0.1	0.05	?	0.07	0.384	0.1	0.1	**0.163**	**Norm**
Commercial institutional (1.A.4.a)	**Gaseous (fossil)**	0.02	0.04	0.05	0.03	0.05	0.013	0.05	0.010	0.02	0.1	0.04	0.097	**0.043**	**Norm**
	Liquid (fossil)	0.005	0.1	0.007	0.05	0.05	0.027	0.05	0.058	0.02	0.1	0.04	0.153	**0.055**	**Norm**
	Solid (fossil)	0.005	0.15	-	0.04	0.05	0.016	0.05	0.014	0.01	0.5	0.04	-	**0.087**	**Norm**
	Other (fossil)	0.1	0.2	-	-	0.05	0.05	-	0.012	0.08	-	0.04	0.1	**0.079**	**Norm**
	Biomass	0.05	0.2	0.1	0.08	0.19	0.1	0.05	?	0.07	0.104	0.1	0.094	**0.103**	**Norm**
Agriculture/Forestry/Fishing (1.A.4.c)	**Gaseous (fossil)**	0.02	0.04	0.05	0.03	0.13	0.013	0.05	0.010	0.02	0.1	0.04	0.1	**0.050**	**Norm**
	Liquid (fossil)	0.005	0.1	0.007	0.05	0.13	0.027	0.05	0.058	0.02	0.1	0.04	0.030	**0.051**	**Norm**
	Solid (fossil)	0.005	0.15	-	0.04	0.13	0.016	0.05	0.014	0.01	0.5	0.04	-	**0.095**	**Norm**
	Other (fossil)	0.1	0.2	-	-	0.13	0.05	-	0.012	0.08	-	0.04	-	**0.087**	**Norm**
	Biomass	0.05	0.2	0.1	0.08	0.13	0.1	0.05	?	0.07	?	0.1	0.080	**0.096**	**Norm**
Other stationary (1.A.5.a)	**Gaseous (fossil)**	-	-	0.007	-	0.03	0.013	-	0.010	0.02	0.5	-	-	**0.097**	**Norm**
	Liquid (fossil)	-	0.2	-	-	0.03	0.027	-	0.058	0.02	0.2	0.05	-	**0.084**	**Norm**
	Solid (fossil)	-	-	-	-	0.03	0.016	-	0.014	0.01	0.5	0.05	-	**0.103**	**Norm**
	Other (fossil)	-	-	-	-	0.03	0.05	-	0.012	0.08	0.5	0.05	-	**0.120**	**Norm**
	Biomass	?	?	?	?	0.03	0.1	?	?	0.07	0.5	0.2	?	**0.180**	**Norm**
Oil and gas production (1.B.2 mainly flaring, 1.B.2.c)	**-**	0..05	0.01	0.05	0.07	0.2	0.075	0.1	0.044	0.02	0.5	0.05	0.175	**0.118**	**Norm**
Agricultural waste burning (3.F)	**-**	-	-	-	-	-	-	-	-	-	-	-	-	**1.609**	**Logn**
Uncontrolled waste burning (5.C.2)	**-**	-	-	-	-	-	-	-	-	-	-	-	-	**1.609**	**Logn**

In case NIRs report multiple uncertainties for a single table entry, the uncertainty of the largest CO2 emission contribution has been assumed

*EF uncertainty (Normal = fraction, Lognormal = Ln(fraction))

Appendix B: Emission factor uncertainty as reported by countries

The table below lists the country-reported uncertainties for the CO_2 emission factors, as taken from the NIRs, for the same set of activities as Appendix A. An average for all countries is also shown. Uncertainties in CO_2 emission factors are often relatively low and symmetrically distributed, i.e. the upper 95% confidence limit is equally distanced from the average as the lower limit, and normal (Gaussian) distributions are assumed for CO_2 emission factors. The table also lists the general uncertainty and distribution for CO emission factors, as derived from literature. Compared to CO_2 emission factors, the uncertainty in CO emission factors is much higher, up to an order of magnitude. Uncertainties in CO emission factors are often lognormally distributed and are assumed equal for all countries in the HR domain. Note that as indicated by the table footnote, the natural logarithm (Ln) of the uncertainty fraction is given in case uncertainty has a lognormal distribution.

