Guidelines for European cities: a flexible and efficient approach for creating city emission inventories

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Executive summary

Motivation: Climate change is a global phenomenon that severely impacts urban life. At the same time, cities are key contributors to climate change, as urban activities are major sources of greenhouse gas (GHG) emissions (UN Human Settlements Programme, 2024). City emission inventories provide an overview of how much GHGs (and air pollutants) are emitted during a specific period, from which activities, and at which location. This type of information assists local stakeholders in making informed decisions to support their climate action plans and other sustainability efforts aimed at creating cleaner, healthier, and more resilient places to live. City emission inventories are, therefore, the foundation for smart, data-driven sustainability strategies at the city level. We believe an emission inventory should be easily achievable for all European cities, independent of their resources.

Goal and target group: We present guidelines to support city/local government stakeholders in the process of creating city emission inventories, with a specific focus on direct GHG emissions occurring within the city boundaries. This report describes a step-by-step approach for easy implementation across cities without the need for extensive prior knowledge on emission inventories. For cities that can put in more effort, the report also covers additional steps and advice on prioritization.

Summary of contents: The guidelines consist of two parts. The first part ("Prioritization and preparation") describes all the necessary preparatory steps and how to ensure that the envisioned process is feasible, considering limited resources. The second part ("Preparing the emission inventory") describes how to build the emission inventory. The whole process is not necessarily linear, and sometimes iterations are needed to get the most out of the available resources. A summary of all the steps is shown in Figure 1. It starts with defining the purpose the emission inventory will serve. This will give guidance on the requirements an inventory should fulfil. When the requirements are clearly defined, an overview can be made of the required data and resources. In some cases, it is necessary to rethink the aim when resources seem to be insufficient. Finally, priorities can be set and the actual work on the inventory can start.

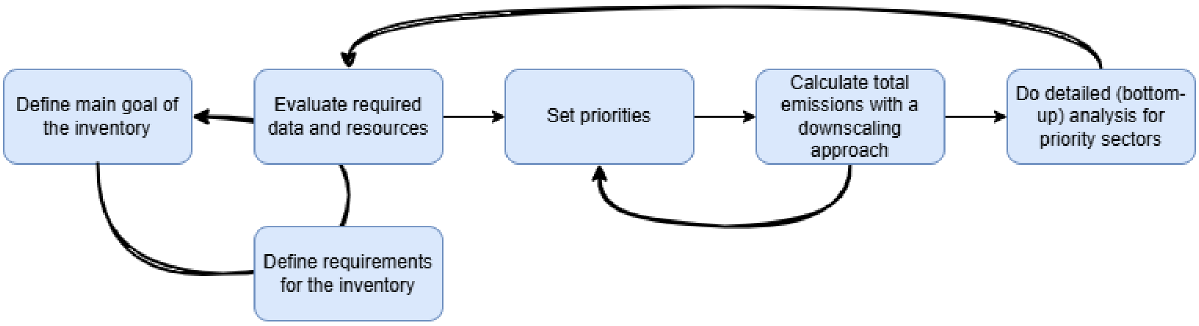

Figure 1. Flowchart depicting the process of creating a first city emission inventory. There are several feedback loops.

We strongly recommend starting with a downscaling approach, which makes use of an existing large-scale gridded emission inventory and provides an emission subset for the selected domain. This gives a first idea of the emissions in a city. Although this method may not provide the most accurate results possible, it is a good starting point for each city without an inventory. Next, based on the priorities set before and considering data and resource availability, specific source sectors can be worked out in more detail, e.g., using local data.

Support: For the downscaling methodology a tool is developed. It has been applied to a range of cities across Europe, and the output is available as an Appendix to this document. An interface that offers policymakers and scientists the opportunity to create their own output is under development.

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1. Introduction

1.1 Cities: Greenhouse gas emission hotspot and driving force in transitions

Climate change is a global phenomenon that severely impacts urban life. At the same time, cities are key contributors to climate change, as urban activities are major sources of greenhouse gas (GHG) emissions (UN Human Settlements Programme, 2024). Estimates suggest that urban areas are responsible for 70 % of global fossil fuel carbon dioxide (CO_2) emissions, with transport and buildings being among the largest contributors (IPCC, 2022; UN Environment Programme, 2025). This is a logical consequence of what cities are: thriving centres of human and economic activities. Cities concentrate large numbers of people in relatively small areas, leading to increased demand for energy, transportation, housing, and goods, all of which contribute to CO_2 emissions. At the same time, each city and each country is different, and generalizations like "responsible for 70 % of global fossil fuel CO_2 emissions" do not provide insights into underlying processes and mitigation potential. Such insights can be obtained through the development of city-specific emission inventories.

City emission inventories provide an overview of how much GHGs (and air pollutants) are emitted, from which activities, and at which location, helping local governments and organizations make informed decisions to support their climate action plans and other sustainability efforts. Since cities concentrate people and businesses, they offer a unique chance to implement large-scale sustainability efforts efficiently. Cities are hubs of innovation and often lead the way in climate policies, testing solutions like green infrastructure, public transport electrification, and clean energy expansion. Moreover, global urbanization is a rapid process. According to the United Nations, only 30 % of the world's population lived in urban areas in 1950, a proportion that grew to 55 % by 2018 (UN Department of Economic and Social Affairs - Population Division, 2018), and this trend is expected to continue. A consequence of this rapid urbanization is that city-based emissions will greatly determine whether global climate goals are met. While this may be motivation enough, it should be stressed that cities that drastically reduce their emissions will not just help the planet—they create cleaner, healthier, and more resilient places to live.

1.2 City emission inventories

A city emission inventory is a comprehensive accounting of all emissions produced within a city over a specific period, usually one year. It helps cities understand where emissions are coming from and how to reduce them. These inventories can contain city-wide emissions, or they can be spatially distributed, assigning emissions to specific locations within the city. Similarly, emissions have a strong temporal variability, e.g., due to rush-hour peaks, which can be covered in the emission inventory. Spatially and temporally explicit emission inventories are also required for monitoring emission reductions through atmospheric observations and modelling.

1.2.1 Scope

Here we focus on GHG emissions, especially CO_2, but we will also briefly discuss co-emitted air pollutants, because the co-benefits of reducing GHG emissions are often related to air pollution and health. For GHG emissions, it is important to define the type of emissions that are being addressed.

- **Scope 1**: Direct emissions from sources within the city (e.g., fuel burned in buildings or vehicles).
- **Scope 2**: Indirect emissions from electricity or heat purchased and used in the city.
- **Scope 3:** Other indirect emissions, such as those from goods and services consumed in the city but produced elsewhere.

In these guidelines, we focus on scope 1 emissions, while we acknowledge the importance of scope 2 and 3 emissions, as scope 1 emissions can be directly measured and influenced within the city domain (Figure 2).

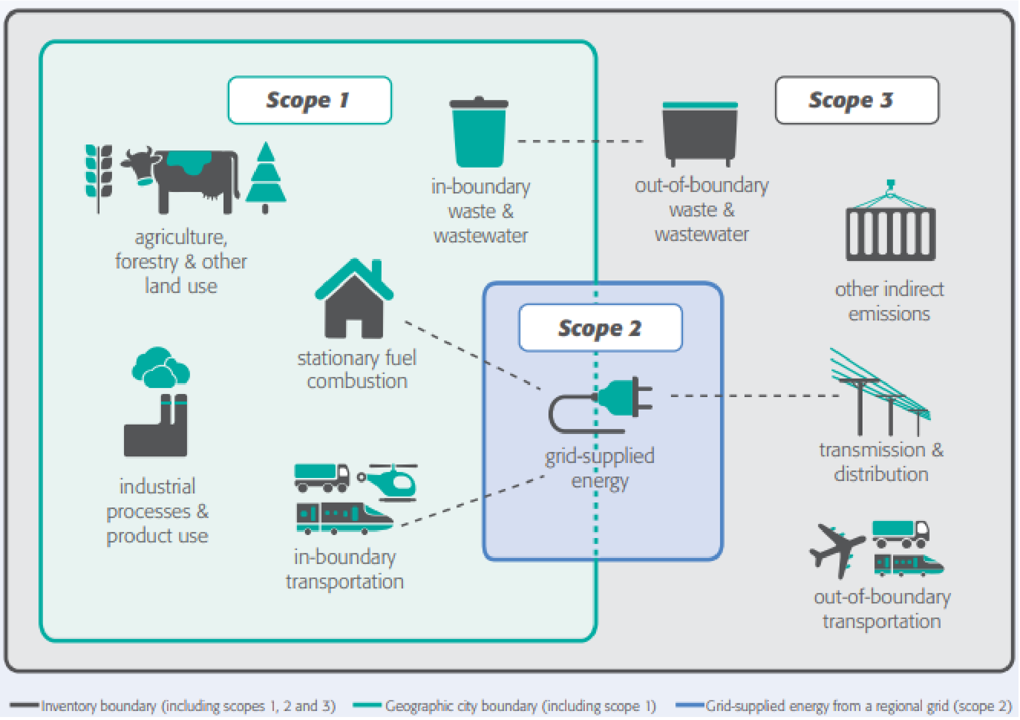


Figure 2: Overview of scope 1, 2 and 3 emissions at the city scale. Source: Greenhouse Gas Protocol, 2025.

1.2.2 Unit of measurement

Emissions are expressed in units of emission per unit of time, e.g., kg CO_2 or CH_4 per year. GHG emission inventories are also often expressed in CO_2 equivalent (CO2eq). This is a unit of measurement used to standardize the climate effects of various GHGs in terms of the amount of CO_2 that would have the same global warming potential (GWP). This includes gases like methane (CH_4) and nitrous oxide (N_2O), which have a greater warming effect than CO_2. The CO2eq unit allows for the comparison of emissions from different sources across GHGs and helps in understanding their impact on climate change. According to the United Nations Framework Convention on Climate Change (UNFCCC) the conversion of GHG emissions to CO2eq should be done by using the 100-year time-horizon GWP values from the IPCC Fifth Assessment Report (Myhre et al., 2013). For CO_2, CH_4 and N_2O these are 1, 28, and 265, respectively. In these guidelines, we prefer to express the emissions in SI units (mass) and not in CO2eq because the use of different GWPs or time horizons can lead to confusion. The expression in CO2eq is, however, easily done as a post-processing step.

1.2.3 Source sectors

Although not a strict rule, we advise in all cases to specify emissions in the inventory per source sector, as this provides valuable insight, e.g., to define sector-specific mitigation measures. In most cases, this will automatically follow from the steps needed to create an inventory, as most data is on a sectoral level.

The key emission sources in cities are:

- **Stationary combustion:** Emissions from the combustion of fuels in buildings, power plants, and industrial facilities.
- **Transportation:** Emissions from vehicles, public transit, and freight.

- **Waste:** Emissions from landfills, wastewater treatment, and waste incineration.
- **Industrial processes:** Emissions from manufacturing and chemical processes.
- **Agriculture and land use (if applicable):** Emissions from urban farming, green spaces, etc.
- **Human respiration (only CO_2):** Emissions from the human respiratory system, including residents, commuters, tourists, etc.

1.2.4 Methods

The methods to develop a city emission inventory can vary. They can be classified based on their calculation approaches:

- **Downscaling approach:** Downscaling approaches use spatial surrogates, such as population data and land use, to distribute global or national total emissions over a defined space and time domain (Section 3.3.1), such as a city (Andres et al., 2012; Gurney et al., 2019; Ramacher et al., 2021). Often, the spatial resolution is such that spatial emission patterns within the city are recognizable. Additionally, this approach gives a first estimate of the city-wide emissions (Section 3.1.1). We reserve the term downscaling approach to activities that use existing inventories (either gridded or not) as a starting point.
- **Bottom-up approach**: This method starts at the source sector level, collecting activity data from individual source sectors, such as factories, vehicles, and households, within the city. It relies on direct measurements and reported data to build an inventory of emissions. Depending on the type of activity data, this approach can directly produce spatially explicit emissions (Sections 3.1.2 and 3.3.3).
- **Top-down approach**: This method starts from an existing emission inventory and uses atmospheric measurements to improve the inventory. Scientists analyse air samples and use atmospheric transport models to trace pollutants back to their sources. While this approach captures real-world emissions, it can be challenging to assign those emissions to anthropogenic emissions sources due to complex atmospheric mixing, transport and biogenic fluxes.

All methods have their strengths and weaknesses. For example, a bottom-up approach provides detailed insights for specific sources, but it is resource-intensive and can sometimes be incomplete or inaccurate if sources are misreported, overlooked, or data is lacking. The downscaling approach is less resource-intensive and assures consistency across scales, but may misrepresent specific local conditions. Finally, the top-down approach provides a broader, real-world validation, but usually does not result in sector-specific emission inventories, which are crucial for policy making and mitigation within cities. These guidelines, therefore, focus on bottom-up and downscaling approaches. For a broader discussion and in-depth comparison of these two methods, we refer to Gurney et al. (2019).

1.3 About these guidelines

These guidelines have been developed because city emission inventories are the foundation for smart, data-driven climate strategies at the city level. Next to abating climate change, there can be enormous benefits in cutting emissions, like cleaner air, better health, and energy savings. Even a basic emission inventory, which can be improved in due time, can give significant insight. We believe a (first) emission inventory should be easily achievable for all European cities, independent of their resources, and the aim of these guidelines is to support cities in that process.

There are other guidelines and/or protocols directly addressing cities, such as the GHG Protocol for Cities (Greenhouse Gas Protocol, 2025) or the IG3IS Urban Greenhouse Gas Emission Observation and Monitoring Good Research Practice Guidelines (World Meteorological Organization, 2022). We encourage readers to visit these resources as they provide valuable, detailed calculation methods. In short, the guidelines presented here are complementary to these resources and provide a pragmatic approach for European cities, including some examples taken from the H2020 project Pilot Application in Urban Landscapes - Towards integrated city observatories for greenhouse gases (Integrated Carbon Observation System, 2025). Unlike the other resources, our focus is on Europe, as we have developed the tools and European-scale gridded emissions for efficient downscaling to provide cities with a first emission inventory, which can be enriched and/or replaced by bottom-up data where suitable and feasible.

The guidelines consist of two parts. Chapter 2 describes all the necessary preparatory steps: defining the aim and requirements for the inventory, specifying the domain boundaries, making an overview of the required and available data and other resources, and setting priorities. All these steps lead to a work plan. Chapter 3 describes in more detail how a city emission inventory can be built. We list options with different levels of detail, accuracy, and effort, such that stakeholders can pick the methods most suitable to their needs. The methods can also be used in a hybrid fashion, for example, by taking a more sophisticated approach for the most important source sector and doing other sectors with the default approach.

2. Prioritization and preparation

The requirements set for the inventory depend largely on the purpose that the inventory will serve. Therefore, policymakers are advised to take sufficient time to think about the aim and scope and consider available resources before starting to develop the emission inventory. Based on this, a priority list can be made that will give guidance to the inventory development and may help to keep track of the resources spent. In this chapter, we go through the most important considerations and provide examples.

2.1 Aim

A city emission inventory can serve different purposes, for example:

- Bookkeeping of greenhouse gas emissions/carbon footprint and changes over time, e.g., to keep track of emission reductions using statistical data.
- Starting point for climate mitigation plans, e.g., knowledge on dominant source sectors.
- Starting point for atmospheric monitoring of greenhouse gas emissions and to keep track of emissions reductions using atmospheric observations.
- Support policymaking towards zero-pollution cities, e.g., taking advantage of the co-benefits between reducing greenhouse gas emissions and air or noise pollution.

Of course, these are just some examples, and each case is different. Note that in some cases multiple purposes may exist, for example, if different administrative units are involved. Therefore, defining the aim should ideally be a combined effort between all stakeholders who may have an interest to avoid having to repeat the same work multiple times.

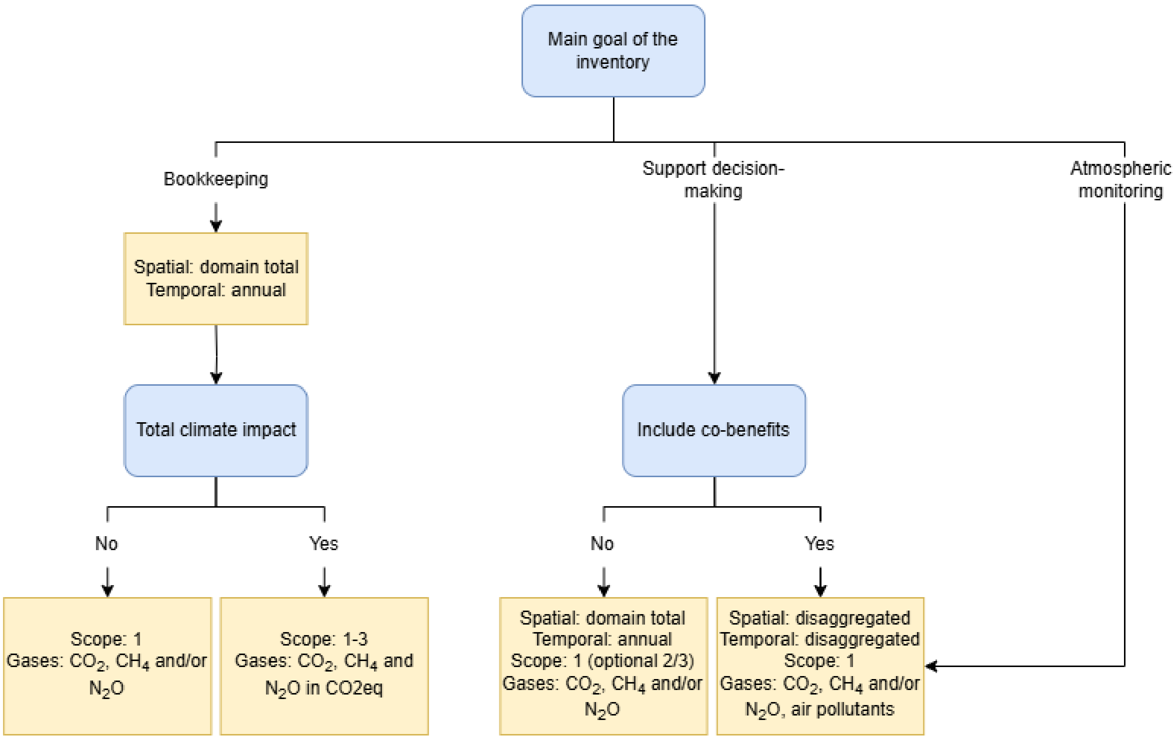


Figure 3. Diagram to support decision making on the requirements of the inventory, based on the aim specified. Deviations are always possible, and thorough consideration of requirements is necessary per case. Blue rectangles indicate choices to be made; yellow rectangles include requirements.

The aim of the emission inventory largely determines what the final product will look like. An example decision tree is shown in Figure 3. For bookkeeping of emissions and carbon footprints, a table with annual data for the whole city will suffice. As a starting point for climate mitigation plans the same is often true. However, for atmospheric monitoring of greenhouse gas emissions and to study the co-benefits with air quality, spatially disaggregated emissions are needed. Often, the need for spatial disaggregation also comes with the need for detailed temporal information. For example, (the impact of climate mitigation measures on) air pollution has a strong spatiotemporal gradient. The required spatial resolution depends on the aim: are stakeholders interested in the impact of climate mitigation measures on air pollution at the neighbourhood scale, or should it be specified at the street level to get a grip on the most vulnerable groups? Moreover, atmospheric modelling of air pollutant concentrations requires emissions at a high temporal resolution (mostly hourly). Finally, the type of observations used for atmospheric monitoring is relevant to consider. Satellite observations can be used at a coarser spatial resolution than in-situ observations.

Another important consideration is the scope of the emissions to include. Most emission inventories only include direct emissions taking place within the region of interest. However, for carbon footprint analysis, scope 2 and 3 emissions should be included as well. These emissions are not of interest for spatially disaggregated emission inventories, as the emissions take place outside of the domain. As mentioned before, throughout these guidelines we only consider scope 1 emissions, i.e., the emissions directly released from the city.

Finally, a decision must be made on which trace gases to include and how. When focusing on the climate impact, all GHG emissions should be included, ideally expressed in CO2eq to allow for direct comparison of CO_2 and other GHGs. If the co-benefits of climate action on air pollution are of interest, the relevant air pollutants, such as particulate matter or nitrogen oxides, can also be included in the same inventory. Even if an inventory for air pollutants exists, it may be worth including air pollutants in the new inventory for the sake of consistency, e.g., in sector definitions.

2.2 Spatial and temporal boundaries

A clear definition of the spatial and temporal extent of the emission inventory is important to ensure consistency throughout the process. These boundaries determine which data and sources should be included.

The spatial boundaries are not only of importance for the spatial disaggregation, but also for the comparison of multiple city-wide emission estimates. If one estimate is based on city administrative boundaries and another on a rectangular area around the city, they are not comparable. The same holds true for the temporal boundaries, which could be a calendar year or an administrative year, for example.

When defining the spatial domain, it is important to consider the aim defined in Section 2.1. For example, if the aim is to monitor city emissions using atmospheric observations, a larger domain should be covered than just the city itself to account for the inflow of pollutants from outside the city. Moreover, data availability may play a crucial role in defining the boundaries. City-specific statistical data are often available within the administrative boundaries, which could be used to set up the emission inventory.

