ICOS Cities

Final version of high-resolution city emission inventory for GHGs and co-emitted species for 2018, 2020 and 2022

Deliverable 1.2.

Project number 101037319

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ICOS Cities

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1 Introduction

The aim of task 1.1 'State-of-the-art emission inventories is to provide complete, spatially explicit, state-of-the-art emission inventories for greenhouse gases, such as CO_2, CH_4 and co-emitted species (CO, NO_x, BC) to WP2 using both available, and new datasets and methods. This research focuses on the three pilot cities: Paris, Munich, and Zurich, for which the emissions have been made available by AIRPARIF, TUM, and EMPA, respectively.

Contrary to the description in the proposal ('Final version of high-resolution city emission inventory for GHGs and co-emitted species for 2019 and 2020'), emissions have been prepared for 2018 (Paris) and for 2020 (Munich and Zurich), but also for 2022 (all cities). This choice was made because the first version of the city emission inventories (for 2019, 2020, or 2021) has been used in WP2 to calculate emissions for the year 2022 (in deliverable 2.1). The emissions from 2022 will match the best with the observation periods in WP3. In order to also provide a final version of the 2022 emissions, the city emission inventories in this deliverable contain emissions for 2018 and 2020, and also emissions for 2022.

The final product consists of 3 spatially explicit city emission inventories, including the following characteristics:

- Pollutants: Emissions from the pollutants CO_2, CH_4, NO_x, CO, and BC.
- Categories: Emissions per GNFR category: A - Public Power, B – Industry, C - Other stationary combustion, D – Fugitives, E - Solvents & product use, F - Road transport, G – Shipping, H – Aviation, I - Off Road, J – Waste, K – AgriLivestock, L – AgriOther, Other. An overview of the emissions sources included in each category is provided in Appendix 1.
- Temporal resolution: Annual emission data for 2018 (Paris), 2020 (Munich), 2020 (Zurich), 2022 (all cities).
- Spatial resolution and grid: Emission data at a resolution of 100x100 meters (Munich & Zurich) and 500x500 meters (Paris). The city emission inventories are all projected in a different coordinate reference system. For harmonization, the lon/lat coordinates of the cells have also been included in each inventory.
- Units: The emissions in the city emission inventories are expressed in kg/cell/year (Munich and Zurich) and kton/cell/year for CO_2 and ton/cell/year for other species (Paris)

The city emission data are available for internal use within the ICOS cities PAUL project through the ICOS-Cities fileshare:

- Paris: https://fileshare.icos-cp.eu/apps/files/files/2801757?dir=/PAUL/WP1/Task%201.1/EI_AIRPARIF/new_version
- Munich: https://fileshare.icos-cp.eu/apps/files/files/3846704?dir=/PAUL/WP1/Task%201.1/Munich%20City%20Inventory%20D1.2
- Zurich: https://fileshare.icos-cp.eu/apps/files/files/3812749?dir=/PAUL/WP1/Task%201.1/Zurich%20City%20Inventory/v1.8

The data will at a later stage, but before the end of the ICOS cities PAUL project, be made publicly available by the involved institutes with the exception of confidential data. To make the best product for

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the city modelling in some cases the teams needed to use data at a resolution that could be made available to the project but without the permit to share it publicly. In such cases a coarser resolution will be made available. The other constraint for making data already public is that some results first need to be published in the peer-reviewed literature. The expectation is that this will be achieved in 2025. Should the publications, unexpectedly, not be realized before the end of the project, then a version of the data will be made public.

The goal of this deliverable report is to describe the final city emission inventories, as provided for deliverable 1.2. Chapters 2-4 provide an overview of the available data and a description of the methodology used to prepare the city inventories (Paris in Chapter 2, Munich in Chapter 3 and Zurich in Chapter 4). Conclusions and discussion of the results are presented in Chapter 5.

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2 Paris emission inventory

The City of Paris, capital of France is located in the Northern part of the country. The city spans 105 $km^{2.}$ with a population of over 2.1 Million inhabitants, making it the most populous city in France. In addition, Paris belongs to the Île-de-France region, the most densely populated region in France. Moreover, Île-de-France hosts 16% of the French total population on a surface covering only 2% of the French total area.

With an estimated gross domestic product (GDP) of 764.8 billion euros and a per capita GDP of 62,105 euros in 2021, it is the region that produces the most wealth in France. Île-de-France is also a major European centre, ranking second in Europe for GDP.

Reference emissions inventories covering both Paris and the whole Île-de-France are produced by Airparif, an independent regional association for air quality monitoring accredited by the French Ministry of Environment for monitoring and informing about air quality in the Île-de-France region.

Airparif builds and updates regularly (3 times in 5 years), the emissions inventory of air pollutants and greenhouse gases in the Île-de-France region. In accordance with the 14th Article of the Order of April 2017 on the national ambient air quality monitoring system, Airparif uses the national guidelines (PCIT guide[1]) to prepare its inventory. In case of changing methodologies, Airparif recalculates the previous reference inventories in order to allow a comparison between the old and new versions.

2.1 Methodology

The city emission inventory for Paris has been prepared by AIRPARIF. The whole Île-de-France region (province) is considered. The emissions are calculated based on regional statistics combined with emission factors and based on reported emissions from individual companies. The AIRPARIF website provides an overview of the emissions (Bilan-Ile-France-Année 2021) and the latest used methodology (Bilan Île-de-France – Année 2018)).

Deliverable 1.2 for Paris consists of a gridded emission inventory for 2018 and 2022 at a resolution of 500x500 m^2. A summary of the characteristics of this emission inventory and the methodology for each sector is included in Table 1.

New developments have been described in more detail in section 2.1.1.

[1] https://www.lcsqa.org/fr/rapport/guide-methodologique-pour-lelaboration-des-inventaires-territoriaux-des-emissions

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Table 1: Characteristics of the city emission inventory of Paris including an overview of the type of data and an indicative summary of the methodology for each sector

Characteristics		
City	Paris	
Years	2018 and 2022	
Pollutants	CO_2, CH_4, NO_x, CO, BC	
Spatial resolution	Gridded at 500x500 m^2	
Temporal resolution	Annual	
Sector	**Type of data**	**Methodology (indicative)**
A - Public Power	Point sources	Punctual: Emissions and activities data are given by industries that have the obligation to declare their emissions in the national register Spatial distribution: Point sources
B – Industry	Point sources, and partly national downscaled	Mix of punctual sites and top-down approaches depending on SNAP sector. Spatial distribution: Partly point sources and partly gridded at 500 x 500 meters according to the specific land use linked to industry (Corine land cover, 2022)
C - Other stationary combustion	City and regional data	Services: regional unitary energy consumption per type of services combined with employees Residential: regional unitary energy consumption per type of houses combined with the number of houses Specific work for wood burning (specific data for people who use wood from regional surveys) Agriculture: regional energy consumption combined with emission factors (EF) and spatialisation according to the number of employees Spatial distribution: Gridded at 500 x 500 meters according to specific land use used for agriculture (agricultural soils)
D – Fugitives	City and regional data	Fugitive emissions from gas distribution and transport are taken into account based on the length of the gas network and the gas consumption per sector. Spatial distribution: Gridded at 500 x 500 meters according to the Corine urban land cover category
E - Solvents & product use	National downscaled	For each sector, use of national EF per inhabitant. Spatial distribution: Gridded at 500 x 500 meters according to the land use from Corine land cover category Pollutants considered here are from "product use" and not from solvents use
F - Road transport	Bottom-up city data	Bottom-up approaches based on traffic loops data, traffic model, regional fleet of vehicles. COPERT V EF Spatial distribution: Gridded at 500 x 500 meters according to the length of the road intersecting the grid