Sector (NFR)	**Fuel type**	**CO_2 Emission factors**														**CO emission factors**	
		AUT	BEL	CHE	CZE	DEU	DNK	FRA	GBR	LUX	NLD	POL	SWE	**Average***	**Distribution**	**Average***	**Distribution**
Sum of all power plants (1.A.1.a)	**Solid (fossil)**	0.005	0.05	0.051	0.04	0.01	0.003	0.02	0.0255	0.03	0.03	0.02	0.073	**0.030**	**Norm**	**0.45**	**Logn**
	Liquid (fossil)	0.005	0.02	0.001	0.05	0.01	0.0013	0.02	0.0253	0.01	0.2	0.01	0.017	**0.031**	**Norm**	**0.40**	**Norm**
	Gaseous (fossil)	0.005	0.01	0.01	0.03	0.01	0.004	0.02	0.0167	0.01	0.003	0.01	0.05	**0.015**	**Norm**	**0.51**	**Norm**
	Biomass	-	-	-	-	-	-	-	-	-	-	0.05	-	**0.05**	**Norm**	**0.69**	**Logn**
	Waste (n-ren.)	0.2	0.1	0.092	0.2	0.01	0.03	0.06	0.1348	0.2	0.057	0.05	0.197	**0.111**	**Norm**	**-**	**-**
Oil and gas refining (1.A.1.b & 1.B.2.d)	**All**	0.02	0.02	0.092	0.03	0.03	0.005	0.02	0.0253	0.01	0.25	0.02	0.0477	**0.048**	**Norm**	**-**	**-**
Iron and steel (1.A.2.a & 2.C.1)	**All**	0.005	0.05	0.01	0.07	0.05	0.1	0.1	0.0485	0.05	0.05	0.1	0.0416	**0.056**	**Norm**	**0.72**	**Logn**
Non-ferrous metals (1.A.2.b & 2.C.2_3)	**All**	0.005	0.01	0.01	0.03	0.09	0.004	0.02	0.0485	0.01	0.05	0.02	0.05	**0.029**	**Norm**	**0.21**	**Norm**
Chemicals (1.A.2.c & 2.B)	**All**	0.005	0.01	0.01	0.03	0.01	0.004	0.06	0.0311	0.01	0.1	0.05	0.172	**0.041**	**Norm**	**0.41**	**Logn**
Pulp, paper and print (1.A.2.d)	**All**	0.005	0.01	0.01	0.03	0.05	0.004	0.02	0.0167	0.01	0.003	0.02	0.0152	**0.016**	**Norm**	**0.41**	**Logn**
Food processing, bev. and tob. (1.A.2.e)	**All**	0.005	0.02	0.01	0.03	0.04	0.004	0.02	0.0167	0.01	0.003	0.02	0.0216	**0.017**	**Norm**	**0.41**	**Logn**
Non-metallic minerals (1.A.2.f & 2.A)	**All**	0.005	0.05	0.02	0.03	0.03	0.02	0.076	0.03	0.03	0.1	0.05	0.05	**0.041**	**Norm**	**1.15**	**Logn**
Other manufacturing industry (1.A.2.g)	**All**	0.005	0.02	0.01	0.03	0.03	0.004	0.02	0.0167	0.01	0.003	0.02	0.002	**0.014**	**Norm**	**0.41**	**Logn**
Aviation (1.A.3.a)	**All**	0.03	0.05	0.002	0.04	0.08	0.05	0.01	0.0323	0.05	0.04	0.05	0.041	**0.040**	**Norm**	**0.69**	**Logn**