Data availability is also important in defining the temporal boundaries. Statistical data needed as input for the emission inventory may sometimes lag a few years behind, and therefore, emission inventories are often made for earlier years. However, it is also possible to make predictions for future years based on economic projections, climate action plans, and/or other scenarios. This can be used, for example, to set a target when the aim is to keep track of greenhouse gas emission reductions over time.

2.3 Data availability

After the aim and spatial/temporal boundaries are defined, a list can be made of all the data needed to make the emission inventory, for example:

- Emissions within the specified boundaries for the trace gases and sectors of interest. If not yet available:
  - Activity data and emission factors for the specified domain and trace gases/sectors of interest to calculate total emissions.
  - An existing national, regional, or global emission inventory that covers the specified domain.
- GIS file of the domain boundaries, which may be helpful to cut out the correct domain from an existing emission inventory.
- Spatial information, for example, spatially explicit activity data (e.g., traffic counts) or spatial data that can be used to put emissions in the correct place (e.g., land use data or road network).

The list should be as concrete as possible. For example, list specific data sources for activity data per sector instead of simply listing 'activity data'.

Local or city-specific data are preferred over national or European data, as local data are more representative of the local situation and therefore increase the accuracy of the emission inventory. Often, state/city offices, municipal works, and other local parties have a lot of knowledge on the local situation and collect all kinds of data that could be useful for a city emission inventory. However, these data are not always publicly available or are only available under certain restrictions.

For some sectors it is difficult to find local data, and it is often unavoidable to use a mix of local data and data from larger-scale products. Luckily, plenty of open-source datasets are available that can provide a backup in case local datasets are lacking or inaccessible. Some other considerations are practical constraints regarding the size of the datasets, limitations in using non-public data, the spatial and temporal boundaries of the data, and data quality.

Including all stakeholders in this exercise is useful, as knowledge on local datasets is often spread out over organizations. In case of large limitations in the data availability, this exercise may result in rethinking the aim and spatial/temporal boundaries, which makes it an iterative process.

2.4 Resource availability

The final preparation step is to make a list of resources that are needed to make the emission inventory. Again, this list should be as specific as possible, such as the time needed to process a specific dataset. Resources can consist of manpower, knowledge, computing capacity, financial resources, etcetera. For specific tasks there may be several options, for example, to hire an external party or do the work internally. Therefore, an important question is how to make optimal use of resources. For example, hiring an external party to do some of the work may sometimes be 'cheaper' than doing the work internally, e.g., when lacking manpower. When dividing resources, it is important to consider the consistency of the work over time, such that updates to the product can be made without unexplainable discrepancies between old and new products due to parties using different methodologies or data.

Additionally, an overview must be made of the available resources that can be spent on the emission inventory. Since it is a large effort to make an emission inventory from scratch, it is likely that the required resources exceed the available resources. Having a clear overview will help to set priorities in the next step.

2.5 Setting priorities

After the preparation steps are finished, a priority list can be made. There is no right or wrong way of doing this, but some guiding questions are:

- Which steps are essential to reach our aim? And which steps are just nice-to-haves?
- Which sectors are the most important, e.g., because they contribute most to the total emissions? (see Section 3.2)
- Where can we make the biggest gain given the limited resources?
- Where can we make use of existing datasets or tools, even if they are sub-optimal?
- If multiple aims are identified, which one is most important?
- What is my deadline, and what amount of work can be achieved?
- What are the risks associated with my strategy, and do I have a backup plan?

3. Preparing the emission inventory

The preparation of the emission inventory is performed in several steps (depending on the goal of the inventory):

- Total emissions – gain an overview of the emissions per sector for the whole city (Section 3.1)
- Sector prioritization – prioritize sectors that are the most important and need additional efforts (Section 3.2)
- Spatial and temporal disaggregation – prepare a spatially and temporally explicit emission inventory (Section 3.3)

3.1 Total emissions

The first step in building the emission inventory consists of preparing an overview of emissions per sector in the city. In this chapter, we do not yet consider spatially explicit emissions. An overview of sectoral emissions will assist in the sector prioritization (see Section 3.2). In some cases, the city administrative bodies may have already prepared a city emission inventory for one or more sectors. If this is not available, there are several possibilities to prepare an overview of the total city emissions.

Having multiple emission estimates from different data sources (e.g., from city administrative bodies and from the downscaling approach (see below)) can be very helpful to get an idea of how accurate these estimates are and where discrepancies occur, or perhaps if specific activities are missing. Note that for the comparison of multiple emission estimates, it is important to check that the sector definitions match and the same scope of emissions is considered (see Box 1).

3.1.1 Downscaling approach

The first option is to use an existing emission inventory covering a larger domain, cut out the emissions within the city boundaries by making a spatial overlay of the gridded emissions and the city boundaries, and sum up the cut-out emissions per source sector. The downscaling approach is the fastest way to get a quick overview of the emissions. The emissions in the grid cells at the border of the city can either be proportionally appointed to the city (e.g., based on the area within/outside the city boundaries) or be 100% appointed to the city.

Most European countries prepare a gridded emission inventory for air pollutants at a 0.1 x 0.1 ° (about 10 x 10 km) resolution or higher (EMEP Centre on Emissions Inventories and Projections, 2025). The national emission inventory might be available within the country in more detail and include greenhouse gases. If the national emission inventory is not available, or if the quality is not high enough, then gridded emission inventories for a larger domain are available, for example:

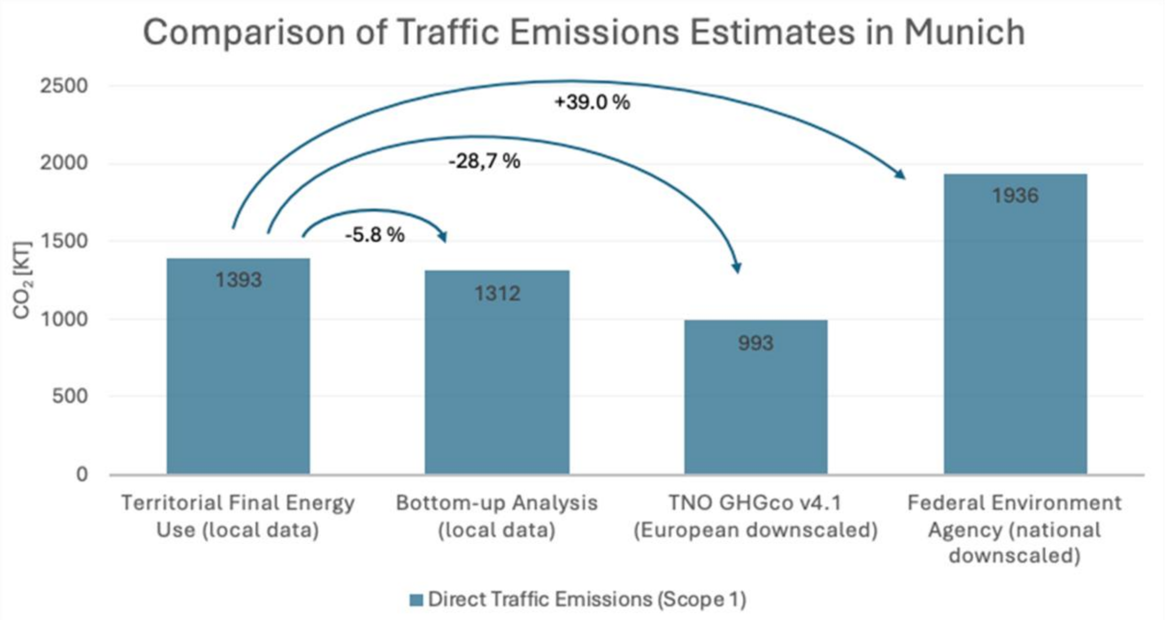
- CAMS-REG (Kuenen et al., 2022): A European emission inventory at 0.05 x 0.1 ° resolution for greenhouse gases and air pollutants. This gridded inventory is based on national reported emissions, which are spatially distributed by relevant proxy data, like land cover, number of inhabitants, or traffic.
- EDGAR (European Commission, 2025): A global emission inventory at 0.1 x 0.1 ° resolution for greenhouse gases and air pollutants. This gridded inventory is based on activity data and emission factors.
- ODIAC (Oda and Maksyutov, 2025): A global emission inventory of fossil CO_2 at 1 x 1 km resolution, which is based on power plant profiles and satellite-observed nighttime lights.
- At the website of ECCAD (https://eccad.aeris-data.fr/) a search can be done for the domain of interest (e.g., Europe) and the species of interest (e.g., CO_2, CH_4, etc.) to find other datasets.

BOX 1: VARIANCE BETWEEN DIFFERENT INVENTORIES: ROAD TRANSPORT IN MUNICH

Munich, Germany's second-largest city, has a population of 1.5 million and spans an area of 310 km². Due to minimal industrial activity with process-related emissions, the city's highest-emitting sectors are power generation, heating, and road transport. The city administration releases annual greenhouse gas (GHG) emission estimates based on territorial final energy use (Scope 1 and 2) (Referat für Klima und Umweltschutz, 2022).

In 2019, the road transport sector in Munich accounted for a total of 1,592 kt CO2eq, which includes upstream emissions from fuel supply. When focusing solely on operational, on-road emissions (approximately 87.5 % of the total), the calculated emissions amount to 1,393 kt CO2eq. This can be equated with CO_2 for the following comparison as emissions from other GHGs in road transport are negligible. Estimates from other inventories available for Munich highlight significant variances in GHG emissions. For instance, the European TNO GHGco v4.1 downscaled inventory (Super et al., 2020, Super et al., 2025) estimates 993 kt CO_2, the national downscaled inventory from the Federal Environmental Agency reports 1,936 kt CO_2 (Gniffke et al., 2024), and an independent bottom-up analysis based on local activity data calculates 1,312 kt CO_2 (Kühbacher et al., 2025).

These variations underline the substantial impact of differing methodologies, data sources, and sector definitions on final emission estimates. In many cases, these differences exceed the magnitude of the reduction targets themselves, complicating efforts to track progress toward climate goals. This also stresses the importance of using local data (such as the bottom-up calculation in this example) for the main emitting sectors where possible.



3.1.2 Bottom-up approach

The second option is to prepare a city emission inventory from scratch, based on activity data and emission factors (bottom-up approach). Sometimes, this will already include spatially explicit data, and for that we refer to Section 3.3.3. Here, we focus on total city-wide emissions.

Preparing a bottom-up city emission inventory based on activity data and emission factors is more labour-intensive than the downscaling approach, but if this is done properly, the quality and accuracy can be higher. Methods to prepare a bottom-up emission inventory for greenhouse gases are described in the Greenhouse Gas Protocol for Cities (Greenhouse Gas Protocol, 2025). This protocol provides a description of the methodologies and refers to the IPCC Guidelines (Eggleston et al., 2006) for relevant emission factors. The methodologies in this protocol could also be applied for calculating the emissions from air pollutants, but then the relevant emission factors are available in the EMEP/EEA Emission Inventory Guidebook (European Environment Agency, 2023). Typically, activity data can come from national statistics agencies or local government bodies.

3.1.3 Hybrid approach

A hybrid city emission inventory, consisting of a combination of the two above-mentioned methods, can be an efficient and successful approach, because the intermediate products are immediately useful and further improvements are added stepwise. The hybrid approach starts with a cut-out from a greater domain and then improves the emission estimates of some selected sectors using a bottom-up approach. This way, efforts can be focused on the most important sectors. When combining multiple approaches or datasets it is important to harmonize the sector definitions to avoid double counting or oversight of specific emission activities.

3.2 Sector prioritization

From the overview created in the previous step, the most important emitting sectors can be identified. This helps in setting priorities, e.g., by reserving resources to calculate bottom-up emissions for the most important sectors, which will have the largest impact. Important considerations are also data availability for making bottom-up emission calculations for certain sectors. A sector prioritization should consider several factors:

- Source sectors that contribute the most to the city's emissions. This should focus on the largest sectors for each GHG/air pollutant separately. For this purpose, rank the sectors from largest to smallest contribution and calculate their cumulative contribution (Table 1). For the national reporting of air pollutants and GHGs, the highest-ranked sectors up to a cumulative contribution of 80% and 95%, respectively, receive more attention. In this case, buildings, energy and road transport should be considered for air pollutants, and industry should additionally be included for GHGs. There is no threshold for the city emission inventories, but as a rule of thumb, city emission inventory compilers could focus on the highest-ranked sectors responsible for at least 80% of the emissions.

Table 1: Example of selecting source sectors based on their contribution to the total emissions.

Sector	Emissions [kg/yr]	Share	Cumulative contribution
Buildings	800	51%	51%
Energy	295	19%	70%
Road transport	225	14%	85%
Industry	190	12%	97%
Off-road transport	41	3%	100%
Other	5	0%	100%

- Source sectors that have the largest uncertainty in total city emissions, for example, because the default activity data are unreliable and better local knowledge is available.
- Source sectors for which it is expected that the spatial distribution is not accurate. Some examples:

  - For residential combustion: If part of the city is using district heating, then the emissions from residential combustion are zero or rather low in this area, while the standard spatial distribution may still allocate a large part of the residential combustion emissions to this area (see Box 2).
  - For road transport: If a low-emission zone is in place for part of the city, then the emissions per vehicle in that area might be lower than in other parts of the city.
  - For major point sources: If the coordinates of a large point source at the edge of the city boundaries are slightly off, then this source could be allocated just inside or outside the city border, with a major impact on the emission totals.

3.3 Spatial disaggregation

With spatial disaggregation we mean the effort of distributing emissions over the domain using knowledge on where emissions occur (Figure 4). Spatially explicit inventories exist for a wide range of air pollutants and greenhouse gases at the European and global scale, and sometimes also at the national scale. However, the resolution of these inventories is often too coarse to be useful for cities. For example, if an entire city block is included in one grid cell, it is impossible to assess the health impact of those emissions at the street level where the people are. Therefore, an additional step is needed to increase the spatial resolution.

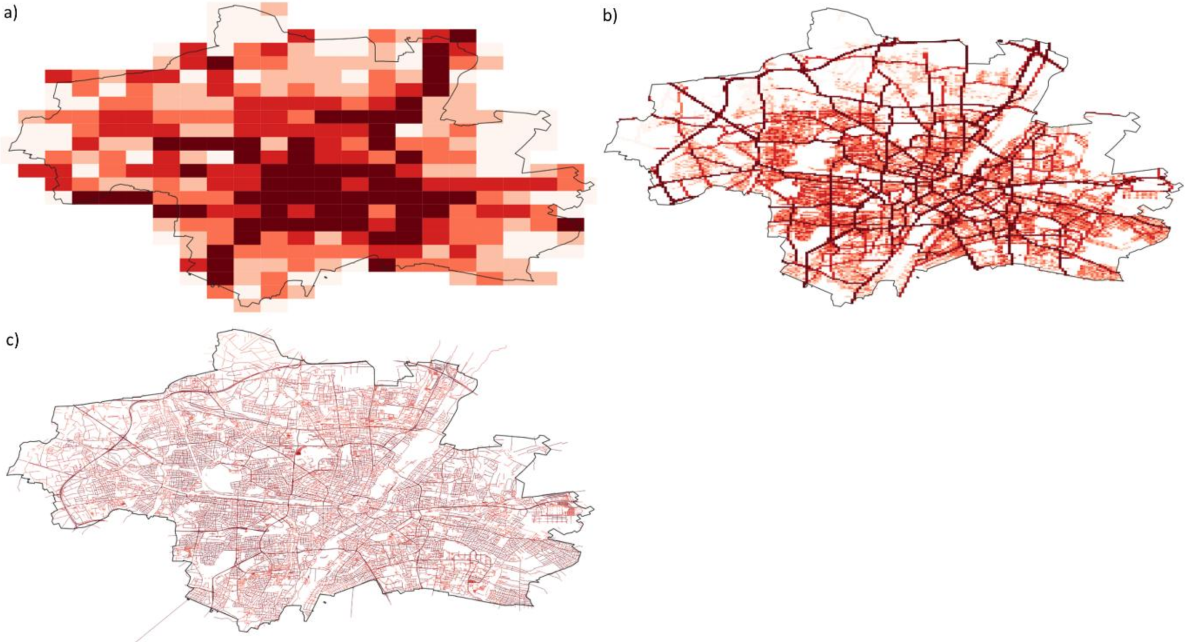


Figure 4. An example of spatially disaggregated emissions for road transport in Munich at a) 1 km, b) 100 m, and c) vector (line) resolution. The black line represents the city boundary.

In this section a tiered approach is suggested. The first tier is the least resource-consuming and most generic one, and with Tier-2 and Tier-3 the level of detail and accuracy (and therefore the effort) increases. Note that different tiers may be applied in one inventory, as some sectors benefit more from a detailed approach than others.

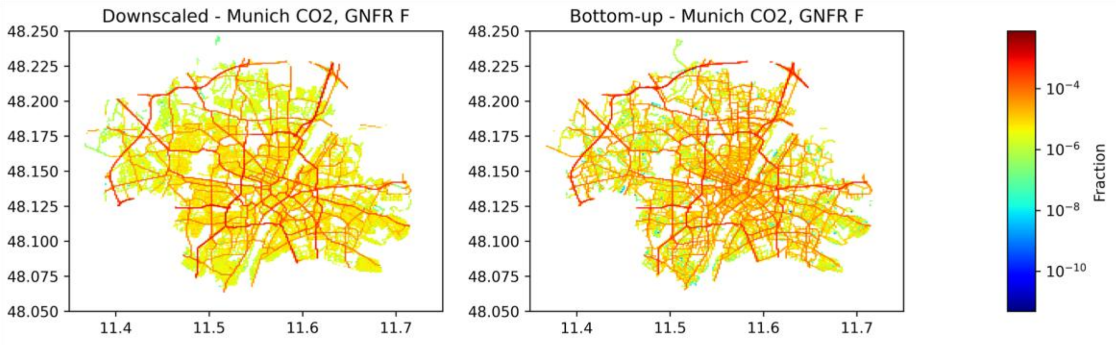
3.3.1 Tier-1: European downscaling approach

The first level of spatial disaggregation makes use of open-source, large-scale (European) datasets and existing tools. The starting point is either a gridded European/national emission inventory or total emissions for the domain. A tool has been developed by TNO as part of the ICOS Cities project (Sect. 4) that makes use of so-called proxy data to downscale the emissions to sub-kilometre resolution (Super et al., 2025). For example, a spatial dataset on total building volume at 10 m resolution is used to assign residential heating emissions to specific areas. The exact resolution that can be reached depends on the resolution of the proxy data, which has been increasing drastically over the past years. For atmospheric monitoring purposes, the major point sources (industry, power plants) should ideally be placed at their exact location. In some existing gridded inventories this is already the case.

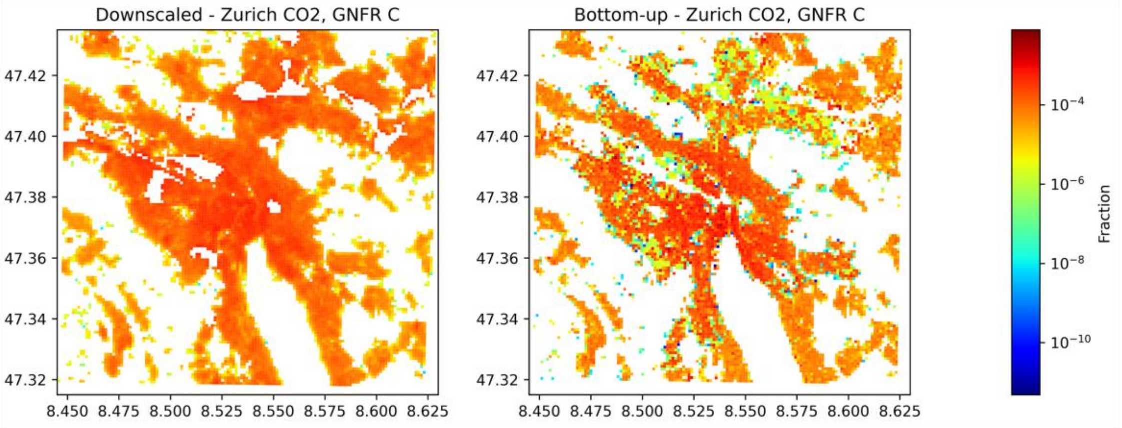
BOX 2: GRIDDED CITY INVENTORY INTERCOMPARISON

The Tier-1 approach has been applied to three European cities and compared to detailed gridded inventories developed by local authorities. The lessons learned from the intercomparison have been used to improve the Tier-1 approach by incorporating more representative proxy data.

The figure below shows the spatial distribution of road transport CO_2 emissions in Munich following the Tier-1 approach (left panel) and from the bottom-up inventory (right panel) (Kühbacher et al., 2025). The patterns look very similar, and the Tier-1 approach shows satisfactory results.



Another example is the spatial distribution of residential heating CO_2 emissions in Zurich following the Tier-1 approach (left panel) and from the bottom-up inventory (right panel) (Stadt Zürich, 2024). Here, we clearly see areas where the Tier-1 approach overestimates emissions. These areas match neighbourhoods where district heating is available.