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G – Shipping	City and regional data	Methodology based on traffic ships data from locks on the Seine river. Recreational shipping and cargo ships are included Spatial distribution: Gridded at 500 x 500 meters according to the length of the river intersecting the grid
H – Aviation	City and regional data	Methodology is taking into account the number of flights, engine types, ICAO EF per LTO phase, specific taxi time Spatial distribution: Point sources. Bundle craft trajectories based on 3D aircraft geolocation
I - Off Road (railways)	National downscaled	Top-down approach based on regional energy consumption for the railway sector. This consumption is spatialized according to the number of trains.km Spatial distribution: Gridded at 500 x 500 meters according to the length of the railway intersecting the grid
I - Off Road (mobile machinery)	Partly national downscaled and partly city bottom-up	Industry top-down based on regional energy consumption and national EF Agriculture: bottom-up based on fleet of specific machines and unitary consumption factor Residential: bottom-up based on fleet of specific machines and unitary consumption factor Construction: top-down based on regional energy consumption and national EF Spatial distribution: Gridded at 500 x 500 meters according to the land use categories from Corine Landcover map.
J – Waste	Point sources	Punctual: Emissions and activities data are given by industrials that have the obligation to declare their emissions in the national register Spatial distribution: Point sources
K – AgriLivestock	Bottom-up city data	Agricultural census of livestock combined with emission factor by type of animal Spatial distribution: Gridded at 500 x 500 meters according to the land use from Corine Landcover map.
L – AgriOther	City and regional data	Tonnages of regional fertilizers delivered and distributed over agricultural land combined with national EF Spatial distribution: Gridded at 500 x 500 meters according to the land use from Corine Landcover map.
Other	City and regional data	NO emissions from soils come from soil denitrification and nitrification phenomena. The methodology takes into account soil temperature and humidity Spatial distribution: Gridded at 500 x 500 meters according to the land use from Corine Landcover map.
O - Respiration	City and regional data	CO2 emissions from human respiration

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		Based on statistical numbers of total population, commuters, and tourists in the city of Paris and the whole Ile-de-France.

2.1.1 New developments

Two additional developments have been realized during the previous months. It concerns two new activity sectors that have never been taken into account in the emissions inventories developed by Airparif.

One is related to emissions due to industrial composting, the other is related to CO_2 linked with human respiration.

Industrial composting emissions are calculated for each industrial composting platform in Île-de-France. The amount of waste treated by each industrial composting platform is known for 2022. This amount of waste is then coupled with emissions factors from national guidelines built by CITEPA to compute emissions. Total CH_4 emission linked to this new sector are significant because they represent more than 1 500t of CH_4 for the whole Île-de-France. This new sector is included in the J-Waste GNFR sector.

Human respiration emissions are calculated with a basic method taking into account both working population and non working population (kids, unemployed and retired people), as well as tourists.

Data used for the working population are the number of employees for all cities in Île-de-France. It is assumed that workers are in their office from 8am to 7pm and at home the rest of the day. These data come from an urban planning agency in île-de-France called Institut Paris Region.

The non working population is provided by INSEE with the national institute dealing with demographical and economic data.

Finally, the evaluation of the number of tourists per city is calculated from the annual numbers of tourists in Paris and Île-de-France and tourist numbers by department. Data for tourists come from Paris Region[2].

[2] "Bilan de l'activité touristique à Paris et en Ile-de-France, résultats annuels 2020" - Paris Region, Comité régionail du Tourisme

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2.2 Gridded emissions

Total emissions for Paris are presented in Table 2 and Table 3, and gridded emissions for CO_2, NO_x and CO are presented in Figure 1, Figure 2 and Figure 3.

Table 2: Emissions of Paris in 2018, as included in Deliverable 1.2.

Sector	CO_2 fossil (kton)	CO_2 bio (kton)	NO_x (ton)	CO (ton)
A - Public Power	2 089.5	711.5	2 408.7	1 657.1
B - Industry	3 962.0	9.9	4 786.3	3 399.6
C - Other stationary combustion	12 529.8	1 567.7	12 411.8	64 477.1
D - Fugitives	673.1	0.2	730.3	0.0
E - Solvents & product use	181.5	0.0	120.8	15.7
F - Road transport	11 795.0	0.0	38 645.6	37 936.7
G - Shipping	102.9	0.0	1 136.6	864.6
H - Aviation	1 365.5	0.0	6 716.0	4 365.9
I - Off Road	605.1	0.0	3 665.0	18 801.6
J - Waste	1 545.0	2 270.7	1 673.8	1 415.1
K - AgriLivestock	0.0	0.0	0.0	0.0
L - AgriOther	0.0	0.0	1 556.4	0.0
Other	0.0	0.0	15.2	0.0
O - Respiration	0.0	0.0	0.0	0.0
Total	**34 849.4**	**4 559.9**	**73 866.6**	**132 933.4**

Table 3: Emissions of Paris in 2022, as included in Deliverable 1.2.

Sector	CO_2 fossil (kton)	CO_2 bio (kton)	CH_4 (ton)	NO_x (ton)	CO (ton)
A - Public Power	1 880.6	502.0	169.6	2 167.8	1 491.4
B - Industry	4 031.0	12.9	739.0	4 038.9	3 426.5
C - Other stationary combustion	10 060.2	9.7	3 596.6	10 002.7	58 217.6
D - Fugitives	673.1	0.2	8 071.9	706.8	0.0
E - Solvents & product use	181.5	0.0	6.6	120.7	15.7
F - Road transport	11 105.1	0.0	841.1	30 377.1	35 717.8
G - Shipping	102.9	0.0	11.8	1 136.6	864.6
H - Aviation	1 160.7	0.0	39.7	5 708.6	3 711.0
I - Off Road	590.7	0.0	661.3	3 588.0	18 731.2
J - Waste	1 539.5	2 270.7	19 321.4	1 421.6	1 414.7
K - AgriLivestock	0.0	0.0	453.1	0.0	0.0
L - AgriOther	0.0	0.0	2 183.1	1 556.4	0.0
Other	0.0	0.0	0.0	15.2	0.0
O - Respiration	3 141.1	0.0	0.0	0.0	0.0
Total	**34 466.4**	**2 795.5**	**36 095.2**	**60 840.4**	**123 590.5**

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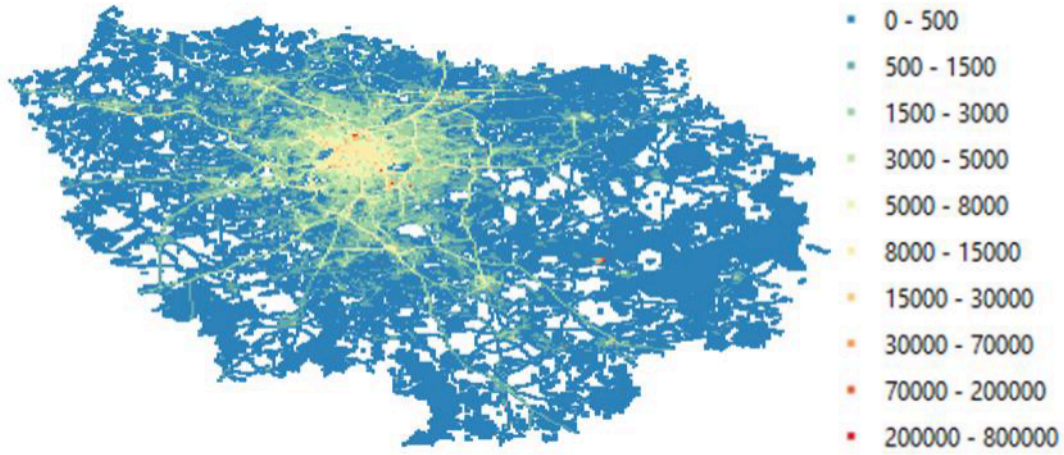

Figure 1: Total emissions of CO_2 (ton/gridcell) of Paris in 2022. Gridcell size is 500x500 meters.