Sum of all road transport (1.A.3.b)	**Gasol. (fossil)**	0.03	0.02	0.001	0.03	0.01	0.05	0.01	0.0199	0.02	0.02	0.05	0.04	**0.025**	**Norm**	**0.85**	**Logn**
	Diesel (fossil)	0.03	0.02	0.001	0.03	0.01	0.05	0.01	0.02	0.02	0.02	0.05	0.05	**0.026**	**Norm**	**0.32**	**Norm**
	Gaseous (fossil)	0.03	0.02	0.01	0.03	0.01	0.05	0.01	0.02	0.02	0.02	0.05	0.05	**0.027**	**Norm**	**0.96**	**Logn**
	LPG	0.03	0.02	0.01	0.03	0.01	0.05	0.01	0.02	0.02	0.02	0.05	0.05	**0.027**	**Norm**	**0.46**	**Norm**
	Biofuels	-	-	-	-	-	-	-	-	-	-	0.05	0.1	**0.075**	**Norm**	**0.69**	**Logn**
Railways (1.A.3.c)	**All**	0.03	0.02	0.001	0.05	0.1	0.05	0.01	0.02	0.02	0.02	0.05	0.05	**0.035**	**Norm**	**-**	**-**
Navigation (1.A.3.d)	**All**	0.03	0.02	0.001	0.05	0.18	0.05	0.01	0.0179	0.02	0.02	0.05	0.0303	**0.040**	**Norm**	**-**	**-**
Other transport (1.A.3.e & 1.A.4 mobile)	**All**	0.005	0.01	0.01	0.04	0.01	0.05	0.01	0.02	0.02	0.003	0.05	0.05	**0.023**	**Norm**	**1.15**	**Logn**
Other mobile (1.A.5.b)	**All**	0.005	0.02	0.001	0.05	0.03	0.05	0.01	0.02	0.02	0.02	0.05	0.0359	**0.026**	**Norm**	**1.15**	**Logn**
Residential (1.A.4.b)	**Gaseous (fossil)**	0.005	0.01	0.01	0.03	0.06	0.004	0.02	0.0167	0.01	0.003	0.05	0.0458	**0.022**	**Norm**	**0.42**	**Logn**
	Liquid (fossil)	0.005	0.02	0.001	0.05	0.06	0.013	0.02	0.0253	0.01	0.003	0.05	0.0254	**0.024**	**Norm**	**0.40**	**Norm**
	Solid (fossil)	0.005	0.05	0.051	0.04	0.06	0.01	0.02	0.0255	-	0.1	0.05	-	**0.041**	**Norm**	**0.42**	**Logn**
	Other (fossil)	0.2	0.2	-	-	0.06	0.1	-	0.1348	0.2	-	0.05	-	**0.135**	**Norm**		
	Biomass	-	-	-	-	0.06	-	-	-	-	-	0.05	?	**0.055**	**Norm**	**1.15**	**Logn**
Commercial institutional (1.A.4.a)	**Gaseous (fossil)**	0.005	0.01	0.01	0.03	0.06	0.004	0.02	0.0167	0.01	0.003	0.05	0.0485	**0.022**	**Norm**	**0.41**	**Logn**
	Liquid (fossil)	0.005	0.02	0.001	0.05	0.06	0.013	0.02	0.0253	0.01	0.003	0.05	0.0138	**0.023**	**Norm**	**1.06**	**Norm**
	Solid (fossil)	0.005	0.05	-	0.04	0.06	0.01	0.02	0.0255	-	0.1	0.05	-	**0.040**	**Norm**	**0.99**	**Norm**
	Other (fossil)	0.2	0.2	-	-	0.06	0.1	-	0.1348	0.2	-	0.05	0.1	**0.131**	**Norm**		
	Biomass	-	-	-	-	0.06	-	-	-	-	-	0.05	?	**0.055**	**Norm**	**2.19**	**Logn**
Agriculture/Forestry/Fishing (1.A.4.c)	**Gaseous (fossil)**	0.005	0.01	0.01	0.03	0.13	0.004	0.02	0.0167	0.01	0.003	0.05	0.05	**0.028**	**Norm**	**0.41**	**Logn**
	Liquid (fossil)	0.005	0.02	0.001	0.05	0.13	0.013	0.02	0.0253	0.01	0.003	0.05	0.0257	**0.029**	**Norm**	**1.06**	**Norm**
	Solid (fossil)	0.005	0.05	-	0.04	0.13	0.01	0.02	0.0255	-	0.1	0.05	-	**0.048**	**Norm**	**0.99**	**Norm**