Useful datasets are provided, for example, by Copernicus. The CORINE land cover product from the Copernicus Land Monitoring Service provides land cover and land use data at high resolution (CLMS, 2020). The Global Human Settlement Layer under the Copernicus Emergency Management Service contains useful information on, amongst others, population (Schiavina et al., 2023) and building volume (Pesaresi and Politis, 2023).

A major advantage of this method is that it can be used by European cities without much effort. A downside is that specific, local conditions may not be properly represented, and, generally, within-city spatial variability is underestimated. Each city has specific characteristics that are not sufficiently covered by this approach. Moreover, we rely on open-source data being available and up to date. Finally, large-scale, high-resolution proxy data is lacking for specific activities, which hampers the downscaling of emissions from some sectors, e.g., for waste. Depending on which source sectors dominate and how typical they are for European cities, stakeholders may consider using a Tier-2 or even Tier-3 approach for specific sectors to improve the representation of these local characteristics.

3.3.2 Tier-2: Downscaling approach with local/regional data

The second level of spatial disaggregation follows mostly the same steps as the Tier-1 approach, except that European data are replaced by national or local data. For example, a national database with house addresses and information on building year and housing type could improve the spatial allocation of residential emissions. Often, this results in a more reliable spatial distribution. The exact impact depends on how representative the European proxy data is. For some sectors, we know the proxies are poorly representative, such as waste and small point sources. Especially the latter, such as small industrial facilities with no reporting obligations, are poorly represented in the Tier-1 approach and are not included explicitly in existing gridded inventories. Therefore, a lot can be gained by adding knowledge on the locations of these facilities.

Additionally, more information may be added on local conditions as an extra filter on European or regional data. An example is using district heating locations to exclude specific neighbourhoods in the spatial disaggregation of residential heating emissions (see Box 2). Or to incorporate knowledge on tunnel locations to correctly allocate road transport emissions. This significantly improves the spatial variability within the domain. It should be noted that a correction on district heating locations will not automatically affect the total domain-wide emissions, which may be overestimated in the gridded inventories used as a starting point if a city has an above-average amount of district heating utilization. This illustrates the importance of comparing total emissions from different data sources (Section 3.1).

The effort required to incorporate a new proxy in a downscaling tool like the one presented in Section 3.3.1 is limited. However, preparing the proxy may be challenging. For example, using a national housing database requires an understanding of how building type and age affects energy demand, which should be translated into a scaling factor per building that can be used as a proxy.

3.3.3 Tier-3: Bottom-up emission models

The third level of spatial disaggregation is a bottom-up approach: using local, spatially (and temporally) explicit activity data and emission factors to calculate gridded emissions (see Box 3). This approach will result in a new, independent emission estimate for the domain, which should be compared against those collected under Section 3.1.

Developing a bottom-up emission model is a significant effort, which requires a lot of local data and knowledge on emission processes. Therefore, priority should be given to sectors with a large contribution to the total domain-wide emissions or sectors for which the Tier-1 and Tier-2 approaches are suspected to give poor results. A major advantage of including bottom-up emission models is that these models are often better at capturing local conditions and therefore improve the spatial variability. For example, with traffic count data and traffic models, areas with high traffic intensity and/or congestion are better represented as emission hotspots. Moreover, the small point sources mentioned under the Tier-2 approach could be included with emission reports from the facilities, if existing, which is a very uncertain source in the first two approaches. Finally, the more detailed accounting in the bottom-up approach will allow for a more accurate quantification of the achieved emission reductions in the city due to the (to be) implemented climate mitigation policies.

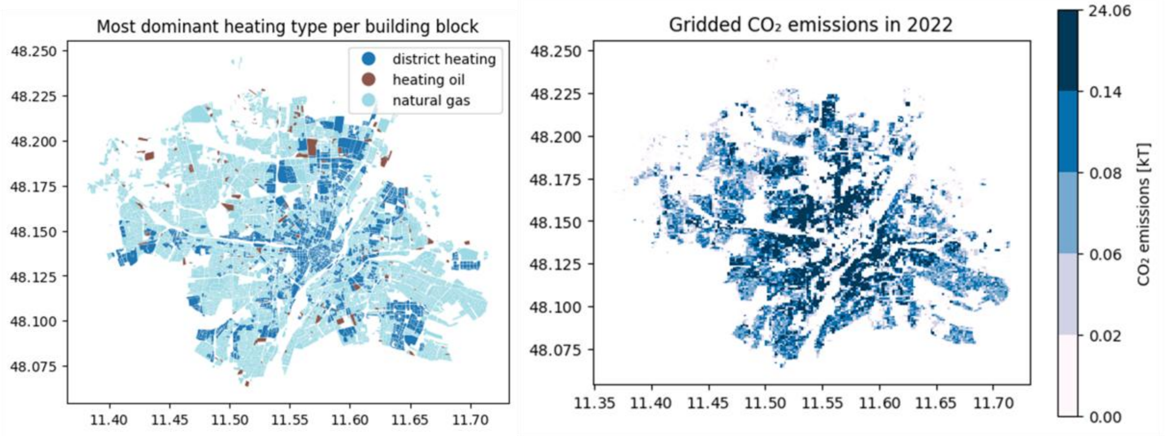
BOX 3: BOTTOM-UP EMISSION MODEL: STATIONARY COMBUSTION IN MUNICH

Annual gas inflow data reported by the Munich local utility provider forms the primary basis for estimating total stationary combustion emissions (right panel). This robust data source introduces only minor uncertainties into the total emission estimates.

High-resolution building data is utilized to allocate emissions spatially[1,2,3]. It allows for differentiating building types, like detached single-family homes, multi-story apartment complexes, and other residential structures. Heat demand is further resolved according to the construction year of each building, capturing differences in energy performance and insulation standards over time.

A key component is information on whether buildings use natural gas, oil, district heating, or other systems[4] (left panel). District heating is widely used in central Munich, shifting the localization of emissions to combined heat and power plants rather than individual buildings.

Temporally resolved district heating load data provides insights into daily and seasonal heating behavior. This reveals temporal patterns related to human activity, such as peak demand during morning routines, evening returns from work, or weekend variations.



[1] Geobasisdaten © Landeshauptstadt München - Kommunalreferat - GeodatenService 2022/2024

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3.4 Temporal disaggregation

When temporal information is required, for example, in the case of atmospheric monitoring, an additional step is needed. Again, the level of detail can be chosen based on available resources and data, like the spatial disaggregation.

A relatively easy option is to use default temporal profiles (Tier-1). These are often provided with gridded inventories or exist as separate datasets, sometimes per country or trace gas. The current state-of-the-art European dataset is CAMS-TEMPO (Guevara et al., 2020; Guevara et al., 2021). Although it only provides temporal profiles for air pollutants, these can easily be transferred to GHGs by selecting a temporal profile for an air pollutant dominated by CO_2-emitting combustion activities.

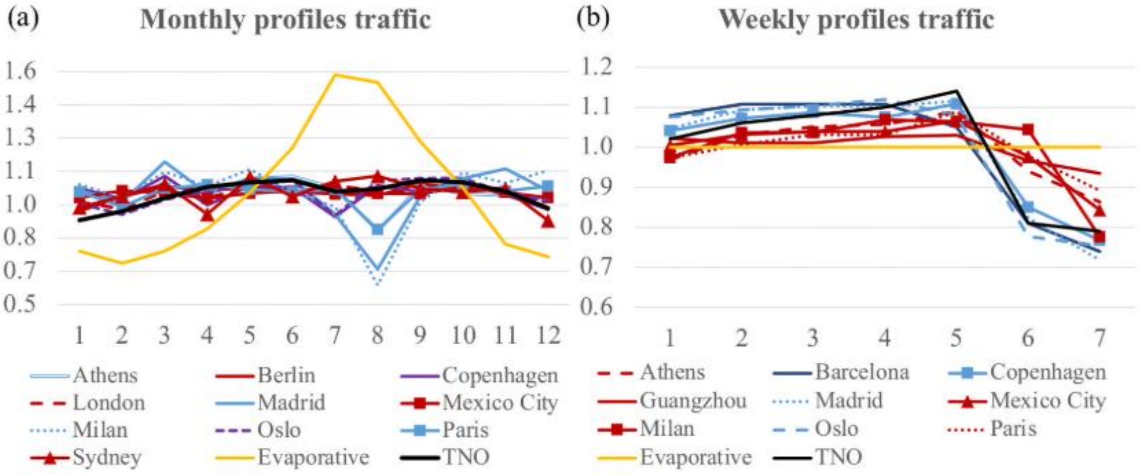

Figure 5: Monthly (a) and weekly (b) temporal profiles derived from measured traffic counts in selected cities. The profile reported by the TNO dataset is plotted for comparison purposes (Denier van der Gon et al., 2011). The monthly and weekly profiles proposed for the gasoline evaporative emissions (Evaporative, yellow line) are also shown. Source: Guevara et al. (2021).

Temporal profiles provide scaling factors for each hour in a year or for each month in a year, day in a week, and hour in a day (Figure 5). By combining these with the annual emissions, temporally explicit emissions can be calculated. These temporal profiles can also be made using local data, such as traffic counts or outdoor temperature (for heating demand) (Tier-2) and applied in a similar fashion. In some cases, temporal variability is already included in the bottom-up emission models developed under Section 3.3.3 (Tier-3).

4. Support

To illustrate the use of the downscaling tool, output has been prepared for a selection of cities across Europe. A selection of data and tables is available in the Appendix of this document. The output includes high-resolution gridded emissions, a table with a summary of the total emissions per sector and pollutant, and some additional useful insights for policymakers.

We hope these guidelines provide useful information. In case questions arise about the use of the guidelines or the downscaling tool feel free to contact us.

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References

Andres, R.J., Boden, T.A., Bréon, F.-M., Ciais, P., Davis, S., Erickson, D., Gregg, J.S., Jacobson, A., Marland, G., Miller, J., Oda, T., Olivier, J.G.J., Raupach, M.R., Rayner, P., and Treanton, K.: A synthesis of carbon dioxide emissions from fossil-fuel combustion, Biogeosciences, 9, 1845–1871, doi:10.5194/bg-9-1845-2012, 2012.

CLMS: European Union's Copernicus Land Monitoring Service information - CORINE Land Cover 2018 (vector/raster 100 m), Europe, 6-yearly, doi:10.2909/71c95a07-e296-44fc-b22b-415f42acfdf0, 2020.

Denier van der Gon, H. A. C., Hendriks, C., Kuenen, J., Segers, A., and Visschedijk, A.: Description of current temporal emission patterns and sensitivity of predicted AQ for temporal emission patterns, TNO, Utrecht, Netherlands, https://atmosphere.copernicus.eu/sites/default/files/2019-07/MACC_TNO_del_1_3_v2.pdf, 2011.

Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. (Eds.): 2006 IPCC Guidelines for National Greenhouse Gas Inventories Prepared by the National Greenhouse Gas Inventories Programme, IGES, Hayama, Japan, ISBN 4-88788-032-4, 2006.

EMEP Centre on Emissions Inventories and Projections: Grid emissions in 0.1°x0.1° long-lat resolution, https://www.ceip.at/the-emep-grid/gridded-emissions, last access: 15 May 2025.

European Commission: EDGAR - Emissions Database for Global Atmospheric Research, https://edgar.jrc.ec.europa.eu/, last access: 15 May 2025.

European Environment Agency: e/EEA air pollutant emission inventory guidebook 2023: Technical guidance to prepare national emission inventories, European Environment Agency, Copenhagen, Denmark, 2023.

Gniffke, P., Kotzulla, M., and Hausmann, K.: German Informative Inventory Report 2024, Web Report, Umweltbundesamt (UBA), Berlin, 2024.

Greenhouse Gas Protocol: GHG Protocol for Cities - An Accounting and Reporting Standard for Cities, https://ghgprotocol.org/ghg-protocol-cities, last access: 15 May 2025.

Guevara, M., Jorba, O., Tena, C., Denier van der Gon, H., Kuenen, J., Elguindi, N., Darras, S., Granier, C., and Pérez García-Pando, C.: Copernicus Atmosphere Monitoring Service TEMPOral profiles for the Regional domain version 2.1 (CAMS-REG-TEMPOv2.1), Copernicus Atmosphere Monitoring Service [publisher], ECCAD [distributor], doi:10.24380/1cx4-zy68, 2020.

Guevara, M., Jorba, O., Tena, C., Denier van der Gon, H., Kuenen, J., Elguindi, N., Darras, S., Granier, C., and Pérez García-Pando, C.: Copernicus Atmosphere Monitoring Service TEMPOral profiles (CAMS-TEMPO): global and European emission temporal profile maps for atmospheric chemistry modelling, Earth Syst. Sci. Data, 13, 367–404, doi:10.5194/essd-13-367-2021, 2021.

Gurney, K.R., Liang, J., O'Keeffe, D., Patarasuk, R., Hutchins, M., Huang, J., Rao, P., and Song, Y.: Comparison of global downscaled versus bottom-up fossil fuel CO2 emissions at the urban scale in four U.S. urban areas. Journal of Geophysical Research: Atmospheres, 124, 2823–2840, doi:10.1029/2018JD028859, 2019.

Integrated Carbon Observation System: ICOS Cities, https://www.icos-cp.eu/projects/icos-cities, last access: 15 May 2025.

IPCC: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)], Cambridge University Press, Cambridge, UK and New York, NY, USA. doi:10.1017/9781009157926, 2022.

Kuenen, J., Dellaert, S., Visschedijk, A., Jalkanen, J.-P., Super, I., and Denier van der Gon, H.: CAMS-REG-v4: a state-of-the-art high-resolution European emission inventory for air quality modelling, Earth Syst. Sci. Data, 14, 491–515, https://doi.org/10.5194/essd-14-491-2022, 2022.

Kühbacher, D., Chen, J., Aigner, P., Ilic, M., Super, I., and Denier van der Gon, H.: DRIVE v1.0: A data-driven framework to estimate road transport emissions and temporal profiles, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-753, 2025.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H.: Anthropogenic and Natural Radiative Forcing, In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Oda, T., and Maksyutov, S.: ODIAC Fossil Fuel CO2 Emissions Dataset, NIES [publisher], doi:10.17595/20170411.001, 2025.

Pesaresi, M. and Politis, P.: GHS-BUILT-V R2023A - GHS built-up volume grids derived from joint assessment of Sentinel2, Landsat, and global DEM data, multitemporal (1975-2030), European Commission, Joint Research Centre (JRC), doi:10.2905/AB2F107A-03CD-47A3-85E5-139D8EC63283, 2023.

Ramacher, M.O.P, Kakouri, A., Speyer, O., Feldner, J., Karl, M., Timmermans, R., Denier van der Gon, H., Kuenen, J., Gerasopoulos, E., and Athanasopoulou, E.: The UrbEm Hybrid Method to Derive High-Resolution Emissions for City-Scale Air Quality Modeling, Atmosphere, 12, 1404, doi:10.3390/atmos12111404, 2021.

Referat für Klima und Umweltschutz: Treibhausgas-Monitoring der Landeshauptstadt München 1990 bis 2019, available from: https://risi.muenchen.de/risi/sitzungsvorlage/detail/7205164, 2022.

Schiavina M., Freire S., Carioli A., and MacManus K.: GHS-POP R2023A - GHS population grid multitemporal (1975-2030), European Commission, Joint Research Centre (JRC), doi:10.2905/2FF68A52-5B5B-4A22-8F40-C41DA8332CFE, 2023.

Stadt Zurich: Quellen der Luftbelastung, available at: https://www.stadt-zuerich.ch/de/gesundheit/gesundheitsschutz/luftqualitaet/quellen-luftbelastung.html#verkehr, last access: 17 December 2024.

Super, I., Dellaert, S. N. C., Visschedijk, A. J. H., and Denier van der Gon, H. A. C.: Uncertainty analysis of a European high-resolution emission inventory of CO2 and CO to support inverse modelling and network design, Atmos. Chem. Phys., 20, 1795–1816, https://doi.org/10.5194/acp-20-1795-2020, 2020.

Super, I., Denier van der Gon, H.A.C., and Dröge, R.: Downscaling tool to construct city emission inventories, TNO, Utrecht, Netherlands, TNO 2025 R12516, 2025.

UN Department of Economic and Social Affairs - Population Division: Popoulation Facts 2018/1 - The speed of urbanization around the world, available from: https://population.un.org/wup/publications, 2018.

UN Environment Programme: https://www.unep.org/explore-topics/resource-efficiency/what-we-do/cities-and-climate-change, last access: 15 May 2025.

UN Human Settlements Programme: World Cities Report 2024 - Cities and Climate Action, United Nations, doi:10.18356/9789211065602, 2024.

World Meteorological Organization: IG3IS Urban Greenhouse Gas Emission Observation and Monitoring Good Research Practice Guidelines, available from: https://library.wmo.int/idurl/4/58055, 2022.

Appendix A – City emissions: output from the downscaling tool

This Appendix provides an overview of selected output from the downscaling tool. With this appendix we demonstrate the capabilities of the tooling and the type of information cities could get from using this tooling. For brevity, we focus on the greenhouse gases CO_2 and CH_4 and the air pollutants CO and NO_x, but from the downscaling other pollutants (like PM) are available as well.

The data provided in this Appendix are a first-order estimate of the city-wide emissions. As shown in Box 1, significant differences can occur between emission estimates from different sources, and therefore these estimates are not an established truth. Nevertheless, the data presented here can provide useful insights for policymakers that want to reduce the city's climate impact or the negative health impacts of air pollution events.

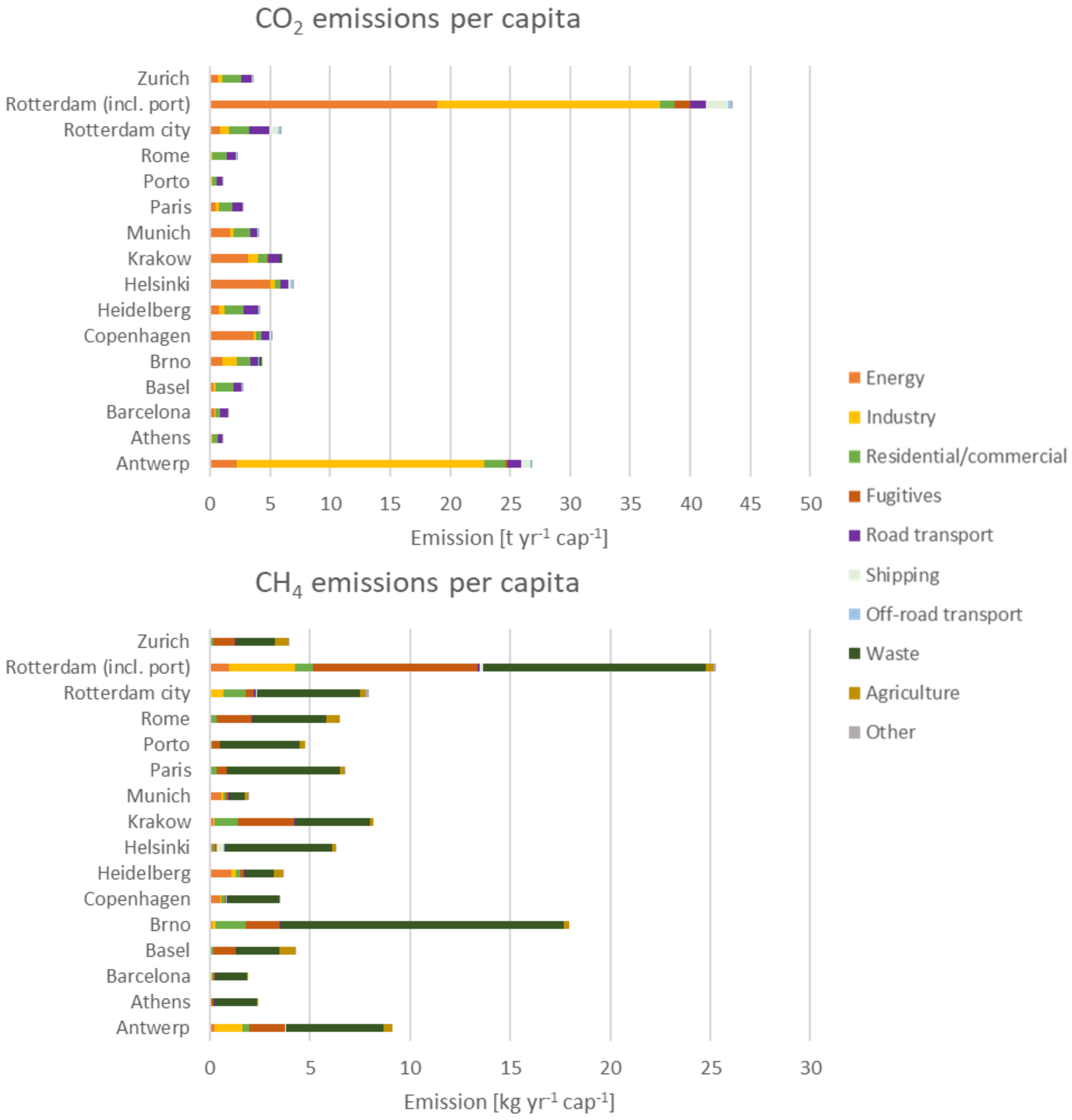

Figure 6. Per capita CO_2 and CH_4 sectoral emissions per city.