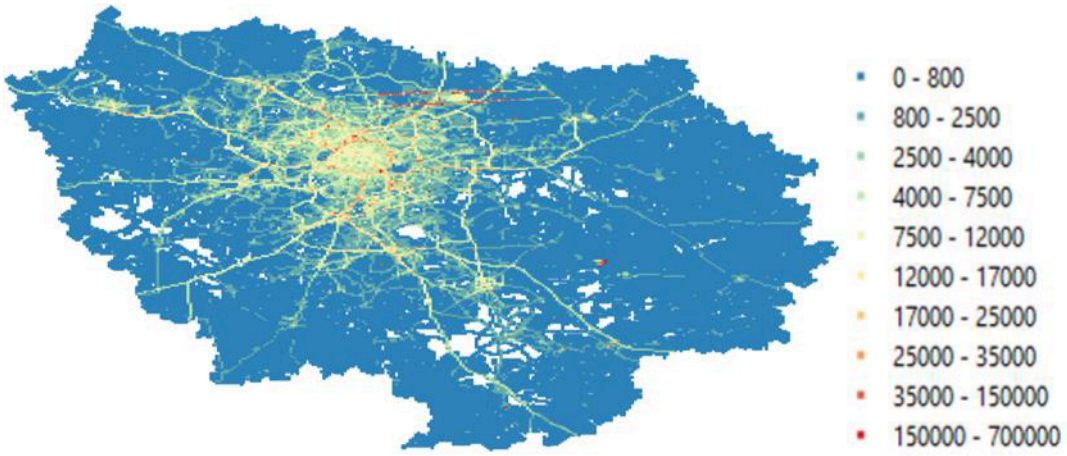

Figure 2: Total emissions of NO_x (kg/gridcell) of Paris in 2022. Gridcell size is 500x500 meters.

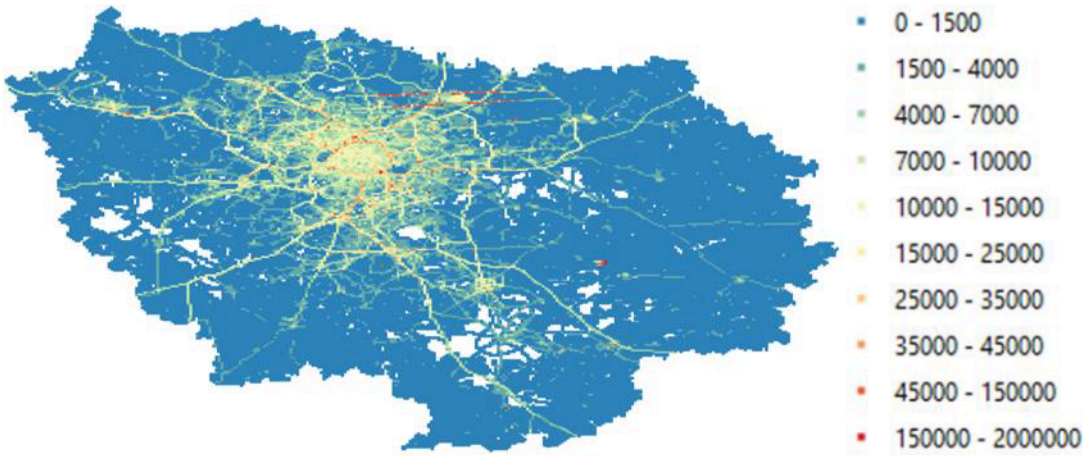

Figure 3: Total emissions of CO (kg/gridcell) of Paris in 2022. Gridcell size is 500x500 meters.

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3 Munich emission inventory

The City of Munich (Landeshauptstadt München, LHM), located in the South East of Germany, spans 310.7 km^2. With a population of over 1.5 Million, it is the third-largest city in Germany. Due to its importance to the economy and its good living conditions, the population is expected to grow to 1.8 Million by 2040. Munich plans to become climate-neutral by 2035.

The City of Munich publishes yearly CO_{2e} estimates for energy, heat and mobility demands of its citizens based on the BISKO methodology (Bilanzierungs-Systematik Kommunal). The latest report is from 2022 and lists emissions from 1990 to 2019. In addition, a spatial inventory is available from the German Environmental Agency (Umweltbundesamt, UBA) and the Netherlands Organisation for Applied Scientific Research (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, TNO) with a spatial resolution of 1x1 km^2 and 1/60° x 1/120°, respectively. Both inventories combine spatially disaggregated bottom-up estimates and point sources with exact locations for some sectors with proxy-based downscaling of national emissions for the remaining ones. However, none of the available spatial emission inventories satisfies the project requirements.

The sectors of public power, stationary combustion, road transport, and human respiration, which represent over 90% of Munich's CO_2 emissions, are created by a bottom-up approach using local data. Based on the resulting street- and building-resolution product, a gridded 100x100 m^2 product was exported. The remaining sectors (Fugitives, Solvents & product use, Shipping, Aviation, Off-road (railways), Off-road (mobile machinery), Waste, AgriLivestock, AgriOther, Other) are based on downscaling the TNO-GHGco V4.1 emission inventory (Dellaert et al., 2022) from 1x1 km^2 to 100x100 m^2.

Deliverable 1.2 for Munich provides a gridded emission inventory for 2019 to 2022 with a spatial resolution of 1/600° x 1/1200° (about 100x100 m^2). A summary of the characteristics of this emission inventory and the methodology for each sector is included in Table 4. An executive summary of the methodology can be found in section 3.1. Figure 4 shows the sum of all gridded emission products and point sources within the administrative boundary of the City of Munich. Densely built-up areas and streets are clearly discernible.

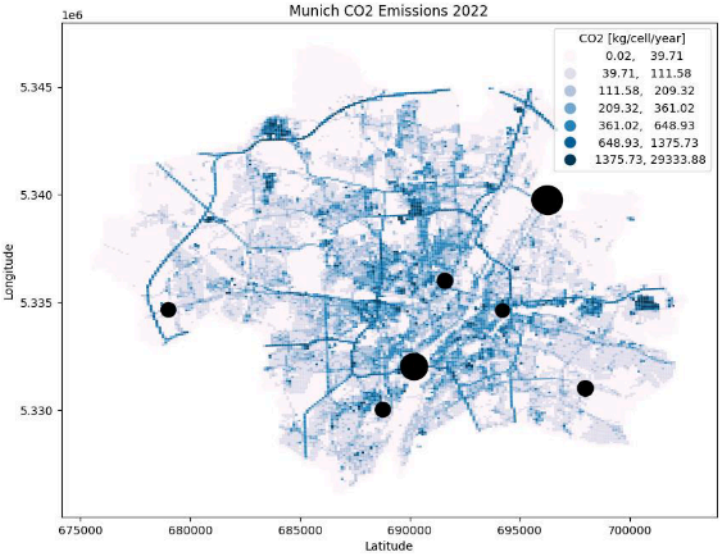

Figure 4: Gridded CO_2 emissions and point sources of the City of Munich

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3.1 Methodology

3.1.1 GNFR A – Public Power

Public power and district heating in Munich are provided through combined heat and power plants (CHP) and heating plants (HP). While the CHP North burns coal, waste, and sewage sludge, the other plants are primarily powered by natural gas. Over the next decades, Munich plans to slowly extend its renewable energy production through geothermal energy.