	Other (fossil)	0.2	0.2	-	-	0.13	0.1	-	0.1348	0.2	-	0.05	-	**0.145**	**Norm**		
	Biomass	-	-	-	-	0.13	-	-	-	-	-	0.05	?	**0.09**	**Norm**	**2.19**	**Logn**
Other stationary (1.A.5.a)	**Gaseous (fossil)**	-	-	0.001	-	0.03	0.004	-	0.0167	0.01	0.05	0.05	-	**0.023**	**Norm**	**0.41**	**Logn**
	Liquid (fossil)	-	0.02	-	-	0.03	0.013	-	0.0253	0.01	0.02	0.03	-	**0.021**	**Norm**	**1.06**	**Norm**
	Solid (fossil)	-	-	-	-	0.03	0.01	-	0.0255	-	0.05	0.05	-	**0.033**	**Norm**	**0.99**	**Norm**
	Other (fossil)	-	-	-	-	0.03	0.1	-	0.1348	0.2	0.05	0.05	-	**0.094**	**Norm**		
	Biomass	-	-	-	-	0.03	-	-	-	-	0.05	-	-	**0.04**	**Norm**	**2.19**	**Logn**
Oil and gas prod. (1.B.2 mainly flar., 1.B.2.c)	**-**	0.005	0.1	0.087	0.07	0.2	0.02	0.02	0.0523	1	0.02	0.066	0.05	**0.141**	**Norm**	**-**	**-**
Agricultural waste burning (3.F)	**-**	-	-	-	-	-	-	-	-	-	-	-	-	**0.2**	**Norm**	**0.43**	**Norm**
Uncontrolled waste burning (5.C.2)	**-**	-	-	-	-	-	-	-	-	-	-	-	-	**0.5**	**Norm**	**1.10**	**Logn**

In case NIRs report multiple uncertainties for a single table entry, the uncertainty of the largest CO_2 emission contribution has been assumed

*** EF uncertainty (Normal = fraction, Lognormal = Ln(fraction))**

Appendix C: Quantification of the uncertainty introduced by the spatial distribution

This appendix describes how the uncertainty introduced by the spatial distribution of the emissions has been quantified at the level of individual grid cells. The key assumptions /considerations have been:

- The LandScan population distribution is assumed to have a negligible uncertainty with regard to proxy location and cell value. In some cases, however, population is assumed as a default proxy for an activity of which the location is unknown. In that case the spatial uncertainty may be high.
- EPRTR source type indicators, source locations and reported emissions have a negligible uncertainty, however:
- The total emission of an industrial sector at country level is usually higher than the EPRTR total for that sector because of incomplete coverage by EPRTR, due to for instance reporting thresholds and missing reports. The remaining non-EPRTR part of the emission is then evenly distributed with a default spatial proxy, like CORINE industrial areas. As a result, many cells get a small part of that emission while in reality the plant locations will likely be limited to a small number of distinct locations. This can lead to particularly high uncertainties **at cell level** when such a default proxy is used. At this stage, this has been modeled by assuming a lognormal distribution of the cell values with a high relative uncertainty. This approach is also followed for other residual emissions.
- A similar situation occurs for incidentally occurring emissions like the open burning of waste (distributed by default with for instance rural population), or the (industrial) use of a more exotic/specific type of fuel. Again a lognormal distribution of the cell values is assumed, with a high relative uncertainty.
- Where no EPRTR data is available, the TNO point source database is used to distribute certain types of industrial emissions. This is an extensive proprietary database of plant locations, types and capacities. It may, however, not be fully up-to-date and plant coordinates are sometimes less accurate. Furthermore there may be (smaller) plants missing and the sector emission is allocated to the TNO point source entries based on plant capacities (instead of actual emission). Emissions distributed with the TNO point source database are therefore assumed to have a medium spatial uncertainty.
- The TNO road transport distribution maps are based on a spatial gridding of the Open Transport Map and the Open Street Map datasets. The location of the road network as derived from these online resources is regarded as very accurate. Somewhat less accurate are the traffic intensities for each road section/road type, as these are partly based on modelled vehicle kilometer distributions instead of direct observations only.
- Several distribution maps are used for the spatial distribution of non-road transport and other mobile machinery. International shipping is AIS-based and considered very accurate with regard to location, representativeness and cell values. Less accurate are the locations for inland shipping, despite also being based on AIS. Emissions from diesel-powered rail transport is approximated by the location of the railway network and cell values are therefore considered highly uncertain. Mobile sources in agriculture, industry and households are distributed with general proxies (arable land, industrial areas and population) and are estimated to have a medium uncertainty.

- The location of the natural gas processing infrastructure is currently approximated by a rough map of high pressure pipelines. As a result the distribution of emissions from this activity is considered highly uncertain.

The estimated uncertainties at cell level resulting from the spatial distribution are listed in the table below. In this table, the proxy-activity combinations that are expected to introduce the largest part of the ultimate uncertainty per substance, cell and GNFR combination are selected. Spatial uncertainties for proxy-activity combinations not shown are assumed to be negligible at this stage.

The values listed represent the relative uncertainty of that activity's emission per cell (i.e. the likelihood of the allocated cell emission being equal to the actual emission of that activity in that cell), solely as a result of the spatial distribution. All values in the table below are based on expert quantification of the issues mentioned above and inevitably include a considerable amount of subjectivity. The data should therefore be considered as a first order indication only.

In case the uncertainty distribution is lognormal, the natural logarithm of the relative uncertainty is given. For instance, the use of the CORINE general industrial area distribution to distribute emission from natural gas refineries (sector 1210) results in a (very large) relative uncertainty at cell level of a factor 50 and the value ln(50) is shown.

TNO SectorID	Sector name	Proxy name	Distribution	Cell spatial uncertainty range (Normal = fraction, Lognormal = Ln(fraction))
1100	Public electricity and heat production	CORINE_2012_Industrial_area	Logn	LN(10) = 2.3
1210	Oil and gas refining (comb)	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
1210	Oil and gas refining (comb)	TNO_PS for Refineries	Logn	LN(5) = 1.6
1220	Oil and gas refining	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
1310	Coal mining (comb)	CORINE_2012_Industrial_area	Logn	LN(100) = 4.6
1310	Coal mining (comb)	TNO_PS for Coal mining	Logn	LN(5) = 1.6
1320	Oil production (comb)	TNO_PS for Oil production	Logn	LN(5) = 1.6
1330	Gas exploration (comb)	TNO_PS for Gas production	Logn	LN(5) = 1.6
1340	Coke ovens (comb)	TNO_PS for Iron and steel - Coke ovens	Logn	LN(5) = 1.6
1420	Solid fuel transformation	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
2110	Iron and steel industry (comb)	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
2120	Iron and steel production	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
2210	Non-ferrous metals (comb)	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
2210	Non-ferrous metals (comb)	TNO_PS for Non-ferrous metals - Other	Logn	LN(5) = 1.6
2220	Aluminium production	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
2220	Aluminium production	TNO_PS for Non-ferrous metals - Aluminium	Logn	LN(5) = 1.6
2230	Other non-ferrous metal production	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
2230	Other non-ferrous metal production	TNO_PS for Non-ferrous metals - Other	Logn	LN(5) = 1.6
2310	Chemical industry (comb)	CORINE_2012_Industrial_area	Logn	LN(10) = 2.3
2310	Chemical industry (comb)	TNO_PS for Chemical industry	Logn	LN(5) = 1.6
2320	Chemical industry	CORINE_2012_Industrial_area	Logn	LN(10) = 2.3
2410	Pulp and paper industry (comb)	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
2420	Pulp and paper industry	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
2510	Food processing, beverages and tobacco (comb)	CORINE_2012_Industrial_area	Logn	LN(10) = 2.3
2520	Food and beverages industry	CORINE_2012_Industrial_area	Logn	LN(10) = 2.3