A first comparison of the cities is provided in Figure 6 and Figure 7, showing the sectoral emissions per capita (based on the Copernicus Global Human Settlement Layer GHS-POP - R2023A population volume dataset[1] for a fair comparison across cities). CO_2 and NO_x emissions are dominated by combustion activities, and the emission intensity is highest in industrial cities, notably Antwerp and Rotterdam (incl. port). These cities also show a large contribution from shipping. In contrast, CH_4 emissions are dominated by the waste sector, and CO emissions are dominated by the residential/commercial sector, road transport and off-road transport. Variability between cities is large for CO

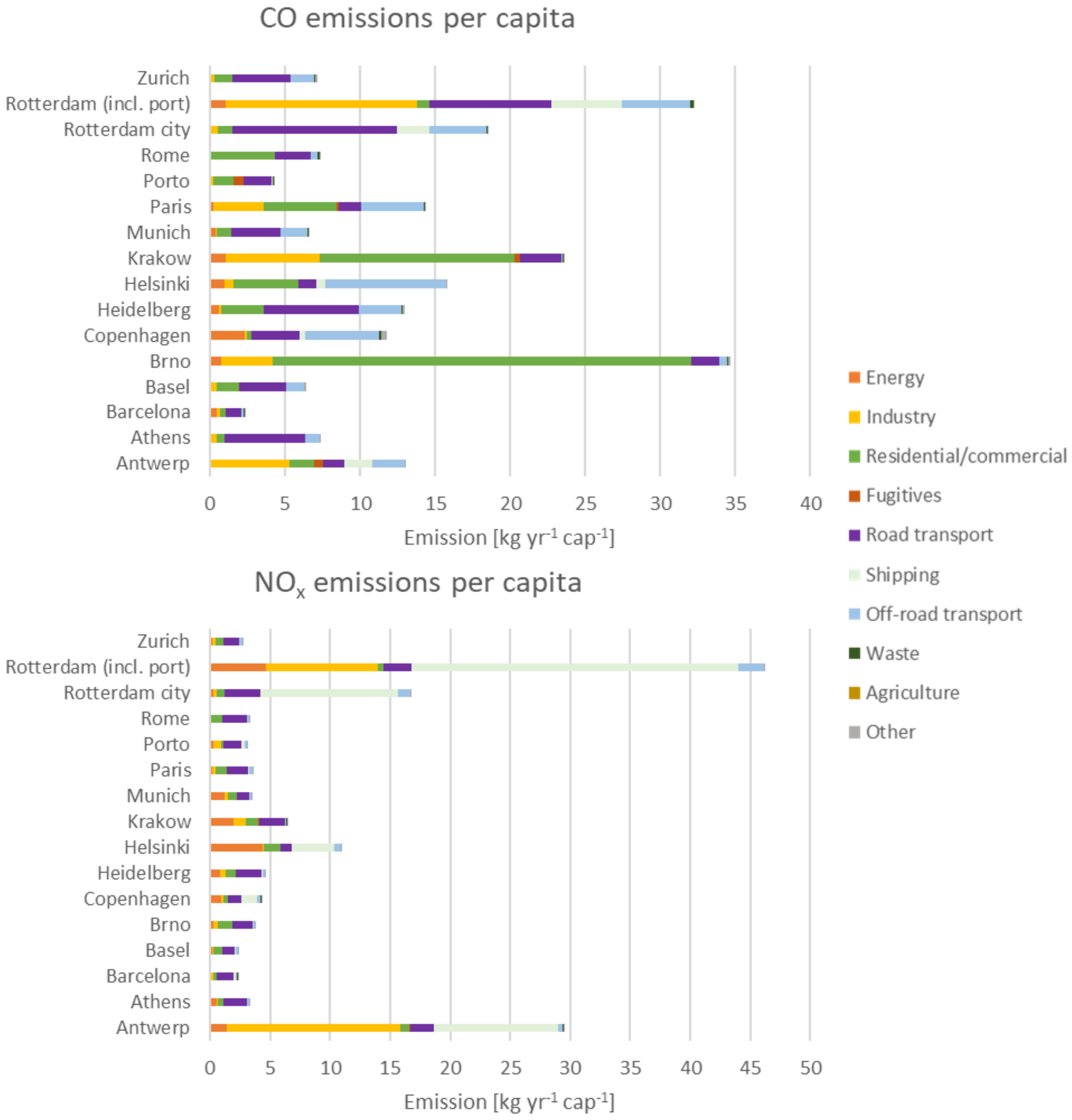

Figure 7. Per capita CO and NO_x sectoral emissions per city.

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[1] Schiavina, M., Freire, S., Carioli, A., and MacManus, K.: GHS-POP R2023A - GHS population grid multitemporal (1975-2030), European Commission, Joint Research Centre (JRC), PID: http://data.europa.eu/89h/2ff68a52-5b5b-4a22-8f40-c41da8332cfe, doi:10.2905/2FF68A52-5B5B-4A22-8F40-C41DA8332CFE, 2023.

For each city the following information is provided:

- A table with the sectoral and total city-wide emissions.
- An emission map illustrating the spatial emission patterns at 100 m resolution (except for Paris, which is at 500 m resolution). Point sources are indicated as red dots, with the size representing the relative importance of each point source: the bigger the dot, the larger the emissions.
- Pie charts showing the relative contribution of each sector to the total emissions for the city and the average for all selected cities.

The average pie charts are based on the median sectoral share from all selected cities, normalized to reach a total of 100% over all sectors. Therefore, each city has the same weight, irrespective of its size. Note that the selected cities are not necessarily representative for the European situation and may be biased towards particular types of cities (e.g., size, northern vs. southern countries).

The different types of emission data presented here should be carefully combined to draw conclusions about the city's main emission sources and opportunities for emission reductions. For example, if a city's pie chart shows an above-average share of road transport CO emissions this could be the result of high road transport emissions, or of low emissions from the other sectors. Looking at the per capita CO emissions compared to other cities can support either of these theories.

City-specific data are provided for the following cities:

- Antwerp
- Athens
- Barcelona
- Basel
- Brno
- Copenhagen
- Heidelberg
- Helsinki
- Krakow
- Munich
- Paris
- Porto
- Rome
- Rotterdam city
- Rotterdam (incl. port)
- Zurich

A.1 Antwerp

Antwerp is characterized by a large industrial port area. This translates into large emissions from industry and shipping, especially for CO_2 and NO_x, causing emissions per capita to be far above average for the selected cities (Figure 6 and Figure 7).

Table 2. Sectoral emissions in Antwerp.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	115	1192	48	740
Industry	743	11008	2793	7702
Residential/commercial	175	912	845	427
Fugitives	954	116	318	58
Road transport	16	608	788	1021
Shipping	20	376	966	5518
Off-road transport	7	74	1174	201
Waste	2599	0	10	29
Agriculture	229	0	0	0
Other	0	5	33	2
Total	4858	14292	6974	15699

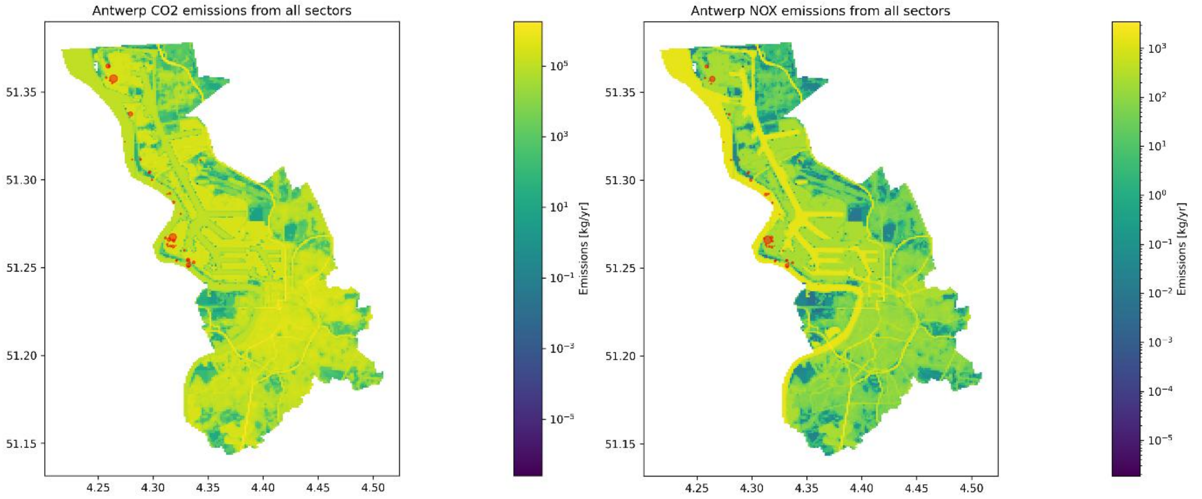

Figure 8. Emission maps of CO_2 (left) and NO_x (right) for Antwerp. The NO_x emission map clearly shows the importance of the shipping sector.

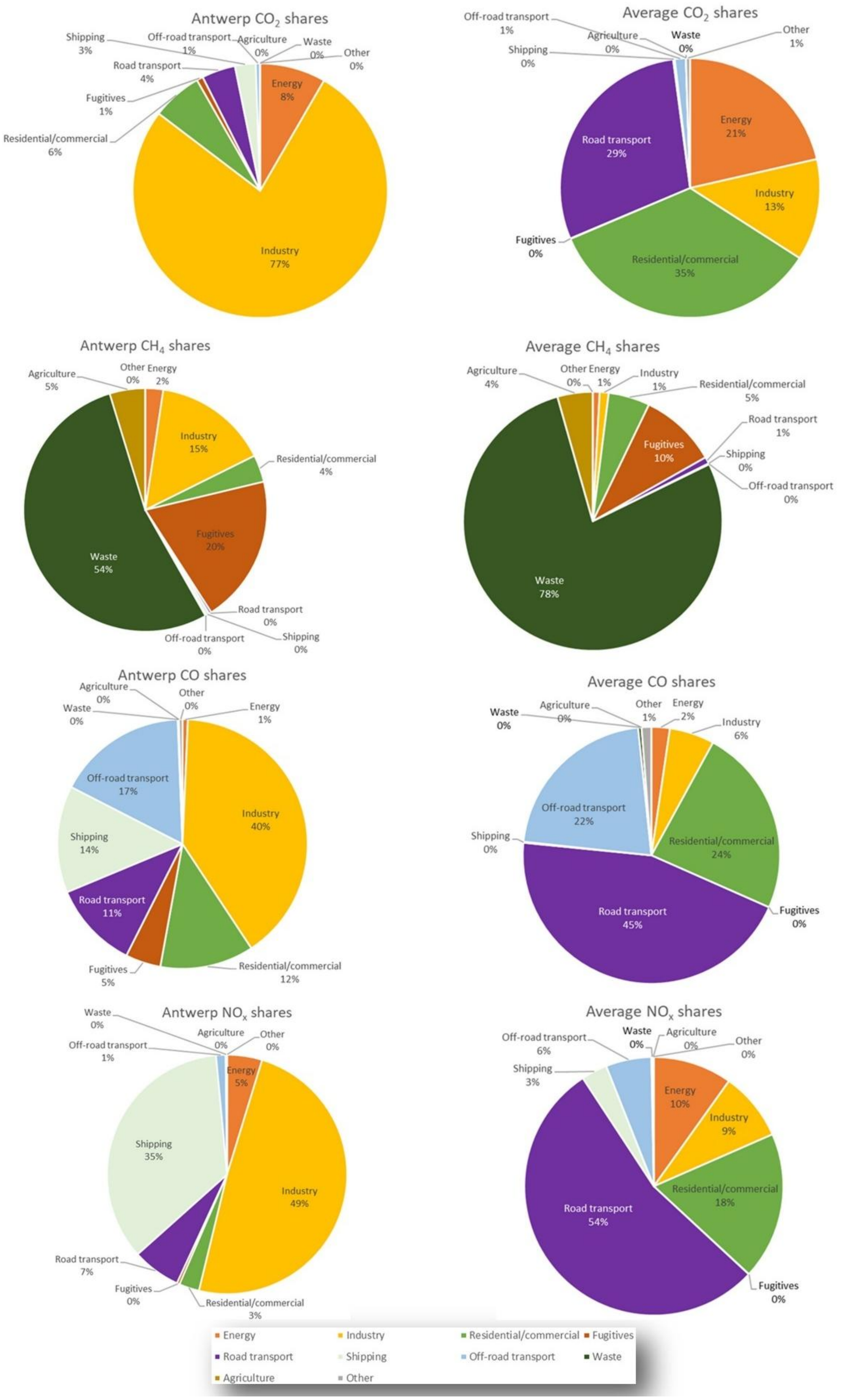

Figure 9. Pie charts showing the relative contribution of each source sector to the total emissions of CO$_2$, CH$_4$, CO and NO$_x$ for Antwerp (left) and the average of all selected cities (right).

A.2 Athens

Athens shows relatively low greenhouse gas emissions per capita (Figure 6 and Figure 7), which can be explained by the absence of significant industrial activities and relatively low emissions from the residential/commercial (heating) sector.

Table 3. Sectoral emissions in Athens.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	0	85	17	352
Industry	3	49	279	103
Residential/commercial	18	282	373	314
Fugitives	80	0	6	0
Road transport	47	305	3644	1330
Shipping	0	0	0	0
Off-road transport	0	7	660	104
Waste	1445	0	0	0
Agriculture	40	0	0	0
Other	0	8	73	2
Total	1633	737	5051	2207

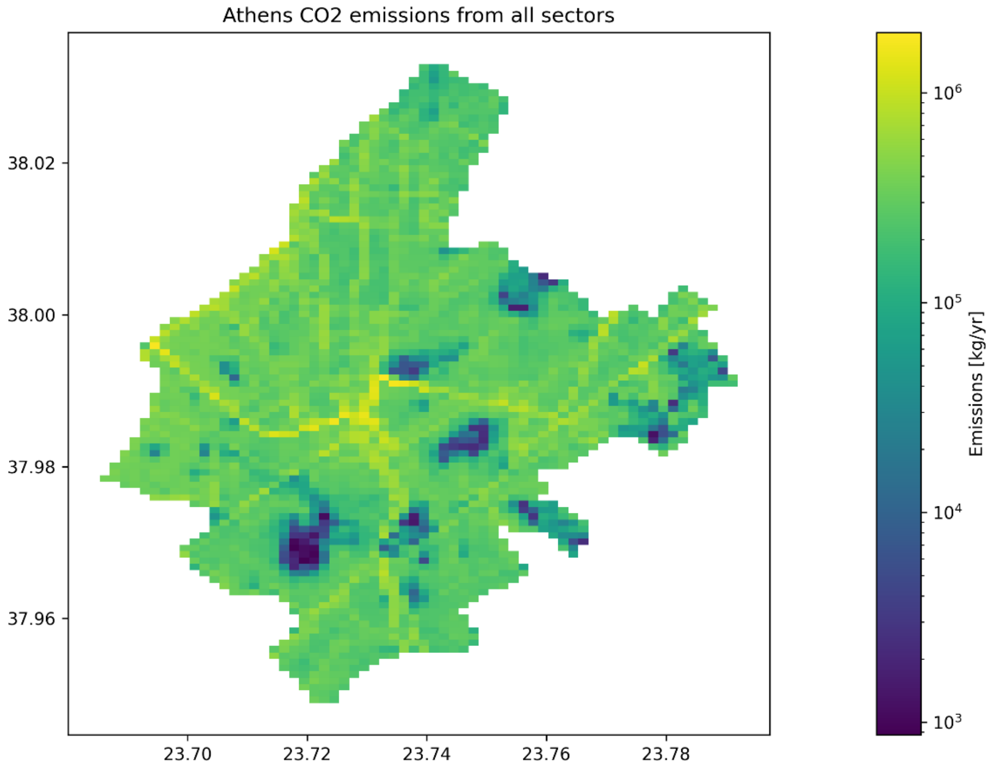

Figure 10. Emission map of CO_2 for Athens.

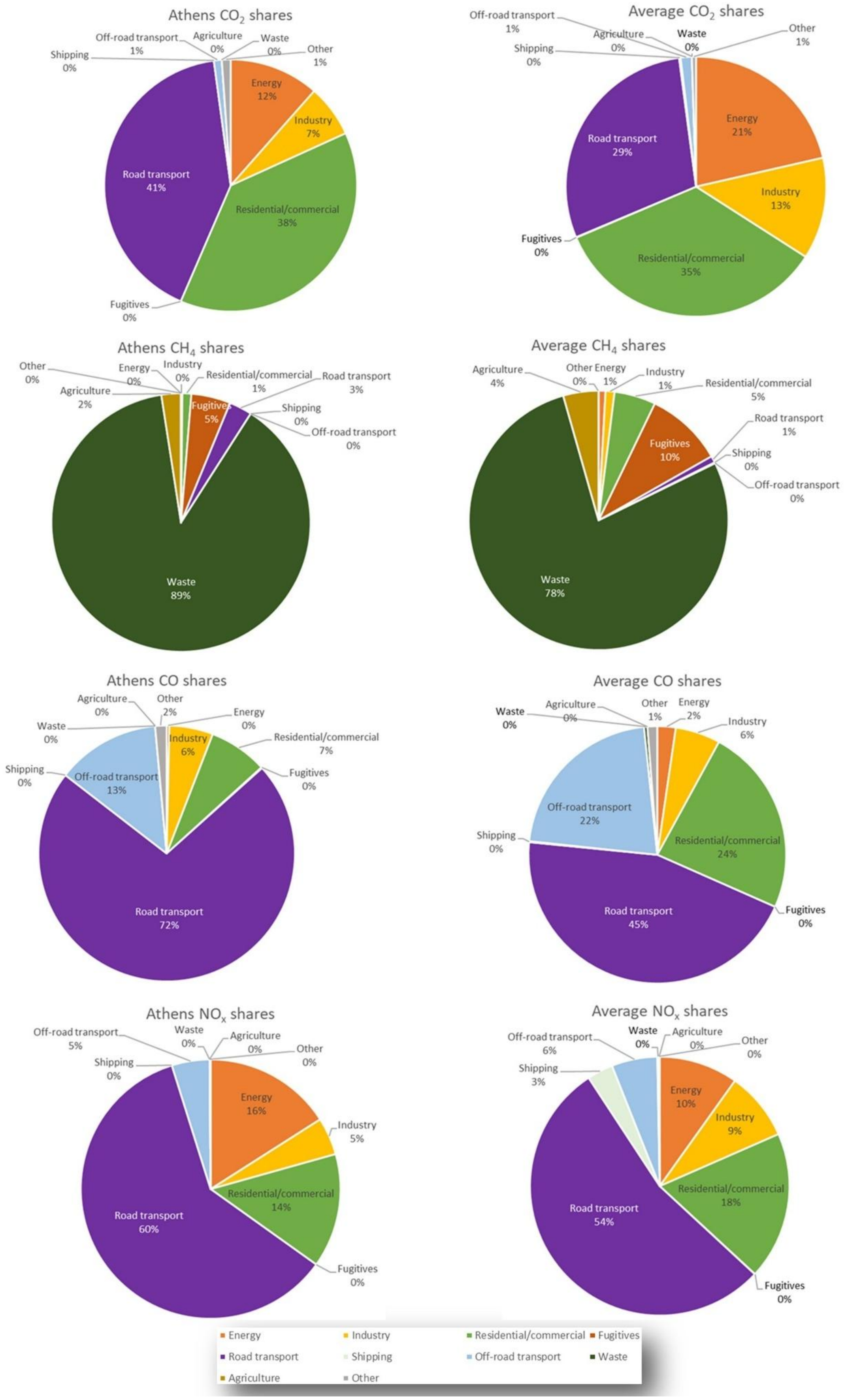

Figure 11. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Athens (left) and the average of all selected cities (right).

A.3 Barcelona

Barcelona shows relatively low greenhouse gas emissions per capita (Figure 6 and Figure 7), which can be explained by relatively low emissions from the residential/commercial (heating) sector. There is a significant amount of shipping emissions, particularly for NO_x.