The main input for this sector is the yearly environmental report of the Municipal Utility Company (Stadtwerke München, SWM) and the shared information for chimney locations and height. The provided 3D point sources pinpoint the exhaust entry into the atmosphere. A quality check for the SWM-reported 2019 emissions was performed based on internal shared hourly fuel consumption, fuel composition, and calculated emission factors for all CHP/HP plants in Munich. Based on these results, the emissions from 2019 - 2022 are extracted directly from public reports [3].

3.1.2 GNFR B - Industry

Munich has no emission-intense industry within its city borders. Most industry-related emissions can be connected to local power generation or the heating of working spaces. While we have information on total industry-related gas consumption, we can not separate these into process and combustion-related shares. Therefore, emissions from industrial areas are bundled into the stationary combustion GNFR C sector.

3.1.3 GNFR C – Stationary Combustion

Munich buildings are primarily heated by natural gas, light heating oil, or district heating. The total emissions of this sector are calculated by the reported yearly natural gas and oil consumption. Emissions from district heating are included in GNFR A. We received the annual numbers for total natural gas consumption of 2019-2022 directly from SWM. The total heating oil consumption is extracted from the annual emissions report (2022) [4] of the City of Munich. Unfortunately, starting from 2019, the data source changed, and LHM is reporting a high uncertainty on oil consumption. The latest consumption information is available for 2019. Oil consumption for 2020 – 2022 is extrapolated with a factor based on the gas consumption numbers of these years. Wherever available, we utilize industry self-reports for natural gas and heating oil consumption based on the Eco Management and Audit Scheme (EMAS). Emissions from industry locations with EMAS reports are calculated and added manually. The reported total yearly consumption from SWM and LHM has been adjusted accordingly.

The total annual energy consumption is distributed using two proxies: heating type and heat demand, calculated from building features. The computed heat demand per building is quality-checked versus a norm-based heat demand building model [Harter 2020], available for a subset of residential buildings. The building features are derived by joining different geospatial datasets provided by contacts from LHM, SWM, and the Bavarian ministry (Landesamt für Breitband, Digitalisierung und

[3] https://risi.muenchen.de/risi/sitzungsvorlage/detail/7205164?dokument=v7222928

[4] https://risi.muenchen.de/risi/sitzungsvorlage/detail/7205164?dokument=v7222928

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Vermessung, LBDV). Emission factors for stationary combustion are taken from the Umweltbundesamt (UBA) [Juhrich2022].

3.1.4 GNFR F – Road Transport

Emissions from the road transport sectors were modeled based on Munich's official macroscopic traffic model, including data from more than 100 traffic counting stations and HBEFA (Handbook Emission Factors of Road Transport) emission factors. The counting data was provided by the city of Munich and BASt (Bundesanstalt für Straßenwesen, eng.: Federal Highway Institute).

The traffic model provides information on the average daily traffic volume during weekdays outside vacation time. The analysis year is 2019. Traffic counting data was used to scale the traffic model temporally and achieve a temporal resolution of 1 hour for 2019, 2020, 2021, and 2022. Additionally, the congestion state was estimated based on the volume capacity ratio of each road section within the city area. Cold start excess emissions were calculated based on the number of vehicle starts in the traffic model.

It's worth noting that while the analysis encapsulated a wide array of factors, public transport and tunnels were intentionally excluded from consideration. Additionally, though congestion levels were estimated, the exact precision of this estimation may vary due to the inherent complexities of traffic dynamics.

The method on Munich's road transport emissions is currently being documented in detail and will be published in a peer-reviewed journal.

3.1.5 Human Respiration

CO_2 from Human respiration is separated into three sectors: "indoor residential," "indoor non-residential," and "outdoor." The total population, commuters, and tourist numbers are extracted from statistical data provided by the municipal statistics department. Based on geospatial information, a split between residential, commercial, and recreational areas is generated. Population density for subdistricts and building data are used to locate emissions in residential areas. The 2022 Time Use Survey (Zeitverwendungserhebung, ZVE) from the German Federal Statistical Office allocates the amount of time spent at different locations. Based on Google Reviews, the popularity of outdoor locations is estimated to distribute outdoor activity.

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Table 4: Characteristics of the city emission inventory of Munich, including an overview of the type of the data and an indicative of the methodology for each sector

Characteristics		
City	Munich	
Years	2019, 2020, 2021, 2022	
Pollutants	CO_2 (divided into CO_2(total) and CO_{2_bio} to account for biogenic sources for some sectors), NO_x, CO, PM (for some sectors), CH_4 (for some sectors)	
Spatial resolution	Gridded at 1/600° x 1/1200° plus point sources	
Temporal resolution	Annual	
Sector	**Type of data**	**Methodology (indicative)**
A - Public Power	Point sources	All powerplants and combined heat and powerplants (CHP) are operated by the city utility company (SWM), which publishes their emissions annually. Emissions were verified based on input data provided by SWM and allocated to the exact point source.
B – Industry	-	No emission-intense industry within the municipal boundaries. Office and workplace heating of industrial areas is included in GNFR C.
C - Other stationary combustion	Bottom-up city data	Energy demand estimate per building to distribute reported annual energy consumption per sector and fuel type based on a block-level energy utilization plan. Spatial resolution: individual building level
D - Fugitives	National downscaled	TNO-GHGco inventory V4.1 inventory at 1x1 km
E - Solvents & product use	National downscaled	TNO-GHGco inventory V4.1 inventory at 1x1 km
F - Road transport	Bottom-up city data	Based on local, macroscopic traffic model, traffic counting data from local and national authorities and national statistics. Spatial distribution: Line sources based on street network. CO_{2_total} and CO_{2_bio} to account for biofules.
G - Shipping	-	Not occurring
H - Aviation	National downscaled	TNO-GHGco inventory V4.1 inventory at 1x1 km
I - Off Road (railways)	National downscaled	TNO-GHGco inventory V4.1 inventory at 1x1 km
I - Off Road (mobile machinery)	National downscaled	Downscaled TNO-GHGco inventory V4.1 inventory to 100x100 meters using ESA WorldCover "arable land" land use type (for the agriculture/forestry sector), using combination of CORINE "Industrial_or_commercial_units" and ESA WorldCover "built-up" land use types (for the construction, industry and commercial sector), and using population from Human Settlement Layer (for the residential sector).

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J - Waste	National downscaled	Point sources at exact location; Remainder TNO-GHGco inventory V4.1 inventory at 1x1 km
K - AgriLivestock	-	Downscaled TNO-GHGco inventory V4.1 inventory to 100x100 meters using a combination of CORINE "Pastures" and ESA WorldCover "grassland" land use types.
L - AgriOther		Downscaled TNO-GHGco inventory V4.1 inventory to 100x100 meters using ESA WorldCover "arable land" land use type.
Other		Not included
HR – Human Respiration	Bottom-up city data	Based on statistical numbers of total population, commuters, and tourists in the city of Munich

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3.2 Gridded emissions

Total emissions for Munich are presented in Table 5 and Table 6, and gridded emissions for CO_2, NO_x and CO are presented in Figure 5, Figure 6 and Figure 7.

Table 5: Emissions of Munich in 2020, as included in Deliverable 1.2.