2610	Non-metallic minerals (comb)	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
2620	Cement production	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
2630	Other non-metallic mineral production	CORINE_2012_Industrial_area	Logn	LN(10) = 2.3
2810	Other manufacturing industry (comb)	CORINE_2012_Industrial_area	Logn	LN(3) = 1.1
2820	Other industrial processes	CORINE_2012_Industrial_area	Logn	LN(3) = 1.1
3100	Passenger cars	RoadTransport_PassengerCars	Norm	0.3
3200	Light duty vehicles	RoadTransport_LightCommercialVehicles	Norm	0.3
3310	Trucks (>3.5t)	RoadTransport_HeavyDutyTrucks	Norm	0.3
3320	Buses	RoadTransport_Buses	Norm	0.3
3410	Motorcycles	RoadTransport_Motorcycles	Norm	0.3
3420	Mopeds	RoadTransport_Mopeds	Norm	0.5
4100	Civil aviation – LTO	Airport distribution for year 2015	Logn	LN(3) = 1.1
4400	Mobile sources in agriculture/Forestry/Fishing	CORINE_2012_Arable_land	Logn	LN(3) = 1.1
4500	Manufacturing industry - Off-road vehicles and other machinery	CORINE_2012_Industrial_area	Logn	LN(3) = 1.1
4610	Other transportation, including pipeline compressors	Population_total_2015	Logn	LN(50) = 3.9
4620	Small combustion - Commercial/institutional – Mobile	CORINE_2012_Industrial_area	Logn	LN(10) = 2.3
4630	Small combustion - Residential - Household and gardening	Population_total_2015	Logn	LN(2) = 0.7
4640	Other mobile combustion	Population_total_2015	Logn	LN(2) = 0.7
5100	Commercial/institutional	Population_total_2015	Norm	0.5
5100	Commercial/institutional	Population_rural_2015	Logn	LN(2) = 0.7
5100	Commercial/institutional	Wood_use_2014	Logn	LN(10) = 2.3
5200	Residential	Population_total_2015	Norm	0.5
5200	Residential	Population_rural_2015	Logn	LN(2) = 0.7
5200	Residential	Wood_use_2014	Logn	LN(3) = 1.1
5300	Agriculture/Forestry/Fishing	CORINE_2012_Arable_land	Logn	LN(3) = 1.1
5300	Agriculture/Forestry/Fishing	Wood_use_2014	Logn	LN(10) = 2.3
5400	Other stationary combustion	Population_total_2015	Logn	LN(2) = 0.7
5400	Other stationary combustion	Population_rural_2015	Logn	LN(2) = 0.7
5400	Other stationary combustion	Wood_use_2014	Logn	LN(3) = 1.1
6520	Field burning of agricultural residues	CORINE_2012_Arable_land	Logn	LN(10) = 2.3
7400	Open burning of waste	CORINE_2012_Industrial_area	Logn	LN(50) = 3.9
7400	Open burning of waste	Population_rural_2015	Logn	LN(50) = 3.9

Note that, after spatial distribution, all emissions are aggregated again to the level of GNFR sectors.