Table 4. Sectoral emissions in Barcelona.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	7	667	776	237
Industry	226	255	487	213
Residential/commercial	125	715	710	652
Fugitives	99	2	7	18
Road transport	48	1076	1885	2533
Shipping	12	29	71	400
Off-road transport	5	34	280	211
Waste	2930	0	124	22
Agriculture	20	0	0	0
Other	0	12	97	3
Total	3472	2790	4436	4290

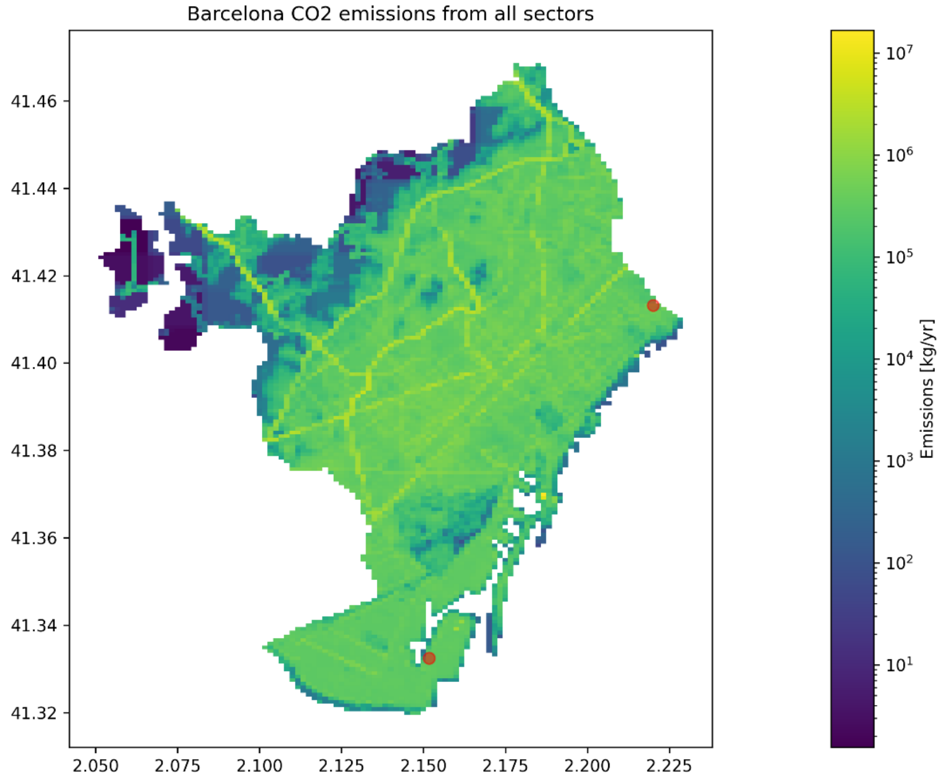

Figure 12. Emission map of CO_2 for Barcelona.

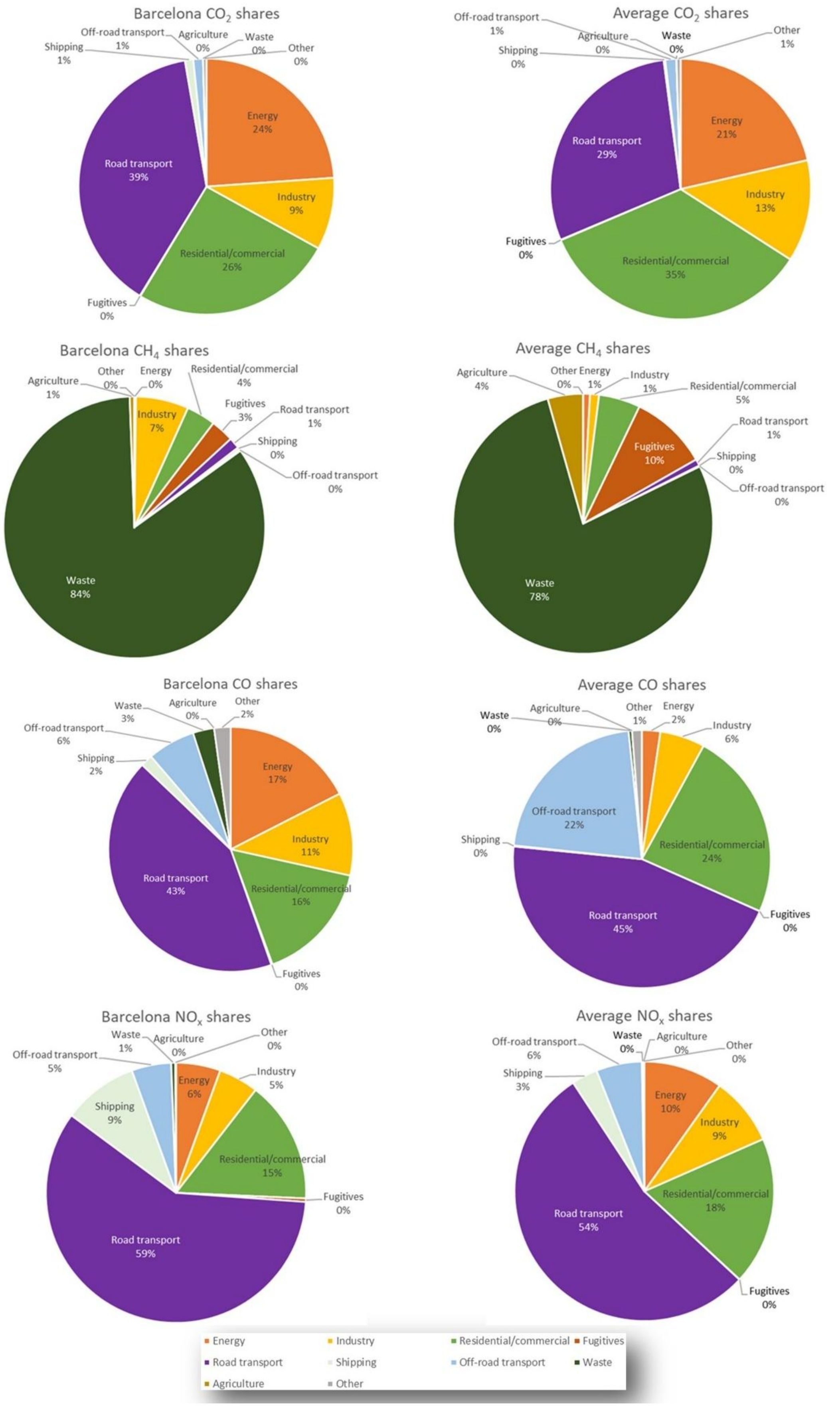

Figure 13. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Barcelona (left) and the average of all selected cities (right).

A.4 Basel

Basel is a small-sized city at mid-latitudes, characterized by relatively high emissions from the residential/commercial (heating) sector compared to more southern cities, like Athens. Moreover, the contribution of the agricultural sector to CH_4 emissions is relatively large.

Table 5. Sectoral emissions in Basel.

Sector	**CH4 [t/yr]**	**CO2 [kt/yr]**	**CO [t/yr]**	**NOX [t/yr]**
Energy	1	46	4	26
Industry	2	35	81	22
Residential/commercial	30	284	270	135
Fugitives	204	0	1	0
Road transport	6	125	580	198
Shipping	0	1	2	19
Off-road transport	1	9	225	33
Waste	398	0	1	1
Agriculture	144	0	0	0
Other	1	2	24	3
Total	785	503	1188	437

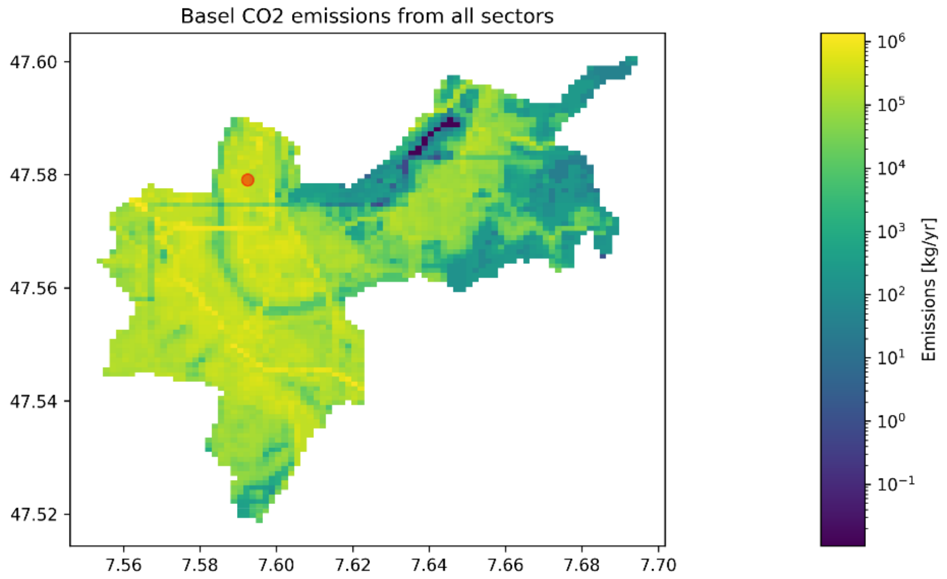

Figure 14. Emission map of CO_2 for Basel.

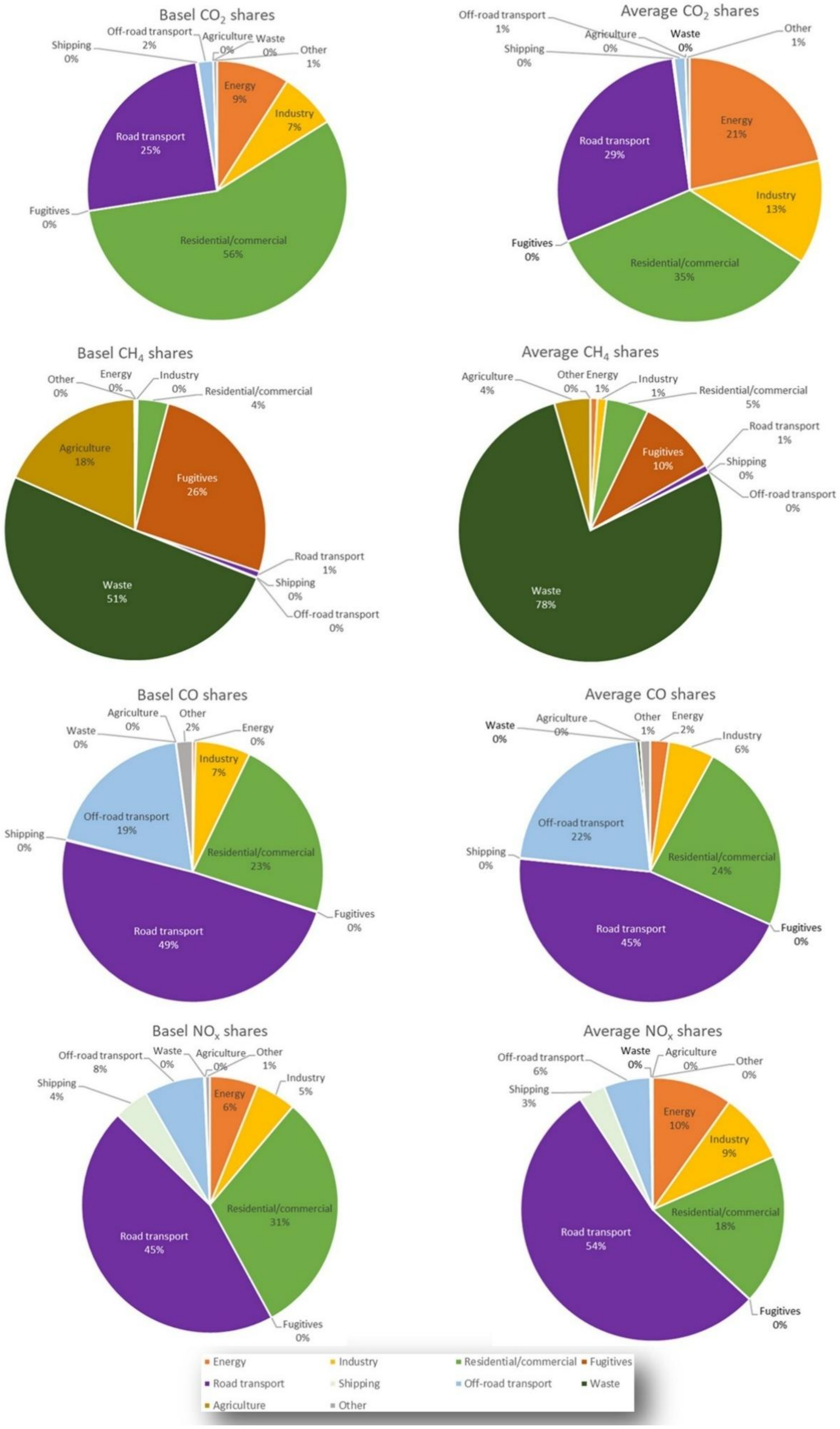

Figure 15. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Basel (left) and the average of all selected cities (right).

A.5 Brno

The city of Brno shows high CH_4 and CO emissions per capita. For CH_4 this is mostly due to the waste sector, whereas CO emissions are strongly dominated by the residential/commercial sector. There is also a significant contribution from the energy and industry sectors, especially to CO_2 and CO emissions.

Table 6. Sectoral emissions in Brno.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	51	408	279	118
Industry	62	445	1337	145
Residential/commercial	586	449	10854	452
Fugitives	649	0	0	2
Road transport	10	275	711	663
Shipping	0	0	0	0
Off-road transport	1	17	223	63
Waste	5509	69	22	3
Agriculture	103	1	0	0
Other	0	6	44	1
Total	6972	1669	13470	1448

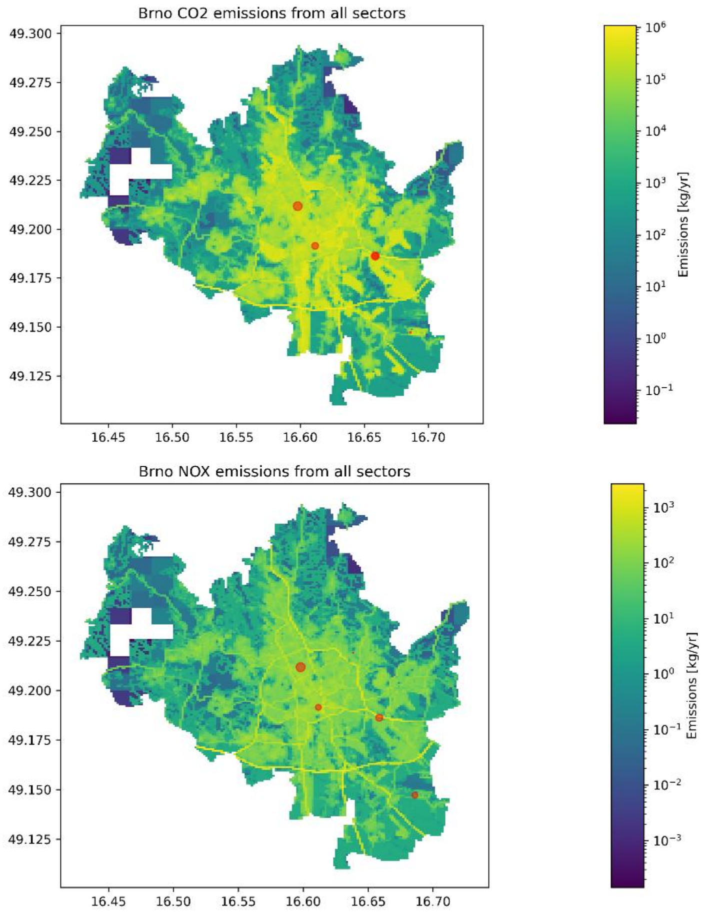

Figure 16. Emission maps of CO_2 (top) and NO_x (bottom) for Brno. The NO_x emission map clearly shows the road network, whereas CO_2 emissions are more evenly spread over the city.

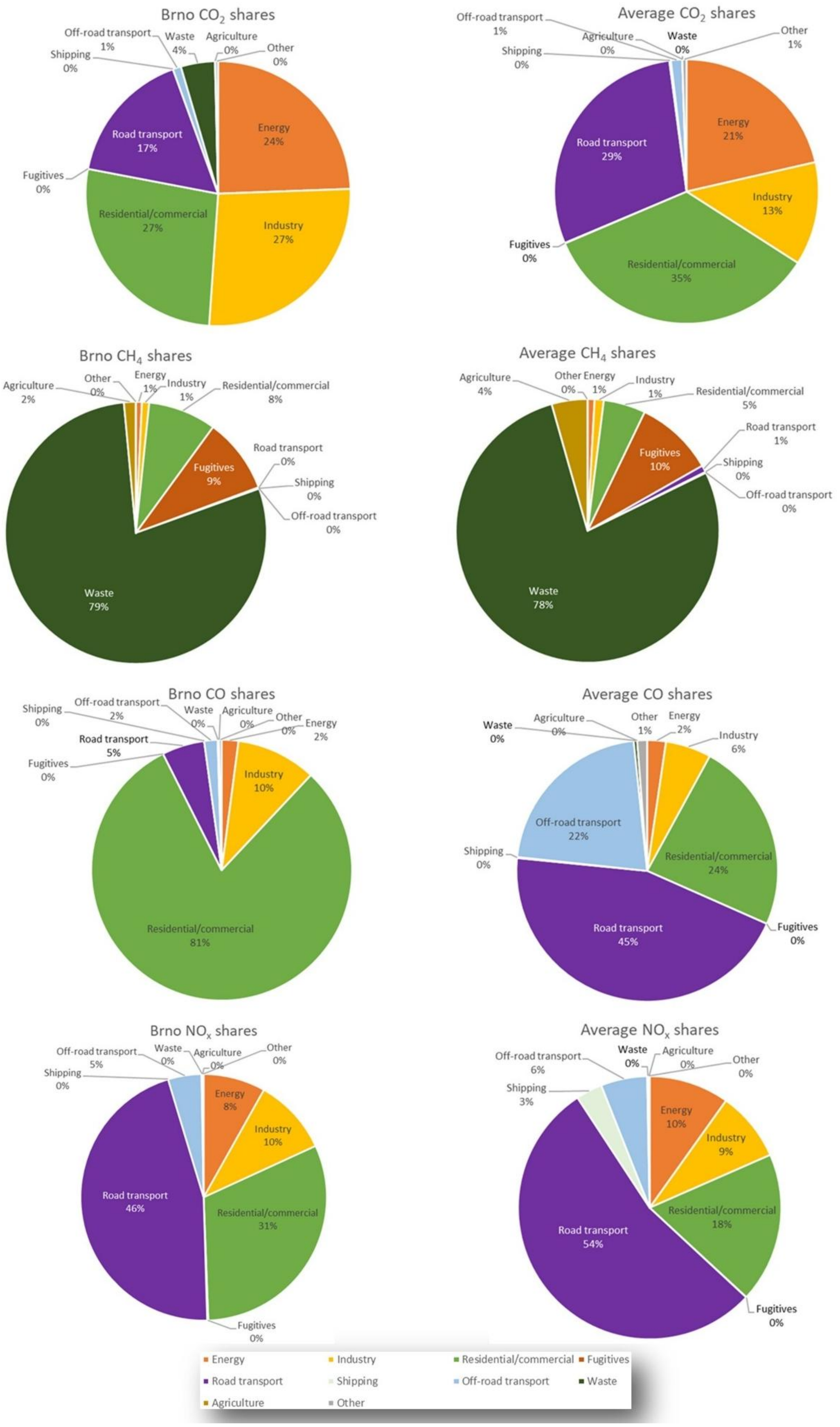

Figure 17. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Brno (left) and the average of all selected cities (right).

A.6 Copenhagen

Copenhagen is characterized by a large energy sector contribution to the total emissions. What stands out is the large CO emissions from off-road transport (mostly from residential mobile machinery) and the contribution from shipping to NO_x emissions.

Table 7. Sectoral emissions in Copenhagen.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	325	2386	1512	605
Industry	48	121	94	149
Residential/commercial	100	292	218	218
Fugitives	46	4	0	0
Road transport	8	457	2062	763
Shipping	0	52	270	806
Off-road transport	6	65	3195	234
Waste	1754	2	106	6
Agriculture	0	0	0	0
Other	9	17	268	4
Total	2296	3398	7724	2785

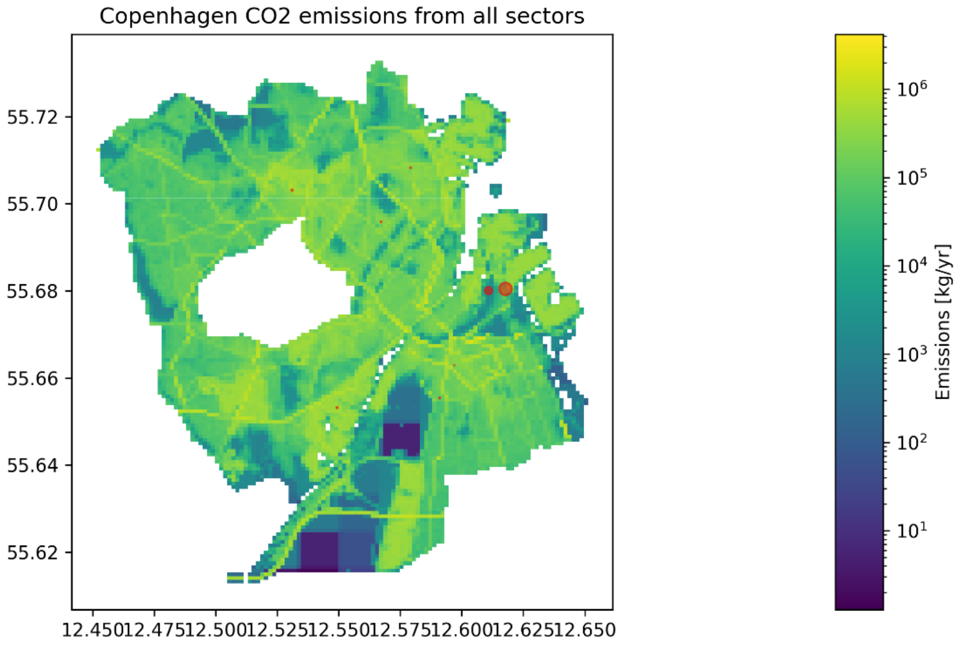

Figure 18. Emission map of CO_2 for Copenhagen.