Sector	CO_2 (kton)	CH_4 (ton)	NO_x (ton)	CO (ton)
A - Public Power	2 898.9	848.4[5]	1 717.2	144.8
B - Industry	-	-	-	-
C - Other stationary combustion	1 868.2	282.0[5]	722.1	397.8
D - Fugitives	0.2	1 686.7	0.0	0.0
E - Solvents & product use	32.8	0.0	3.7	230.0
F - Road transport	1 048.1	53.9	2 378.7	3 176.4
G - Shipping	0.0	0.0	0.0	0.0
H - Aviation	0.0	0.0	0.0	0.0
I - Off Road	67.4	10.6	276.3	3 018.0
J - Waste	0.0	2 386.7	9.7	5.1
K - AgriLivestock	0.0	86.2	0.0	0.0
L - AgriOther	0.8	15.8	0.0	0.2
Human Respiration	445.9	0.0	0.0	0.0
Total	**6 362.3**	**4 239.9**	**5 107.6**	**6 972.2**

Table 6: Emissions of Munich in 2022, as included in Deliverable 1.2.

Sector	CO_2 (kton)	CH_4 (ton)	NO_x (ton)	CO (ton)
A - Public Power	2 382.4	778.1[5]	1 286.4	76.9
B - Industry	-	-	-	-
C - Other stationary combustion	1 785.3	212.4[5]	681.4	388.6
D - Fugitives	41.3	250.6	0.0	0.0
E - Solvents & product use	34.5	14.4	3.7	227.9
F - Road transport	1 070.7	53.2	1 995.9	2 967.3
G - Shipping	0.0	0.0	0.0	0.0
H - Aviation	0.0	0.0	0.0	0.0
I - Off Road	69.8	11.5	270.3	3 047.0
J - Waste	0.0	1 060.5	11.4	5.0
K - AgriLivestock	0.0	83.8	0.0	0.0
L - AgriOther	0.8	16.2	0.0	0.2
Human Respiration	445.9	0.0	0.0	0.0
Total	**5 830.7**	**2 480.7**	**4 595.6**	**6714.87**

[5] Value retrieved from TNO-GHGco inventory V4.1 for completeness of the table but not included in the spatial inventory.

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Figure 5: Total emissions of CO_2 (ton/gridcell) of Munich in 2022. Gridcell size is 100x100 meters.

Figure 6: Total emissions of NO_x (kg/gridcell) of Munich in 2022. Gridcell size is 100x100 meters.

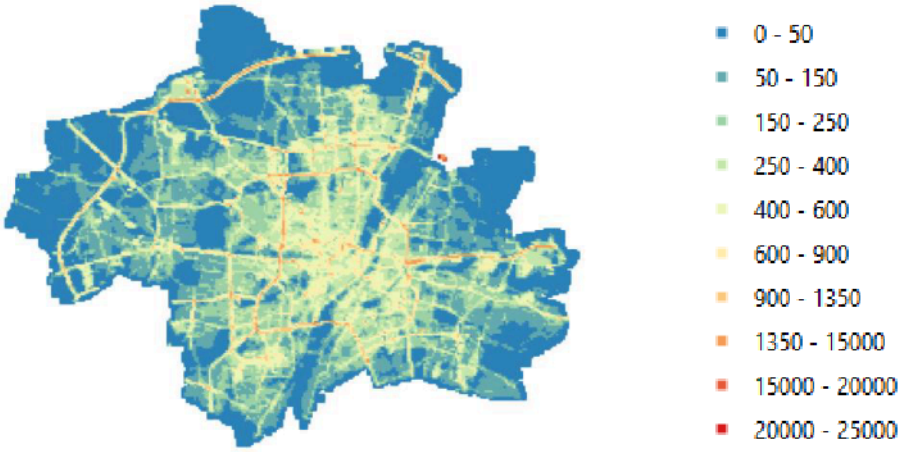

Figure 7: Total emissions of CO (kg/gridcell) of Munich in 2022. Gridcell size is 100x100 meters.

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4 Zurich emission inventory

Zurich is the largest city in Switzerland, with approximately 422,000 inhabitants (31 Dec 2020) within the city boundaries. The greater Zurich metropolitan area, or agglomeration, has an additional population of around 1,000,000, making it the largest agglomeration in Switzerland.

The city of Zurich has developed a detailed inventory of point, line, and area sources, called MapLuft. The inventory is currently available for the years 2010, 2015, 2020, and 2022 and is planned to be updated every 2 years. Here we only use the inventories for the years 2020 and 2022. The inventory covers 9 air pollutants (PM_{10}, $PM_{2.5}$, NO_x, CO, SO_2, NH_3, VOCs, soot, benzene) and 3 greenhouse gases (CO_2, CH_4, N_2O) divided into 65 different source categories. In addition to anthropogenic emissions, we have included emissions from human respiration for both CO_2 and CH_4. A map of total CO_2 emission in the city is presented in Fig. 8 (left), and a pie chart of the relative share of different sectors in Fig. 8 (right).

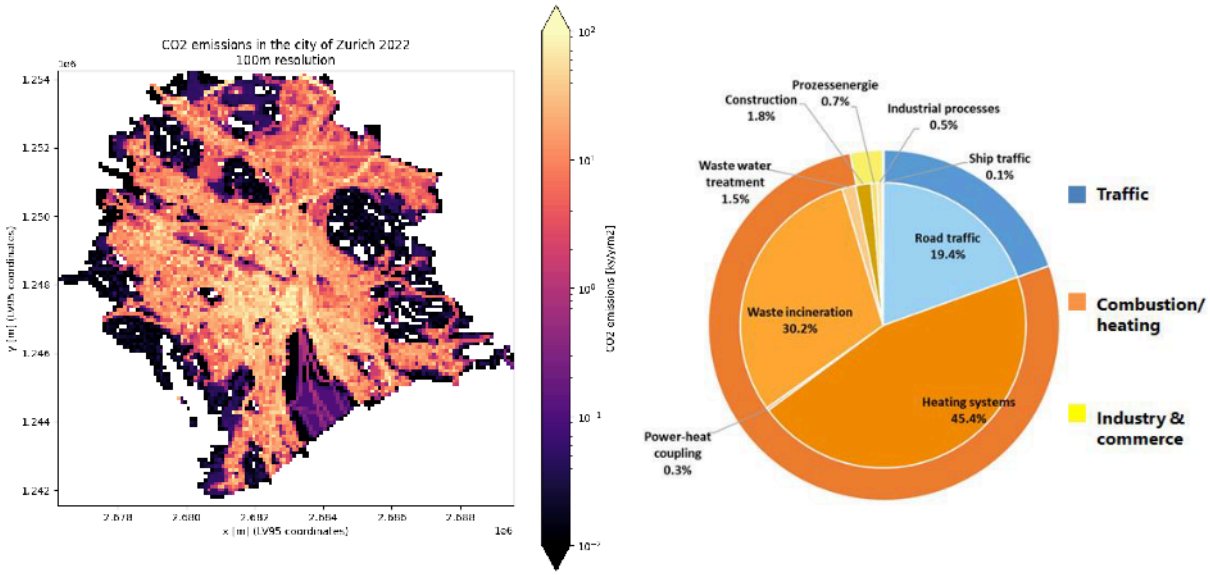

Figure 8 : Anthropogenic CO_2 emissions in Zurich. Left: Map of total emissions in 2022 at 100 m x 100 m resolution. Right: Relative share of different sectors in 2020 when both waste incinerators were still active.

4.1 Methodology

The emission inventory of Zurich was prepared in two versions. In the first version ("Zurich_cropped"), only emissions within the political boundaries of the city of Zurich are reported. In the second version ("Zurich_inside_swiss"), the emissions in the city are complemented by emissions from the official Swiss national emission inventory for a larger region around the city. The emissions of the original 65 categories were aggregated into the 14 GNFR categories listed in the table below. The Swiss inventory was aggregated in a similar way so that the merging of the two data sets was straightforward.

The anthropogenic emissions of CO_2 were additionally split into fossil and non-fossil contributions. For this, the following assumptions about the biogenic fraction were made: Wood burning: 100%, waste

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incineration: 52% (based on a study by Mohn et al. (2012) on radiocarbon content in waste incineration exhaust), traffic: 2.4% (same value as used in Swiss national inventory), plant residue burning: 100%.

The emissions in Zurich are calculated based on regional statistics combined with emission factors. The website of the city of Zurich provides an overview of the emissions and a general description of the methodology (Emissionskataster Zurich).

Deliverable 1.2 for Zurich consists of a gridded emission inventory for 2020 and 2022 at a resolution of 100x100 m^2. A summary of the characteristics of this emission inventory and the methodology for each sector is included in Table 7.

Table 7: Characteristics of the city emission inventory of Zurich, including an overview of the type of the data and an indicative of the methodology for each sector

Characteristics		
City	Zurich	
Years	2020 and 2022	
Pollutants	CO_2, CH_4, NO_x, CO, BC, SO2, benzene, VOC, NH3, PM10, PM2.5 CO_2 is divided into fossil (CO2_fos) and biogenic (CO2_bio) $PM_{2.5}$ and PM_{10} is divided into exhaust (PM_ex) and non-exhauts (PM_non)	
Spatial resolution	Gridded at 100x100 square meter	
Temporal resolution	Annual	
Sector	**Type of data**	**Methodology (indicative)**
A - Public Power	Point sources	Reported fuel consumption from combined heat and power plants and reported waste and fuel consumption from waste incineration facility. One of the two waste incinerators (at Josefstrasse) was closed in 2020 and is no longer present in the 2022 inventory. Spatial distribution: Point sources
B - Industry	Point sources, and partly national downscaled	Divided into emissions from fuel consumption for process energy production and into other, usually fugitive, emissions. Big industries (only few within the city) have to report fuel consumption. For smaller businesses, the emissions for process energy production are estimated by assigning a representative emission factor based on technical data available for the business. For other emissions, an emission factor per employee is assumed and scaled by the number of employees Spatial distribution: Point sources
C - Other stationary combustion	City data	Based on building-level information on heating system, fuel type, fuel consumption in the current and previous years and the heating degree days in this year relative to average conditions Spatial distribution: Point sources for each building with stationary combustion

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D - Fugitives	City data	Emission factor times the petrol usage per gas station. Relevant for VOCs but not for species considered here. Spatial distribution: point sources
E - Solvents & product use	-	Included in 'other'
F - Road transport	Bottom-up city data	Based on Handbook of Emission Factors (HBEFA) accounting for road properties, traffic volume, fleet composition, driving/congestion conditions, slope of streets, start/stop of cars, fugitive losses from tanks, abrasion, etc. Spatial distribution: Line and point sources based on street network
G - Shipping	City data	For public ships/ferries the schedule and fuel consumption are known. For private/recreational ships information about engine types and number of boats is available Spatial distribution: Line sources for ferries, polygons for private shipping
H - Aviation	-	Not occurring within the city boundaries of Zurich, but included in the Swiss inventory
I - Off Road (railways)	-	Railway emissions only relevant for PM10.
I - Off Road (mobile machinery)	Partly national downscaled and partly city bottom-up	Construction: duration x average machine use per day. Industry: downscaling of Swiss emissions. Agriculture/Forestry: Duration of annual use of different machineries are known Spatial distribution: Lines for forestry, polygons for agriculture and construction
J - Waste	Point sources, and partly national downscaled	For waste incinerators the emission numbers are reported by the operators, private (illegal) waste incineration is estimated. Spatial distribution: Point sources at incineration plant, polygons for private waste incineration. Warning: Emissions of CH_4 and N_2O from waste water treatment plants are currently not considered.
K - AgriLivestock	Bottom-up city data	Number of various animals are known, multiplied by emission factors for different livestock processes Spatial distribution: Polygons
L - AgriOther	National downscaled	Downscaling of Swiss emissions Spatial distribution: Polygons
O - HumanRespiration	Bottom-up from city data	Scaled up based on number of persons living and working in each building, occupancy profiles from the Swiss Architecture and Engineering Society, and an emission factor per person from literature.
Other	City data	Natural emissions are based on area and estimated emission factors per area Spatial distribution: Polygons

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4.2 Gridded emissions

Total emissions for Zurich are presented in Table 8 and Table 9, and gridded emissions for CO_2, NO_x and CO are presented in Figure 9, Figure 10 and Figure 11.

Table 8: Emissions of Zurich in 2020, as included in Deliverable 1.2.

Sector	CO_2 fos (kton)	CO_2 bio (kton)	CH_4 (ton)	NO_x (ton)	CO (ton)	BC (ton)
A - Public Power	204.7	213.3	1.4	185.1	15.2	0.0
B - Industry	10.6	0.0	1.0	20.9	8.8	0.5
C - Other stationary combustion	603.5	20.9	56.7	234.2	376.6	5.5
D - Fugitives	0.2	0.0	0.0	0.0	0.0	0.0
E - Solvents & product use	0.0	0.0	0.0	0.0	0.0	0.0
F - Road transport	376.0	9.2	14.2	751.3	788.5	3.7
G - Shipping	0.7	0.0	0.1	7.4	22.4	0.0
H - Aviation	0.0	0.0	0.0	0.0	0.0	0.0
I - Off Road	13.3	0.0	0.3	50.2	112.3	0.7
J - Waste	24.8	0.0	40.1	9.7	39.5	0.8
K - AgriLivestock	0.0	0.0	54.9	0.9	0.0	0.0
L - AgriOther	0.0	0.0	0.0	0.7	0.0	0.0
O - HumanRespiration	0.0	162.4	24.2	0.0	0.0	0.0
R - Other	0.1	0.7	0.7	7.1	43.1	8.9
Total	**1 233.9**	**406.6**	**193.5**	**1 267.5**	**1 406.3**	**20.2**

Table 9: Emissions of Zurich in 2022, as included in Deliverable 1.2.

Sector	CO_2 fos (kton)	CO_2 bio (kton)	CH_4 (ton)	NO_x (ton)	CO (ton)	BC (ton)
A - Public Power	134.7	127.2	2.1	90.3	4.7	0.0
B - Industry	10.0	0.0	1.0	16.8	9.8	0.4
C - Other stationary combustion	554.2	21.5	54.0	204.6	412.4	5.7
D - Fugitives	0.0	0.0	0.0	0.0	0.0	0.0
E - Solvents & product use	0.0	0.0	0.0	0.0	0.0	0.0
F - Road transport	354.4	8.7	13.0	559.6	660.8	2.1
G - Shipping	0.9	0.0	0.1	9.1	23.7	0.0
H - Aviation	0.0	0.0	0.0	0.0	0.0	0.0
I - Off Road	16.0	0.0	0.3	59.1	120.4	0.8
J - Waste	27.8	0.0	35.6	12.9	39.8	0.9
K - AgriLivestock	0.0	0.0	56.3	1.0	0.0	0.0
L - AgriOther	0.0	0.0	0.0	0.6	0.0	0.0
O - HumanRespiration	0.0	162.4	24.2	0.0	0.0	0.0
R - Other	0.1	0.7	0.7	7.1	43.5	5.2
Total	**1 098.0**	**320.6**	**187.3**	**961.0**	**1 315.1**	**15.1**