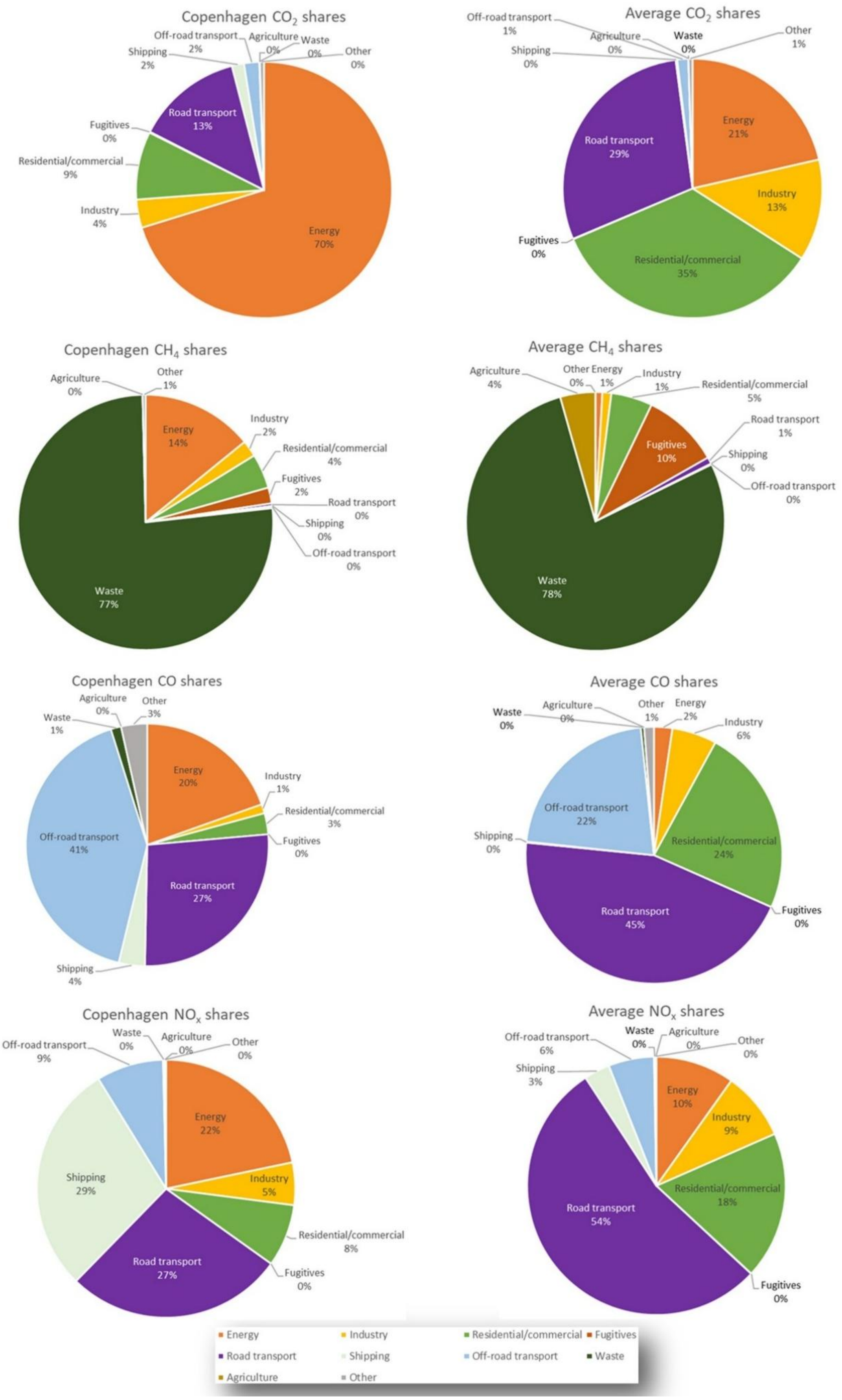

Figure 19. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Copenhagen (left) and the average of all selected cities (right).

A.7 Heidelberg

Heidelberg has no particularly noticeable deviations from the average over all cities, except for the relatively high shares of energy and agriculture in the CH_4 emissions.

Table 8. Sectoral emissions in Heidelberg.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	163	108	98	135
Industry	34	86	22	74
Residential/commercial	36	238	435	127
Fugitives	24	0	0	0
Road transport	9	182	979	330
Shipping	0	0	1	5
Off-road transport	1	11	436	39
Waste	224	0	7	1
Agriculture	72	1	0	0
Other	2	4	22	0
Total	565	631	2000	711

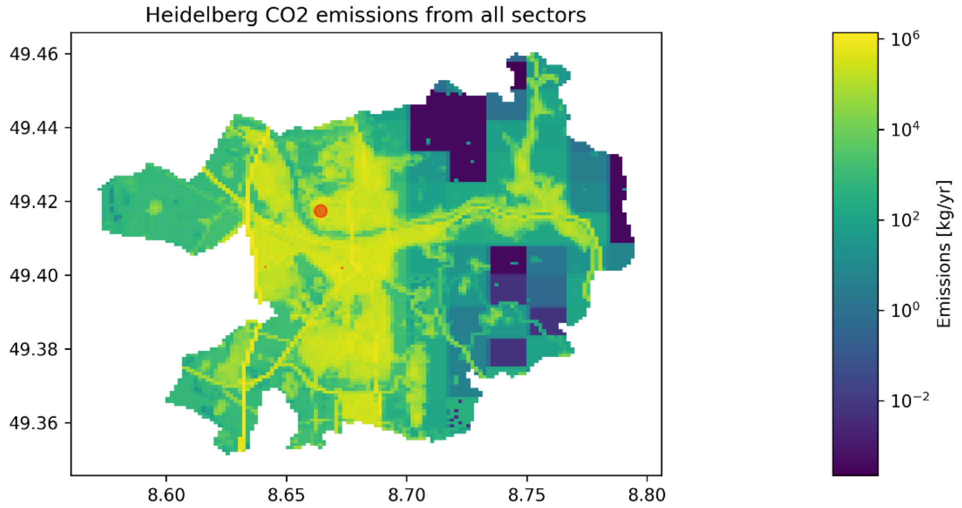

Figure 20. Emission map of CO_2 for Heidelberg.

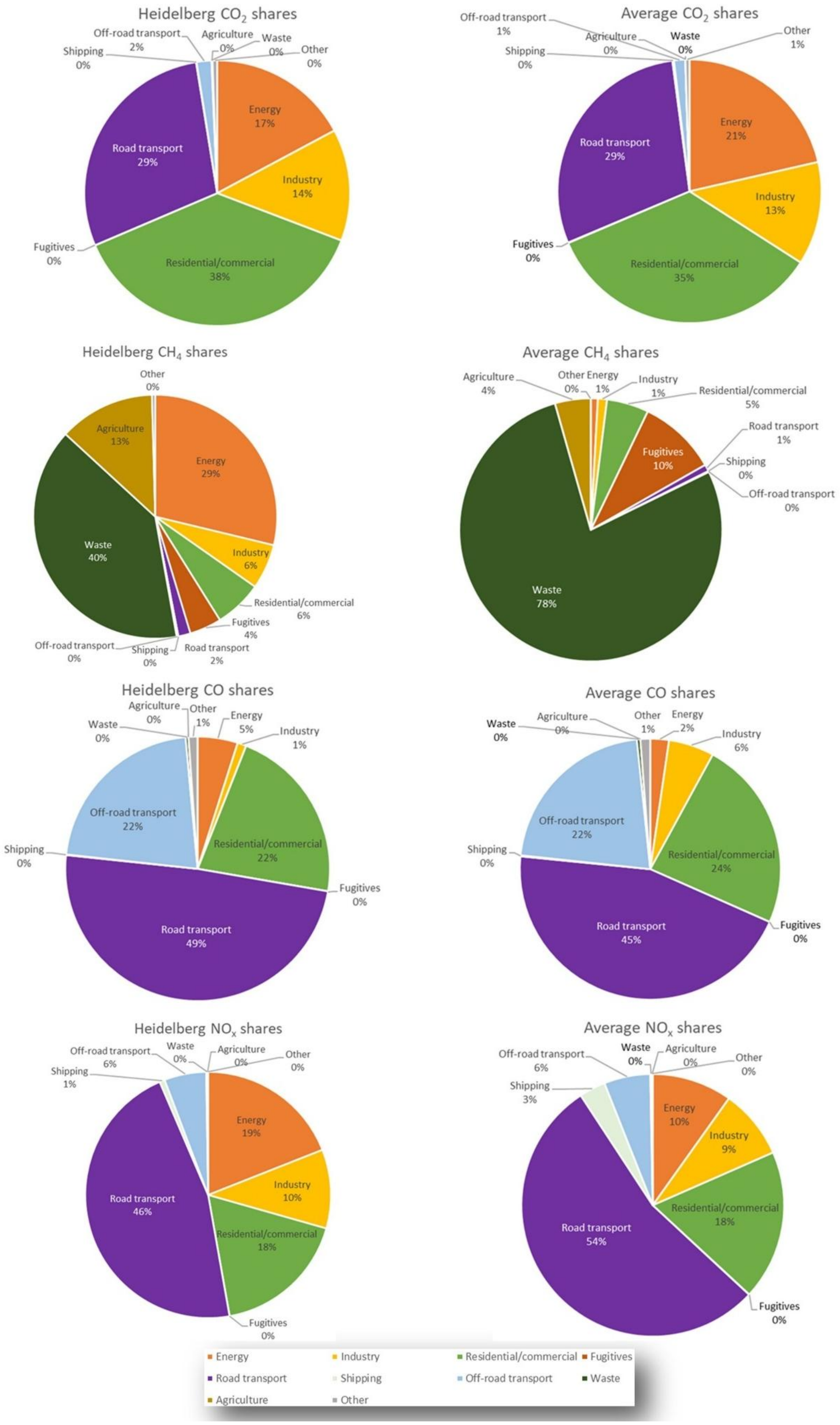

Figure 21. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Heidelberg (left) and the average of all selected cities (right).

A.8 Helsinki

Helsinki shows relatively high CO_2 emissions per capita, dominated by the energy sector. Shipping emissions contribute significantly to emissions of NO_x, whereas CO is strongly dominated by emissions from off-road transport (mostly from residential mobile machinery).

Table 9. Sectoral emissions in Helsinki.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	74	3243	642	2813
Industry	17	255	386	109
Residential/commercial	68	329	2779	901
Fugitives	64	0	0	0
Road transport	6	373	795	585
Shipping	206	166	383	2321
Off-road transport	29	85	5186	358
Waste	3499	0	0	0
Agriculture	80	0	0	0
Other	1	19	15	0
Total	4043	4470	10185	7087

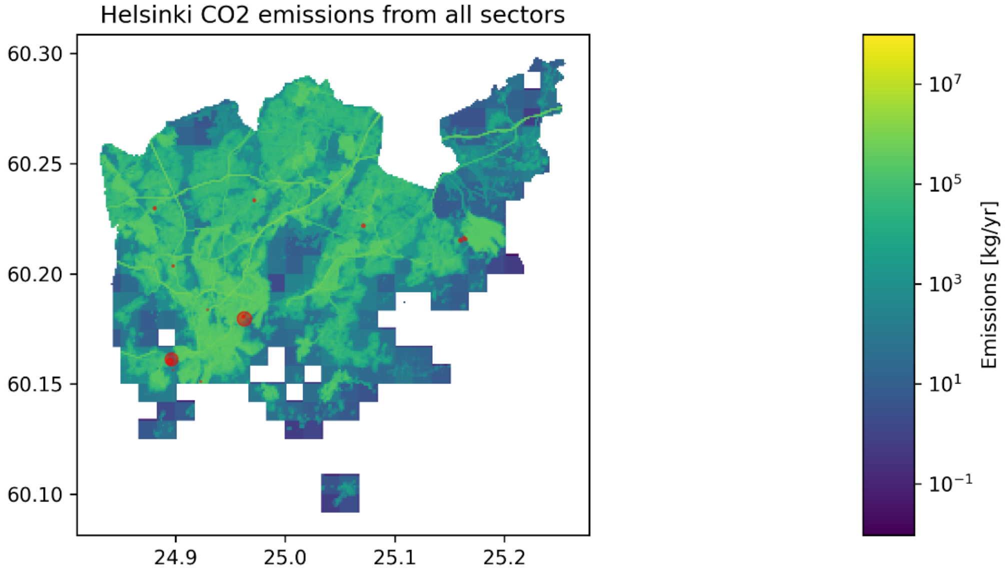

Figure 22. Emission map of CO_2 for Helsinki.

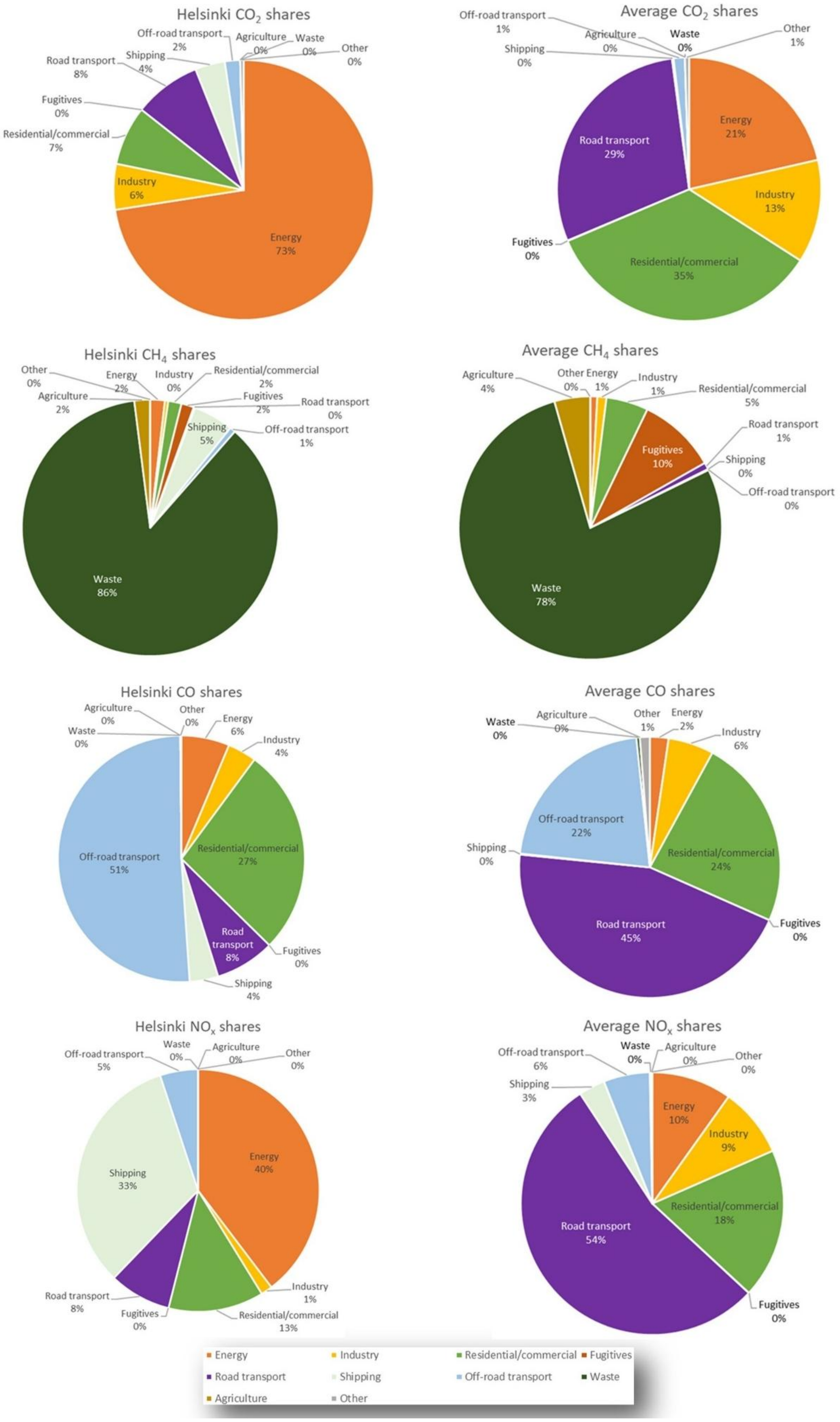

Figure 23. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Helsinki (left) and the average of all selected cities (right).

A.9 Krakow

Krakow shows large contributions from the energy and industry sectors, particularly for CO_2 and NO_x. The CH_4 emissions show relatively large contributions from the residential/commercial sector and fugitives. CO emissions are dominated by the residential/commercial sector, causing above-average CO emissions per capita.

Table 10. Sectoral emissions in Krakow.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	124	2396	812	1525
Industry	53	637	4753	765
Residential/commercial	902	584	9940	788
Fugitives	2114	116	276	66
Road transport	34	678	2119	1653
Shipping	0	0	0	0
Off-road transport	1	23	18	63
Waste	2861	94	65	60
Agriculture	126	1	0	0
Other	0	6	44	1
Total	6215	4535	18027	4921

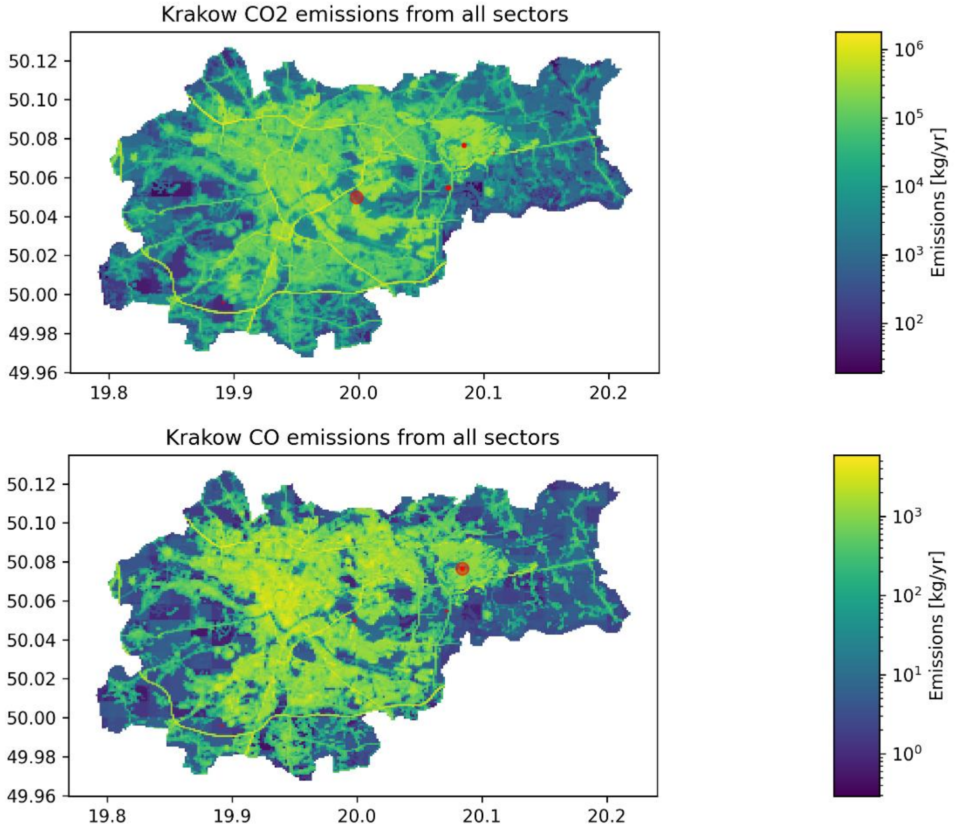

Figure 24. Emission maps of CO_2 (top) and CO (bottom) for Krakow. The CO emission map shows the dominance of the residential/commercial sector.