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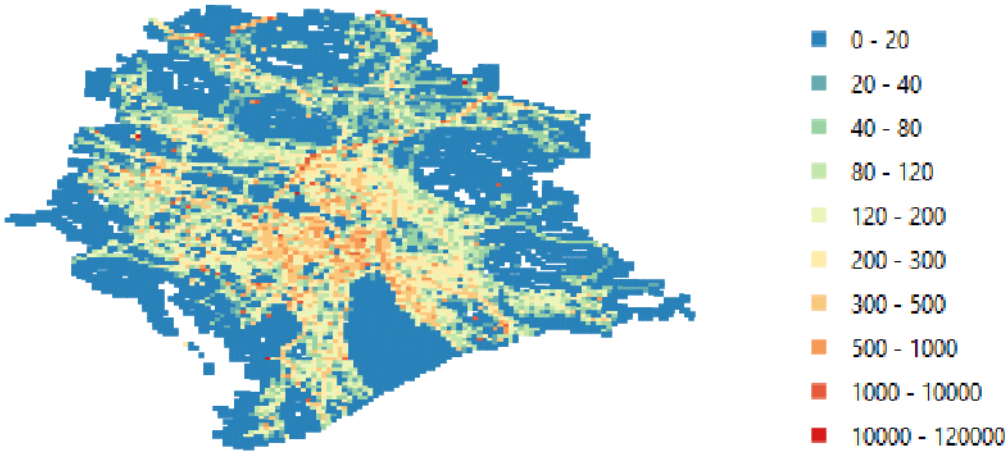

Figure 9: Total emissions of CO_2 (ton/gridcell) of Zurich in 2022. Gridcell size is 100x100 meters.

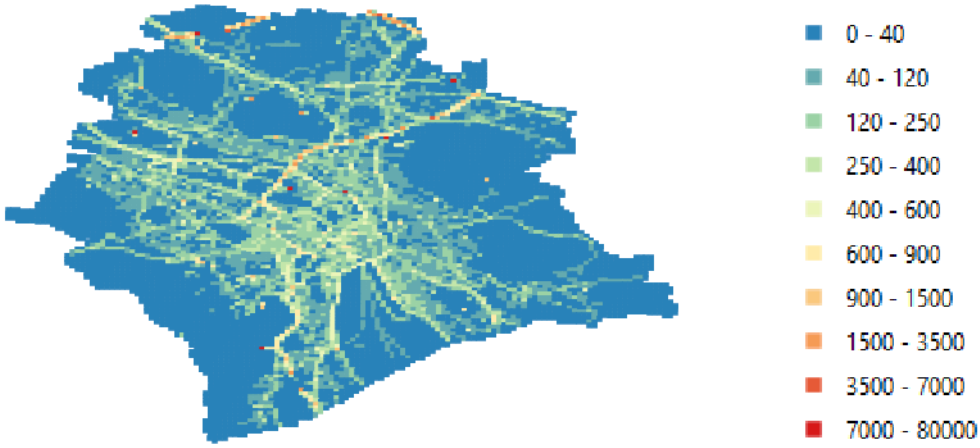

Figure 10: Total emissions of NO_x (kg/gridcell) of Zurich in 2022. Gridcell size is 100x100 meters.

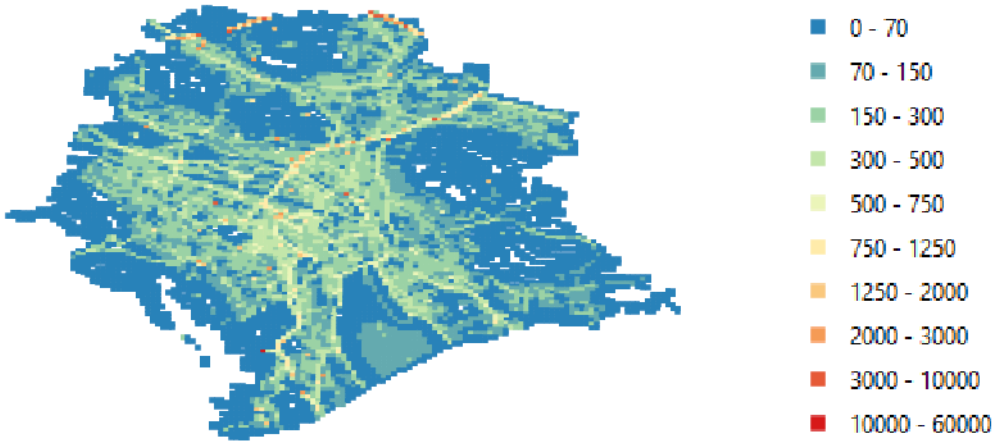

Figure 11: Total emissions of CO (kg/gridcell) of Zurich in 2022. Gridcell size is 100x100 meters.

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5 Discussion and conclusions

This deliverable report described the final city emission inventory (provided as ICOS Cities deliverable 1.2), including an indicative, brief description of the methodology used. Compared to the first city emission inventory (provided as ICOS Cities deliverable 1.1), the emission inventory has been considerably improved:

- For Munich, local emission models have been developed for GNFR A, C, and F, replacing the downscaled emissions from the TNO GHGco inventory.
- Missing sources have been added: CO_2 emissions from human respiration in all cities, composting in Paris, and gas distribution in Zurich..
- Some minor updates/corrections in the other emission sources
- A final version of the 2022 emissions has also been prepared to include missing emission sources (human respiration in all cities, composting in Paris and gas distribution in Zurich), and are included in this deliverable. This is an update of the 2022 emissions provided for ICOS cities deliverable 2.1.
- The emission inventories have been harmonized, using the same netcdf format.

The aim of this deliverable is to provide complete, spatially explicit, state-of-the-art emission inventories for greenhouse gases CO_2 and CH_4 and co-emitted species (CO, NO_x, BC) to WP2 for Paris, Munich, and Zurich.

The city emission data are available for internal use within the ICOS Cities PAUL project through the ICOS Cities file share. The data will at a later stage, but before the end of the ICOS cities PAUL project, be made publicly available by the involved institutes with the exception of confidential data. To make the best product for the city modelling in some cases the teams needed to use data at a resolution that could be made available to the project but without the permit to share it publicly. In such cases a coarser resolution will be made available. The other constraint for making data already public is that some results first need to be published in the peer-reviewed literature. The expectation is that this will be achieved in 2025. Should the publications, unexpectedly, not be realized before the end of the project, then a version of the data will be made public.

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ICOS Cities

Appendix 1 Sector overview

Table 10 provides an overview of the completeness of categories in the city inventories. Crossed out sectors are not included in the city inventories. Sectors displayed in grey colour are not occurring in the city.

Table 10: Assessment of completeness of categories in the city emission inventories. Crossed out sectors are not included in the city inventories. Sectors displayed in grey colour are not occuring in the city.

Sector	Paris	Munich	Zurich
A - Public Power	Fossil and biogenic fuel combustion	Fossil ~~and biogenic~~ fuel combustion in combined heat and power plants, fossil and biogenic waste incineration, all assumed to be fossil	Fossil and biogenic fuel combustion in combined heat and power plants, fossil and biogenic waste incineration
B - Industry	Fossil and biogenic fuel combustion, process emissions	~~Fossil and biogenic fuel combustion, process emissions~~	Fuel combustion and process emissions, all assumed to be fossil
C - Other stationary combustion	Fossil and biogenic fuel combustion in services, residential and agricultural/forestry sector	Fossil ~~and biogenic~~ fuel combustion in services, residential, commercial and industry ~~and agricultural/forestry~~ sector, process emission (where available)	Fossil and biogenic (wood) fuel combustion in services, residential and agricultural/forestry sector
D – Fugitives	Fugitives from oil/gas distribution, gas transport	Fugitives from oil/gas distribution, gas transport	Fugitives from gas stations
E - Solvents & product use	Fireworks, smoking	Fireworks, smoking	Solvent use in households and commerce (only VOC). Fireworks and smoking included in “others”
F - Road transport	Combustion of fossil and biogenic fuels, wear	Combustion of fossil and biogenic fuels, ~~wear~~	Combustion of fossil and biogenic fuels; exhaust and non-exhaust emissions are reported separately for PM
G – Shipping	Combustion of fuels from ships in ports, ferries, cruise ships,	Combustion of fuels from ships in ports, ferries, cruise ships,	Combustion of fuels from cruise ships and