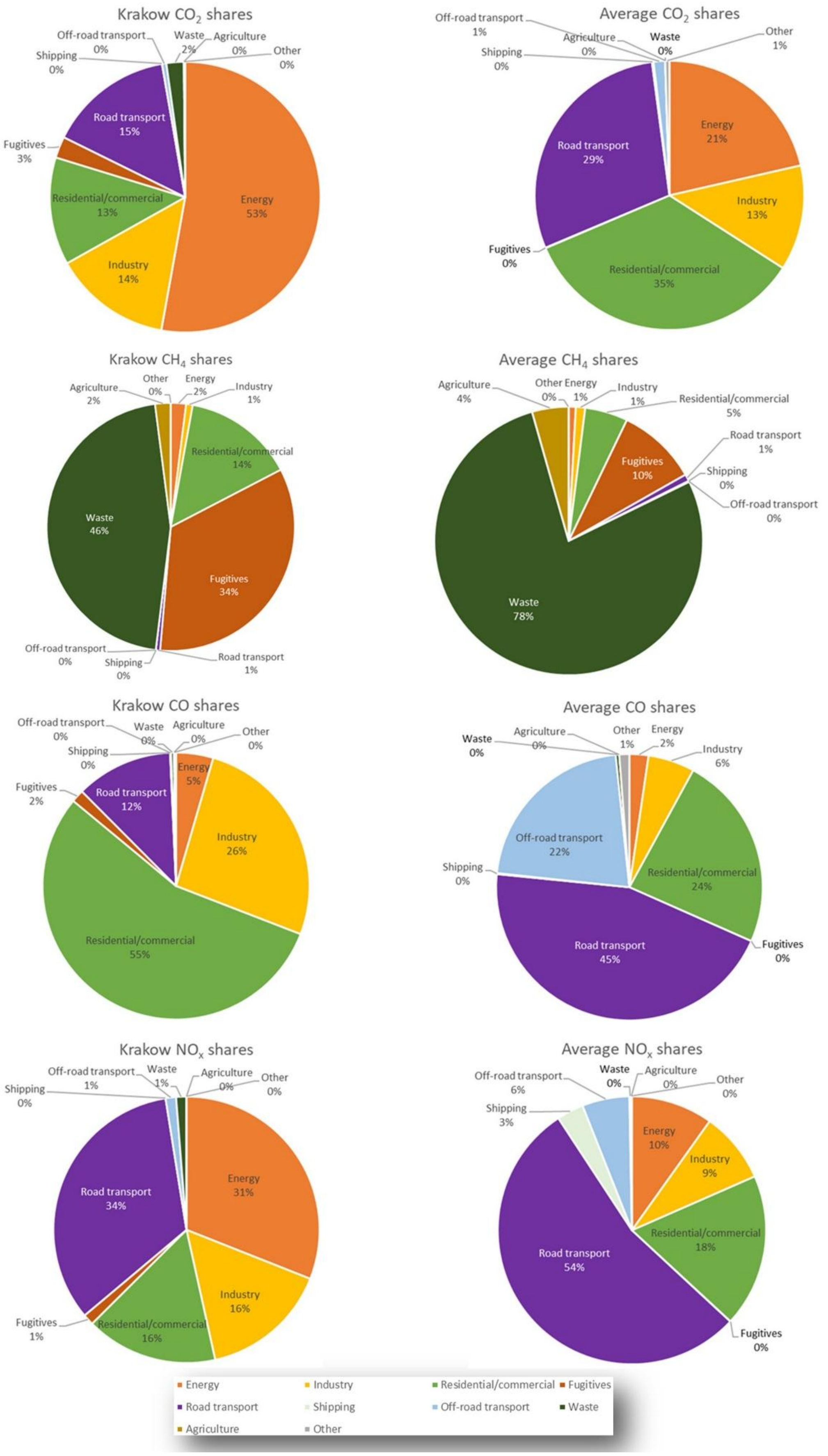

Figure 25. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Krakow (left) and the average of all selected cities (right).

A.10 Munich

The city of Munich is characterized by a large energy sector, contributing especially to the CO_2, CH_4 and NO_x emissions.

Table 11. Sectoral emissions in Munich.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	891	2618	598	1909
Industry	165	425	104	361
Residential/commercial	129	2096	1530	1139
Fugitives	209	1	2	1
Road transport	47	934	5028	1691
Shipping	0	0	0	0
Off-road transport	10	70	2845	211
Waste	1267	0	11	12
Agriculture	248	1	0	0
Other	23	34	208	3
Total	2989	6179	10325	5327

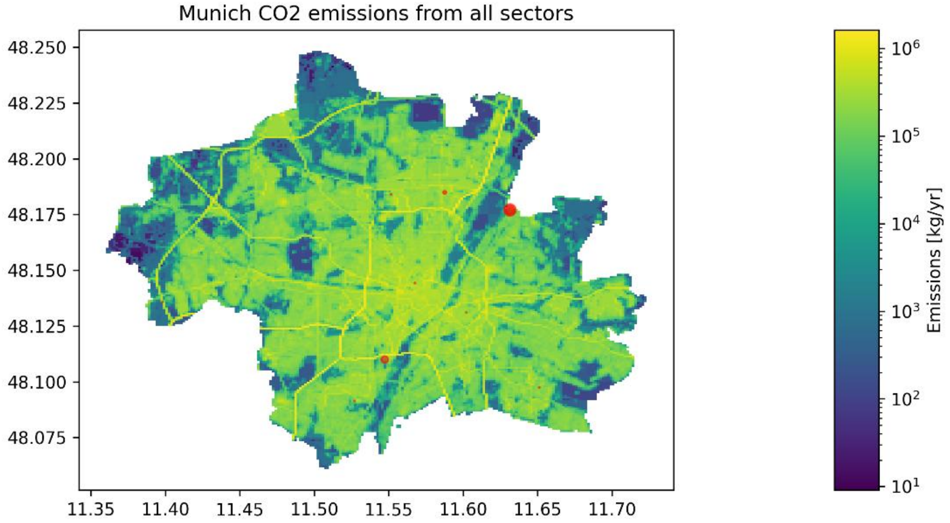

Figure 26. Emission map of CO_2 for Munich.

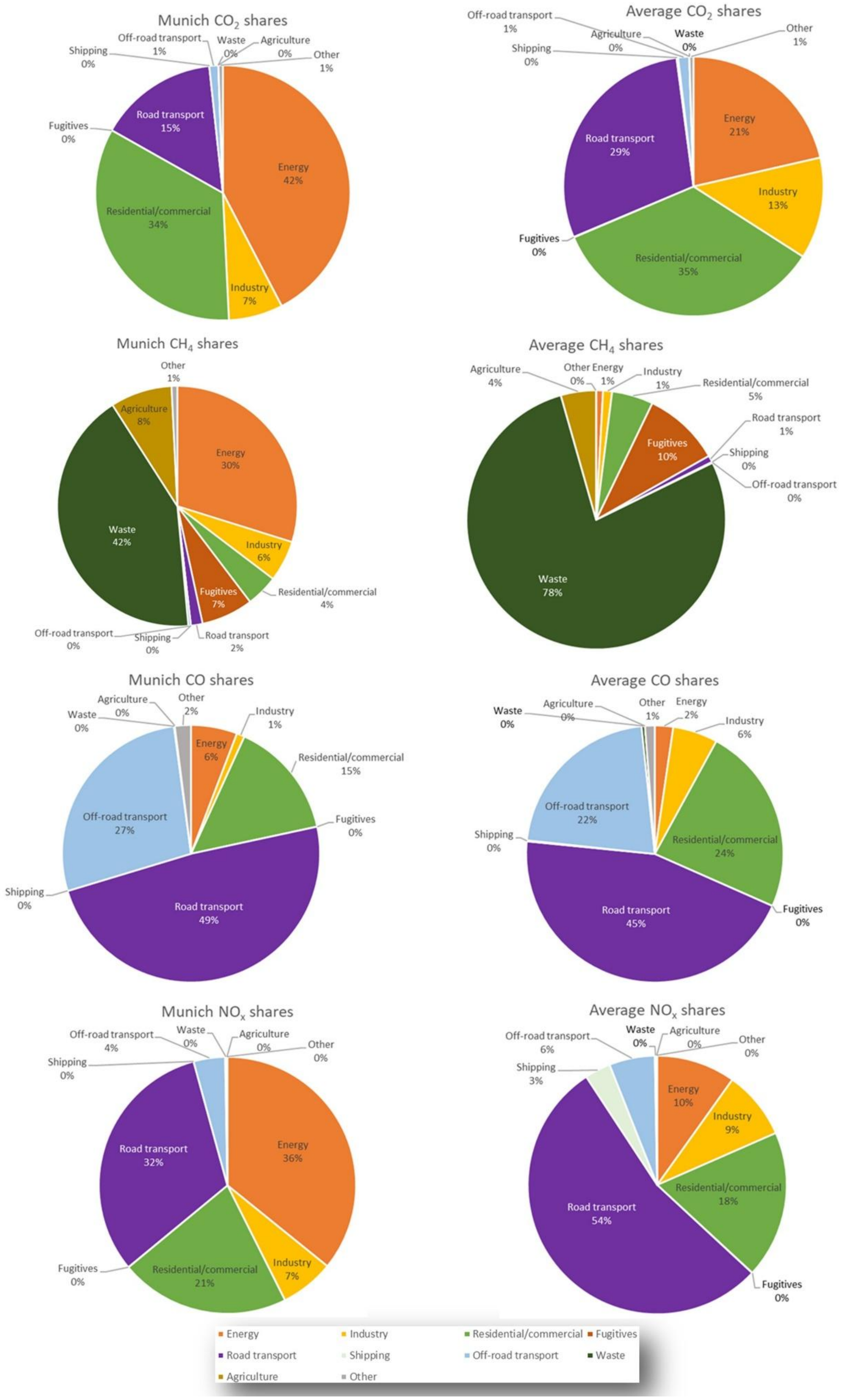

Figure 27. Pie charts showing the relative contribution of each source sector to the total emissions of CO$_2$, CH$_4$, CO and NO$_x$ for Munich (left) and the average of all selected cities (right).

A.11 Paris

Paris is a large-sized city with average emission characteristics. Most notable is the large industrial share in CO emissions. In contrast, the road transport share in CO emissions is relatively small, also looking at the per capita emissions.

Table 12. Sectoral emissions in Paris.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	242	5328	2703	2507
Industry	102	4048	40550	3322
Residential/commercial	3677	13468	58635	11034
Fugitives	6080	66	1994	21
Road transport	332	9497	17805	21712
Shipping	7	29	29	465
Off-road transport	26	354	50449	3355
Waste	67812	429	925	324
Agriculture	2765	59	0	0
Other	2	134	540	159
Total	81046	33413	173630	42899

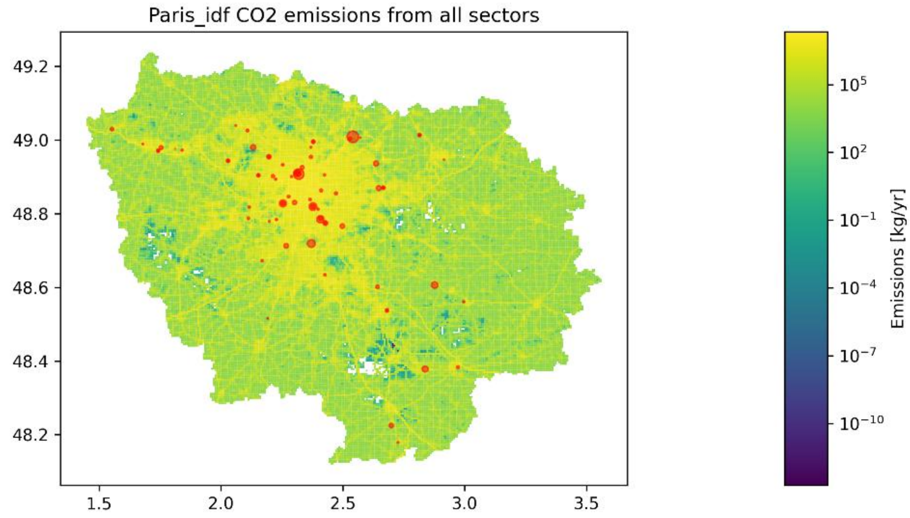

Figure 28. Emission map of CO_2 for Paris.

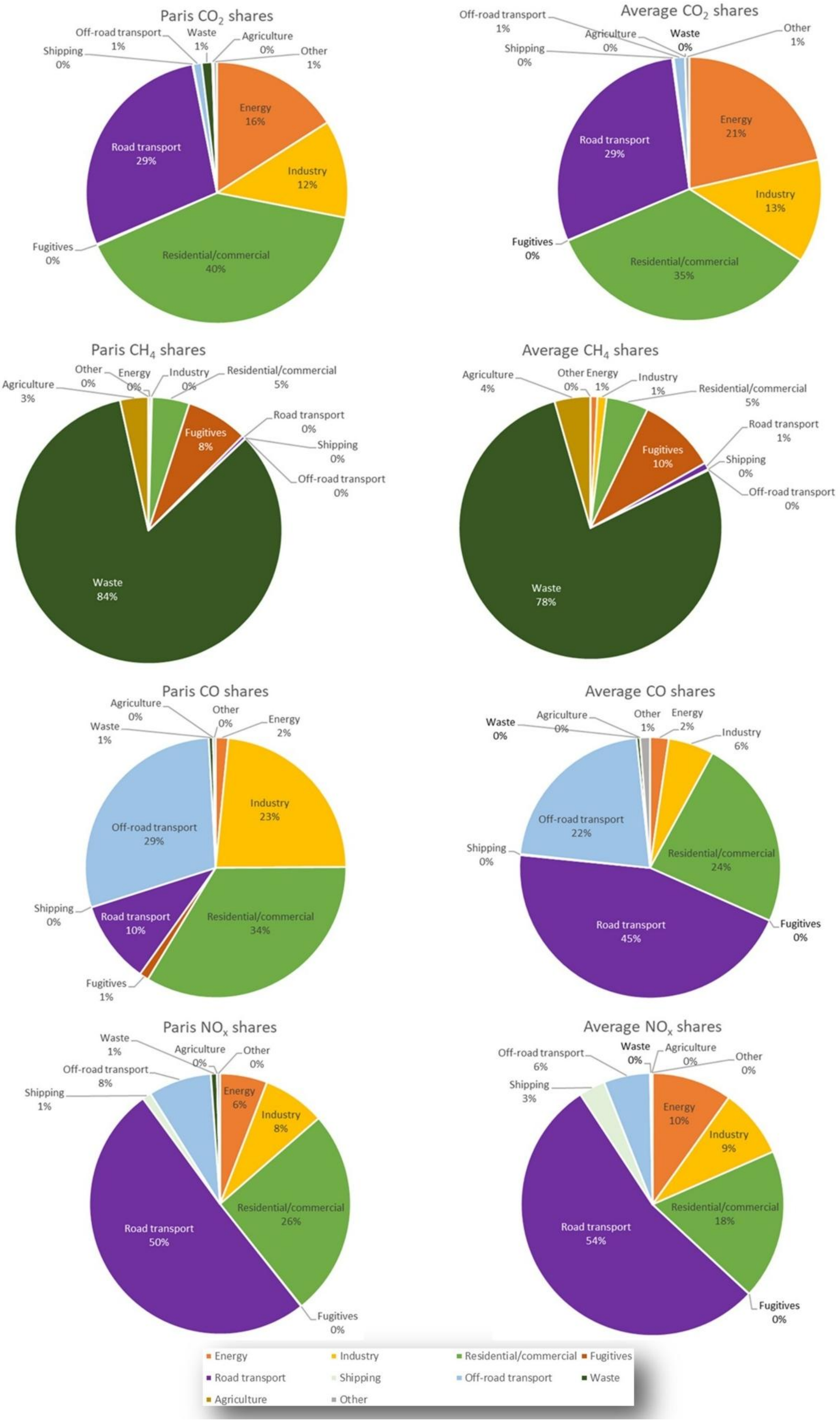

Figure 29. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Paris (left) and the average of all selected cities (right).

A.12 Porto

The contribution of the energy sector to the CO_2 emissions in Porto is relatively small, whereas the share of road transport is high. The contribution of fugitives to CO emissions is remarkable, as well as the very small contribution of the off-road transport sector.

Table 13. Sectoral emissions in Porto.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	2	19	19	62
Industry	9	35	41	166
Residential/commercial	24	83	332	66
Fugitives	90	2	175	0
Road transport	4	122	468	375
Shipping	0	5	16	71
Off-road transport	0	3	10	29
Waste	1005	0	5	1
Agriculture	58	0	0	0
Other	0	4	25	1
Total	1192	273	1092	770

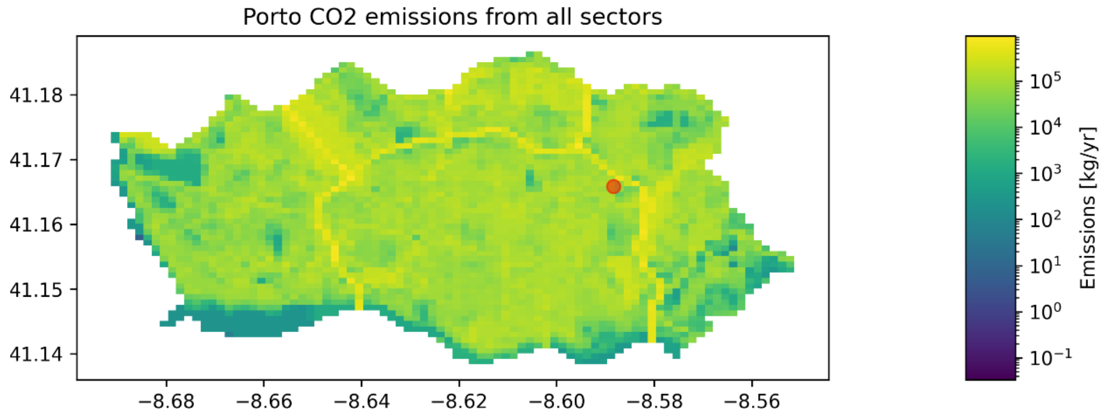

Figure 30. Emission map of CO_2 for Porto.

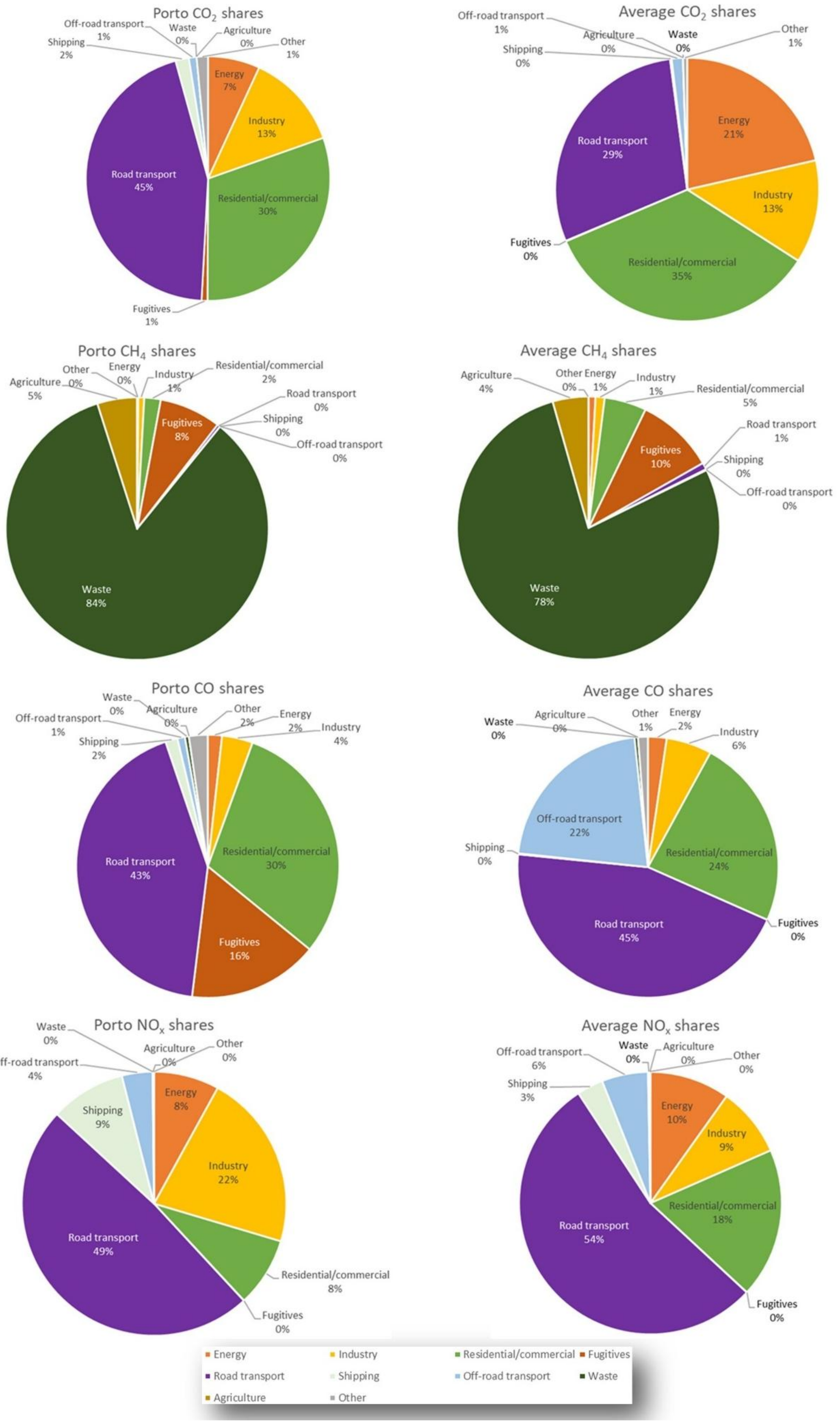

Figure 31. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Porto (left) and the average of all selected cities (right).

A.13 Rome

Rome is characterized by the absence of significant contributions from the energy and industry sectors. CO_2 and CO emissions are dominated by the residential/commercial sector, whereas for NO_x the road transport sector is the largest contributor. CH_4 emissions show a large share of fugitives.