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	recreational shipping, ~~fishing, domestic/international shipping~~	recreational shipping, ~~fishing, domestic/international shipping~~	recreational/private shipping
H – Aviation	LTO domestic and international, stationary combustion at the airport, mobile machinery in airports	LTO domestic and international, stationary combustion at the airport, ~~mobile machinery in airports~~	No airport within city limits
I - Off Road (railways)	Combustion of fossil ~~and biogenic~~ fuels. Wear and tyre abrasion	Combustion of fossil ~~and biogenic~~ fuels. ~~Wear~~	Rail transport is mostly electric, small emissions from freight transport. Rail and power line abrasion for PM.
I - Off Road (mobile machinery)	Mobile machinery in the construction, industry, residential, agriculture/forestry sector, ~~container terminals~~. Tyre, brake and road wear.	Mobile machinery in the construction, industry, residential, agriculture/forestry sector, ~~container terminals~~. Tyre, brake and road wear.	Mobile machinery in the construction, industry, agriculture/forestry sector.
J – Waste	Managed/~~unmanaged~~ landfills, waste incineration, cremation, open burning of waste, composting, domestic waste combustion, wastewater treatment, ~~anaerobic digestion~~, ~~bonfires~~.	Managed/unmanaged landfills, waste incineration, cremation, open burning of waste, composting, domestic waste combustion, wastewater treatment, anaerobic digestion, bonfires.	Cremation, open burning of waste, composting, domestic waste combustion, fermentation plant
K - AgriLivestock	Enteric fermentation and manure management	Enteric fermentation and manure management	Enteric fermentation and manure management
L - AgriOther	Fertilizer/manure application, urea application, ~~liming~~, ~~field burning of agricultural residues~~	Fertilizer/manure application, urea application, liming, field burning of agricultural residues	Fertilizer/manure application, ~~urea application~~, liming, ~~field burning of agricultural residues~~
Other	Natural NO from soils, ~~accidental fires~~, human respiration	~~Natural NO from soils, accidental fires~~, human respiration	Natural NO from soils, accidental fires, human respiration, fireworks, smoking

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Appendix 2 Detailed source aggregation for the city of Zurich

The MapLuft inventory of the city of Zurich provides data for 65 individual source categories. The mapping from these categories to the 14 GNFR classes is listed below.

```
# PublicPower
  "GNFR_A": [
     "c2201_BHKW_Emissionen_Kanton",
     "c2301_KHKWKehricht_Emissionen_Kanton",
     "c2302_KHKWErdgas_Emissionen_Kanton",
     "c2303_KHKWHeizoel_Emissionen_Kanton",
  ],
  # Industry
  "GNFR_B": [
     "c3201_Notstromanlagen_Emissionen_Kanton",
     "c3301_Prozessenergie_Emissionen_Kanton",
     "c3401_Metallreinigung_Emissionen_Kanton",
     "c3402_Holzbearbeitung_Emissionen_Kanton",
     "c3403_Malereien_Emissionen_Kanton",
     "c3404_Textilreinigung_Emissionen_Kanton",
     "c3405_Karosserien_Emissionen_Kanton",
     "c3406_Raeuchereien_Emissionen_Kanton",
     "c3407_Roestereien_Emissionen_Kanton",
     "c3408_Druckereien_Emissionen_Kanton",
     "c3409_Laboratorien_Emissionen_Kanton",
     "c3410_Bierbrauereien_Emissionen_Kanton",
     "c3411_Brotproduktion_Emissionen_Kanton",
     "c3412_MedizinischePraxen_Emissionen_Kanton",
     "c3413_Gesundheitswesen_Emissionen_Kanton",
  ],
  # Other stationary combustion (services, residential, agriculture)
  "GNFR_C": [
     "c2101_Oelheizungen_Emissionen_Kanton",
     "c2102_Gasheizungen_Emissionen_Kanton",
     "c2103_HolzheizungenLokalisiert_Emissionen_Kanton",
     "c2104_HolzheizungenDispers_Emissionen_Kanton",
     "c2105_Warmwassererzeuger_Emissionen_Kanton",
  ],
  # Fugitives
  "GNFR_D": [
     "c3416_Tankstellen_Emissionen_Kanton",
  ],
  # Solvents and product use
  "GNFR_E": [
     "c3417_LoesemittelIG_Emissionen_Kanton",
     "c5101_LoesemittelHH_Emissionen_Kanton",
  ],
  # Road transport
  "GNFR_F": [
     "c1301_Personenwagen_Emissionen_Kanton",
     "c1302_Lastwagen_Emissionen_Kanton",
     "c1303_Motorraeder_Emissionen_Kanton",
     "c1304_Linienbusse_Emissionen_Kanton",
     "c1305_Trolleybusse_Emissionen_Kanton",
     "c1306_StartStopTankatmung_Emissionen_Kanton",
```


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```
    "c1307_Lieferwagen_Emissionen_Kanton",
    "c1308_Reisebusse_Emissionen_Kanton",
],
# Shipping
"GNFR_G": [
    "c1101_Linienschiffe_Emissionen_Kanton",
    "c1102_PrivaterBootsverkehr_Emissionen_Kanton",
],
# Offroad mobility
"GNFR_I": [
    "c1201_BahnPersonenverkehr_Emissionen_Kanton",
    "c1202_BahnGueterverkehr_Emissionen_Kanton",
    "c1203_Tramverkehr_Emissionen_Kanton",
    "c1204_Kleinbahnen_Emissionen_Kanton",
    # c31xx are construction stuff
    "c3101_MaschinenHochbau_Emissionen_Kanton",
    "c3102_Bitumen_Emissionen_Kanton",
    "c3103_FarbenBaustelle_Emissionen_Kanton",
    "c3104_MaschinenTiefbau_Emissionen_Kanton",
    "c3105_Strassenbelag_Emissionen_Kanton",
    "c3419_IndustrielleFZ_Emissionen_Kanton",
    "c4101_ForstwirtschaftlicheFZ_Emissionen_Kanton",
    "c4201_LandwirtschaftlicheFZ_Emissionen_Kanton",
],
# Waste
"GNFR_J": [
    "c2401_Klaerschlammverwertung_Emissionen_Kanton",
    "c3418_Vergaerwerk_Emissionen_Kanton",
    "c3414_Krematorium_Emissionen_Kanton",
    "c5201_Gruenabfallverbrennung_Emissionen_Kanton",
    "c5301_HolzoefenKleingarten_Emissionen_Kanton",
    "c5401_AbfallverbrennungHaus_Emissionen_Kanton",
],
# AgriLivestock
"GNFR_K": [
    "c4401_Nutztierhaltung_Emissionen_Kanton",
],
# AgriOther
"GNFR_L": [
    "c4301_Nutzflaechen_Emissionen_Kanton",
],
# Others
"GNFR_R": [
    "c5501_HausZooZirkustiere_Emissionen_Kanton",
    "c5601_Feuerwerke_Emissionen_Kanton",
    "c5701_Tabakwaren_Emissionen_Kanton",
    "c5801_BrandFeuerschaeden_Emissionen_Kanton",
    "c6101_Waelder_Emissionen_Kanton",
    "c6201_Grasflaechen_Emissionen_Kanton",
    "c6301_Gewaesser_Emissionen_Kanton",
    "c6401_Blitze_Emissionen_Kanton",
],
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