Table 14. Sectoral emissions in Rome.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	39	78	60	49
Industry	125	446	64	190
Residential/commercial	829	3244	11937	2709
Fugitives	4677	16	0	2
Road transport	146	2254	6444	5648
Shipping	0	1	6	21
Off-road transport	6	91	1314	345
Waste	10223	0	336	16
Agriculture	1938	3	0	0
Other	0	51	186	6
Total	17983	6184	20346	8987

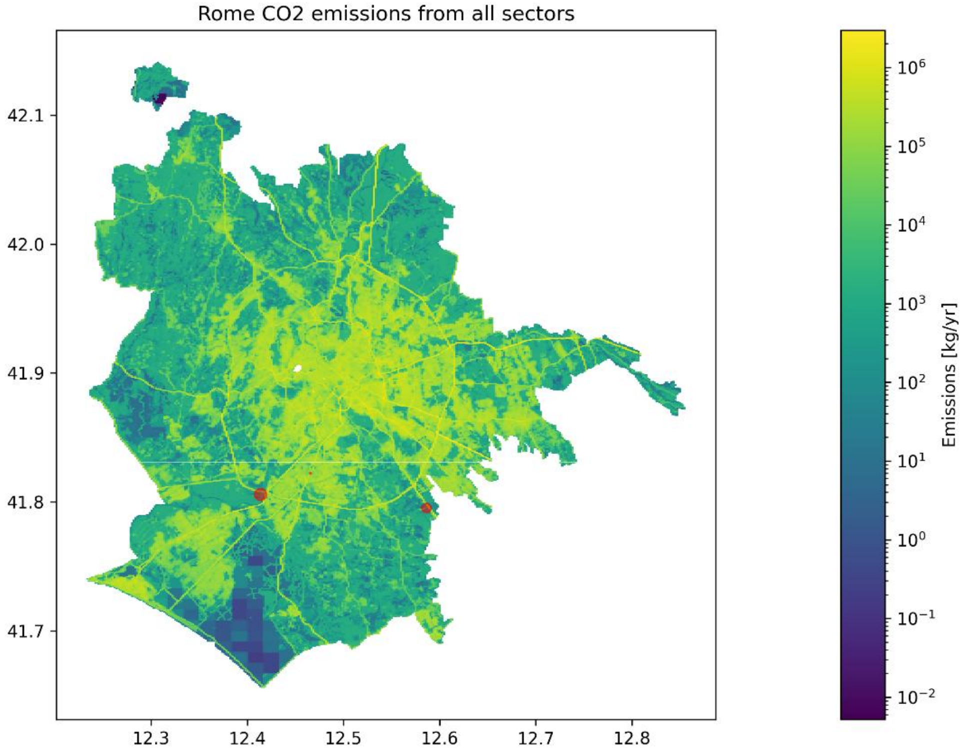

Figure 32. Emission map of CO_2 for Rome.

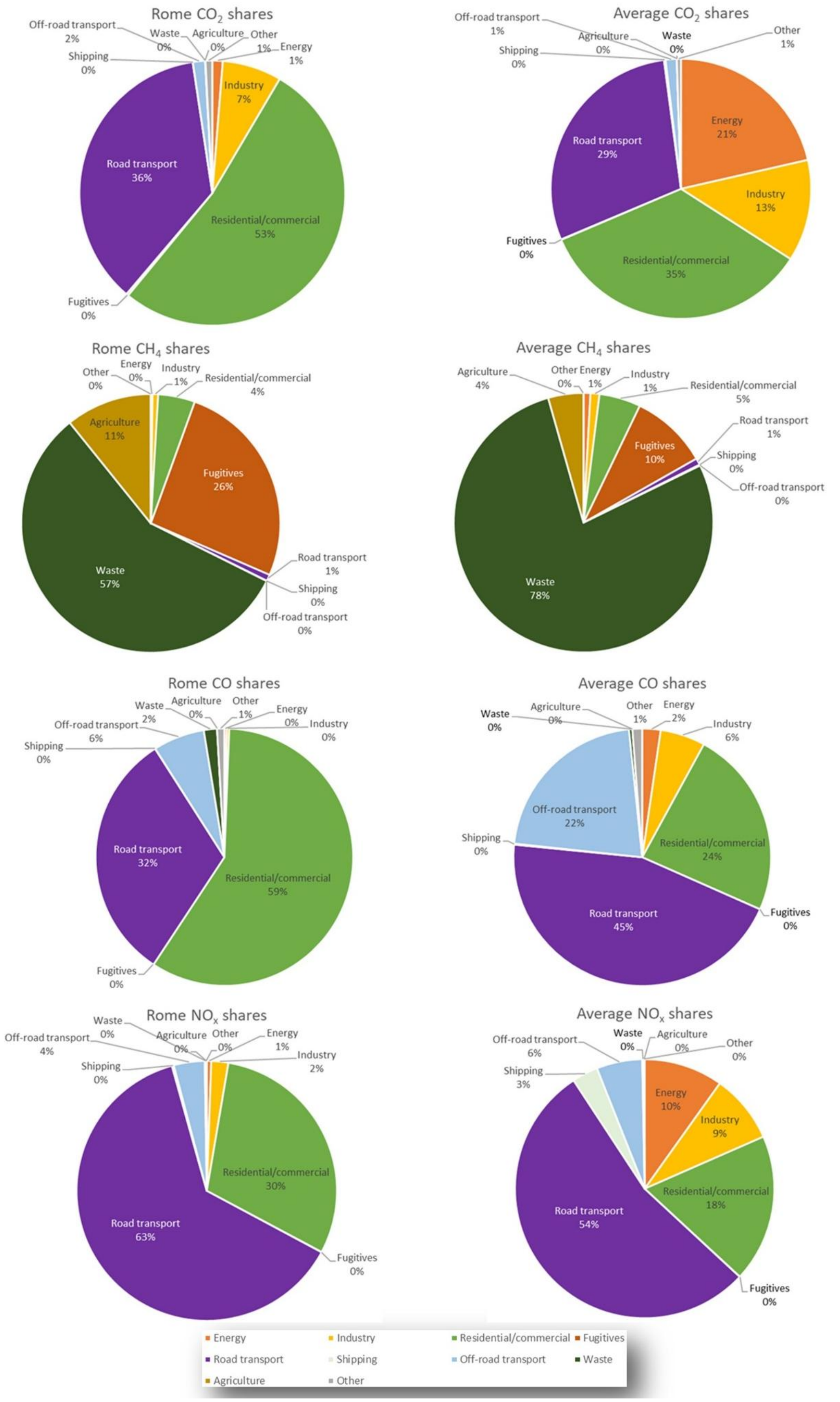

Figure 33. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Rome (left) and the average of all selected cities (right).

A.14 Rotterdam city

Rotterdam is a city characterized by shipping activities, causing large contributions of this sector to emissions of CO_2, CO and NO_x, even without including the port area. The contribution of the residential/commercial sector to CO and NO_x emissions is relatively small. The CO emissions from road transport are above-average, also considering the per capita emissions.

Table 15. Sectoral emissions in Rotterdam city.

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	19	332	10	110
Industry	260	308	192	136
Residential/commercial	447	682	401	236
Fugitives	155	0	0	0
Road transport	53	681	4450	1224
Shipping	21	319	883	4659
Off-road transport	3	55	1546	420
Waste	2094	0	25	6
Agriculture	111	0	0	0
Other	57	10	28	1
Total	3221	2388	7535	6792

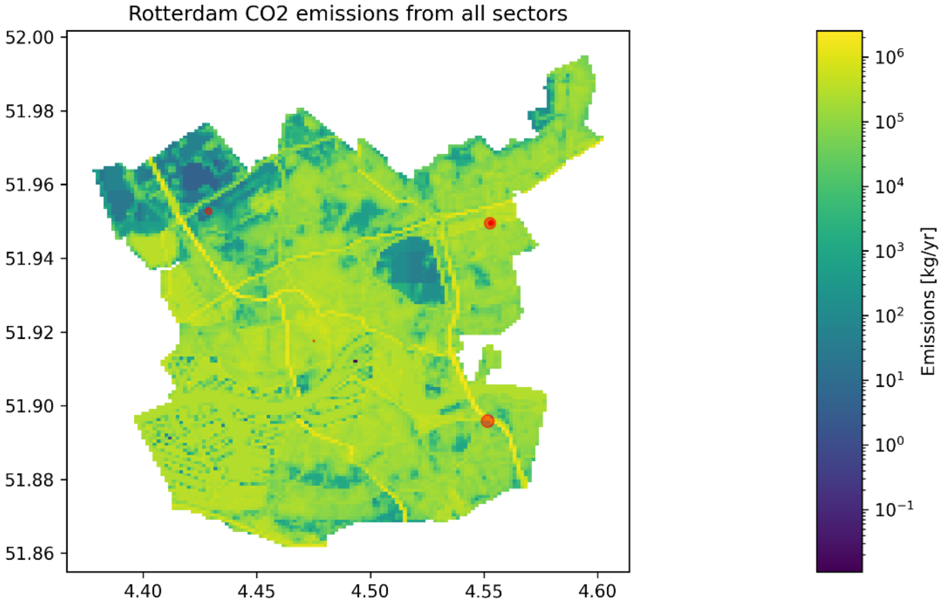

Figure 34. Emission map of CO_2 for Rotterdam city.

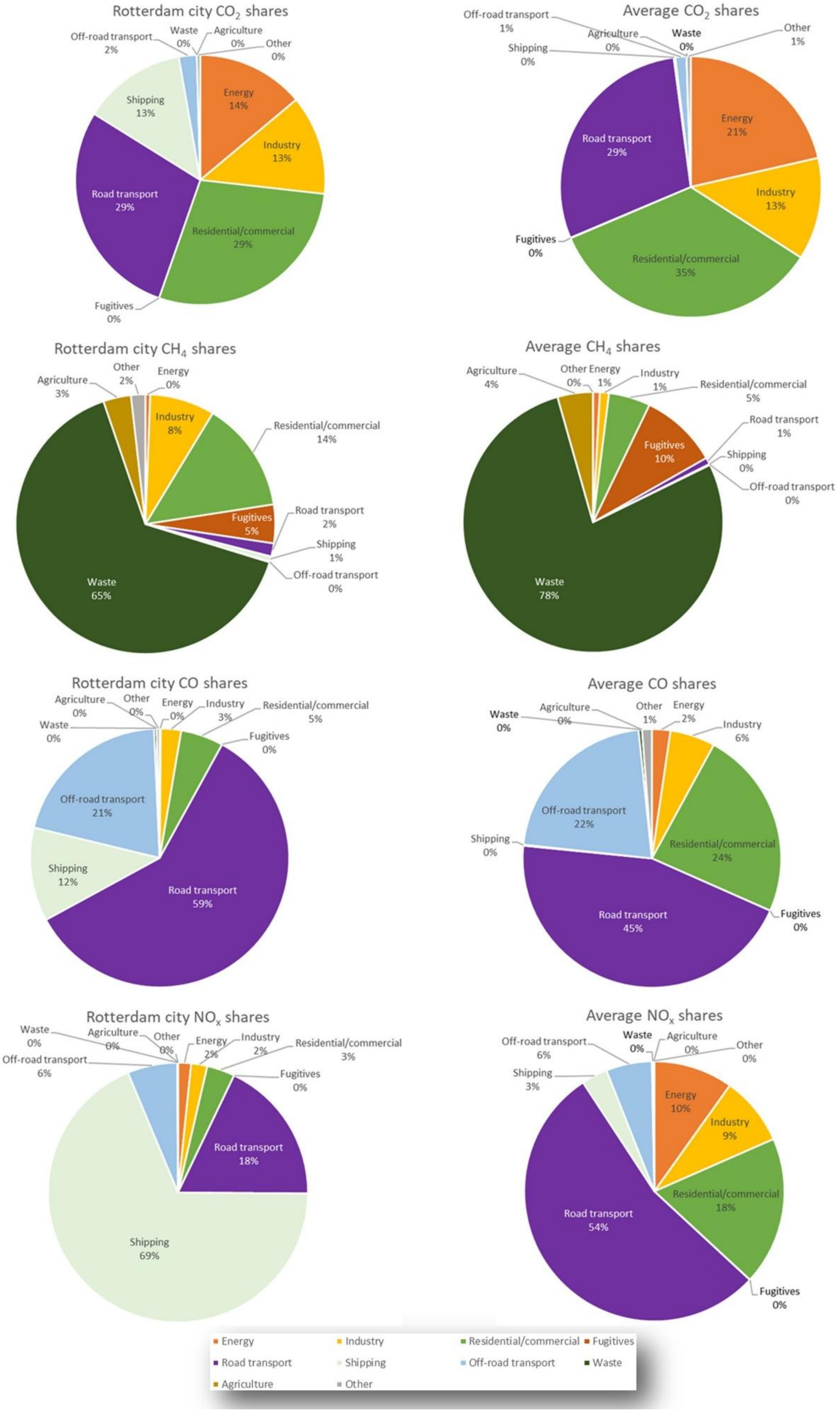

Figure 35. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Rotterdam city (left) and the average of all selected cities (right).

A.15 Rotterdam (incl. port)

If we consider Rotterdam including the port, the energy and industry sectors are dominant, and shipping plays an important role in the NO_x emissions. The share of fugitives in CH_4 emissions is also large. The emissions per capita are the largest of all selected cities, except for CO.

Table 16. Sectoral emissions in Rotterdam (incl. port).

Sector	CH4 [t/yr]	CO2 [kt/yr]	CO [t/yr]	NOX [t/yr]
Energy	622	11983	684	2968
Industry	2083	11775	8061	5931
Residential/commercial	546	771	532	267
Fugitives	5228	846	0	0
Road transport	62	815	5156	1466
Shipping	112	1192	2990	17301
Off-road transport	7	189	2894	1352
Waste	7070	0	102	8
Agriculture	251	0	0	0
Other	68	12	33	1
Total	16049	27584	20452	29296

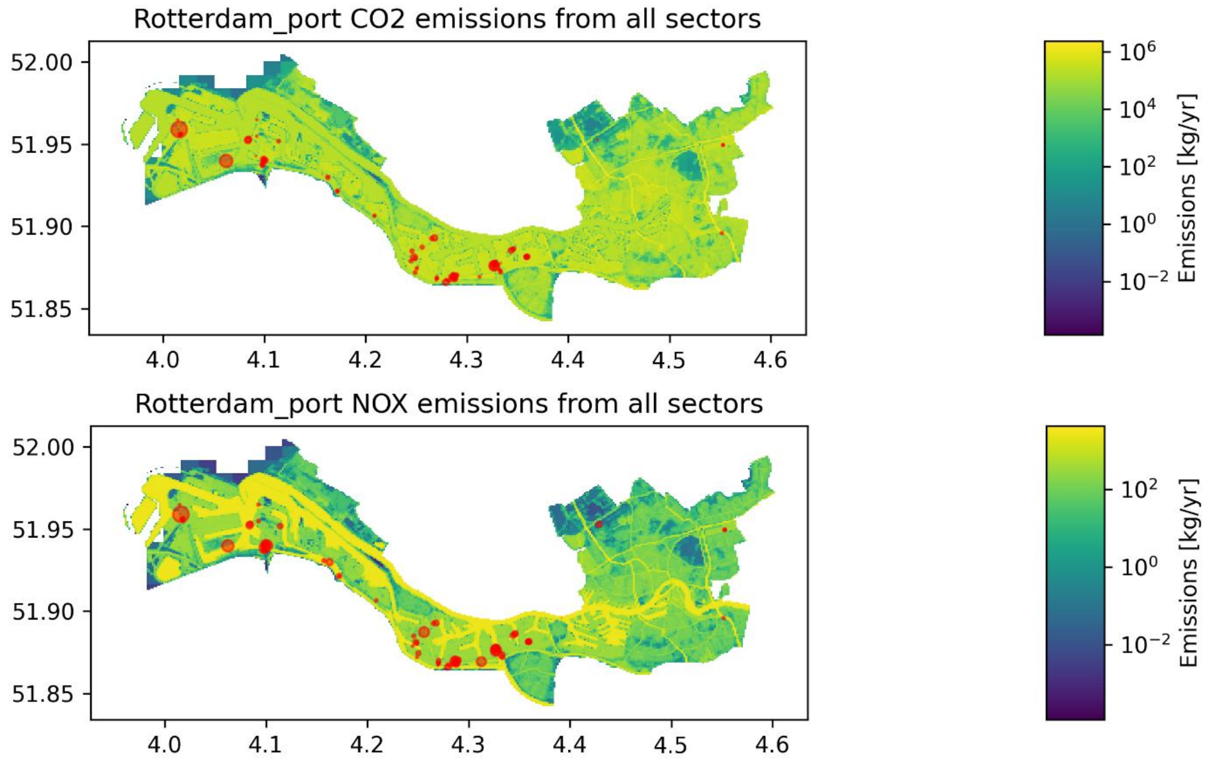

Figure 36. Emission maps of CO_2 (top) and NO_x (bottom) for Rotterdam (incl. port). The NO_x emission map clearly shows the importance of shipping emissions.

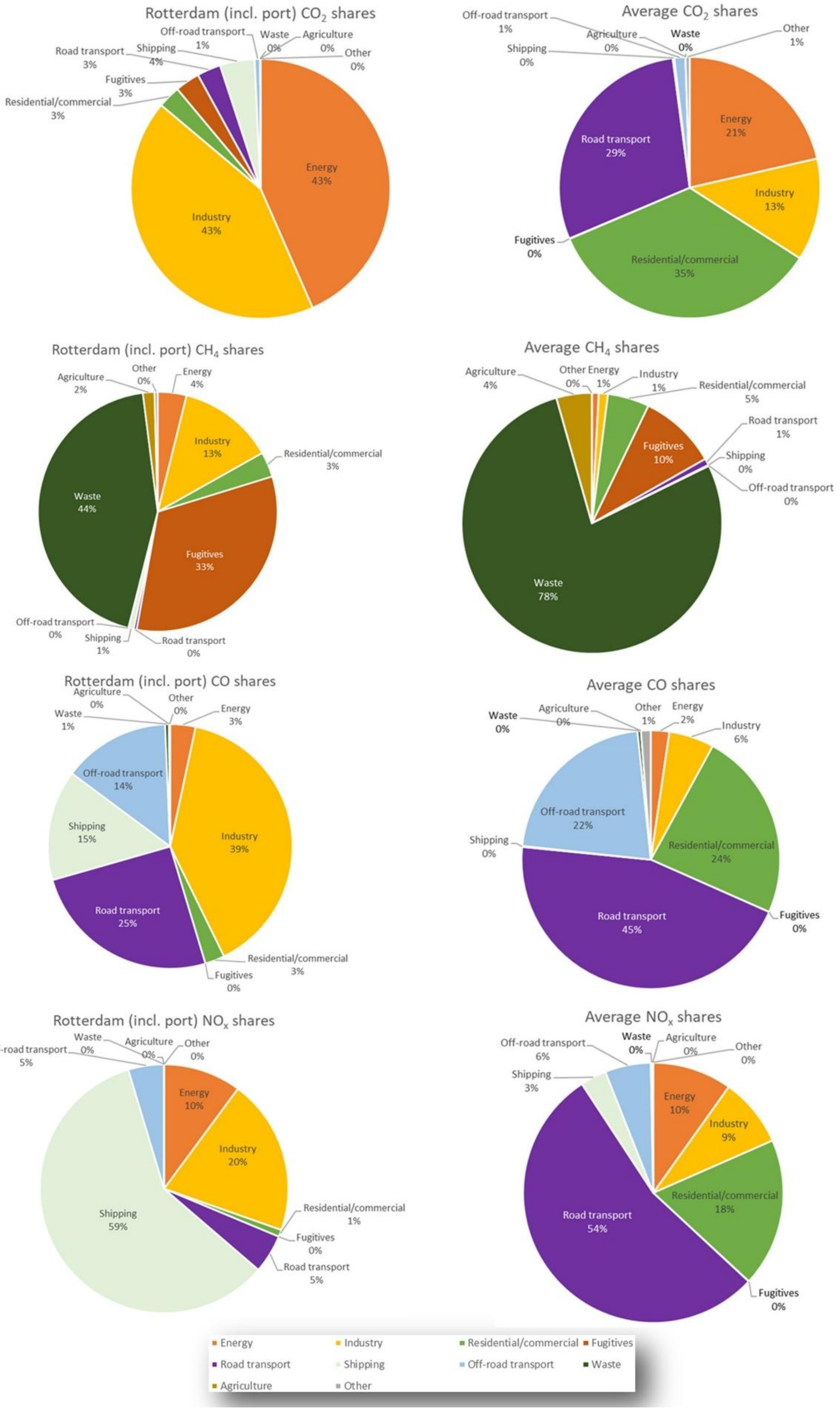

Figure 37. Pie charts showing the relative contribution of each source sector to the total emissions of CO$_2$, CH$_4$, CO and NO$_x$ for Rotterdam (incl. port) (left) and the average of all selected cities (right).

A.16 Zurich

Zurich is a small city with average emission characteristics. The CH_4 emissions show a relatively large share of fugitives and agricultural emissions.

Table 17. Sectoral emissions in Zurich.

Sector	**CH4 [t/yr]**	**CO2 [kt/yr]**	**CO [t/yr]**	**NOX [t/yr]**
Energy	0	396	23	130
Industry	10	194	137	118
Residential/commercial	81	872	706	406
Fugitives	606	0	0	0
Road transport	25	513	2199	751
Shipping	0	0	0	0
Off-road transport	2	43	881	116
Waste	1110	6	52	2
Agriculture	384	0	0	0
Other	2	7	73	8
Total	2220	2032	4072	1531

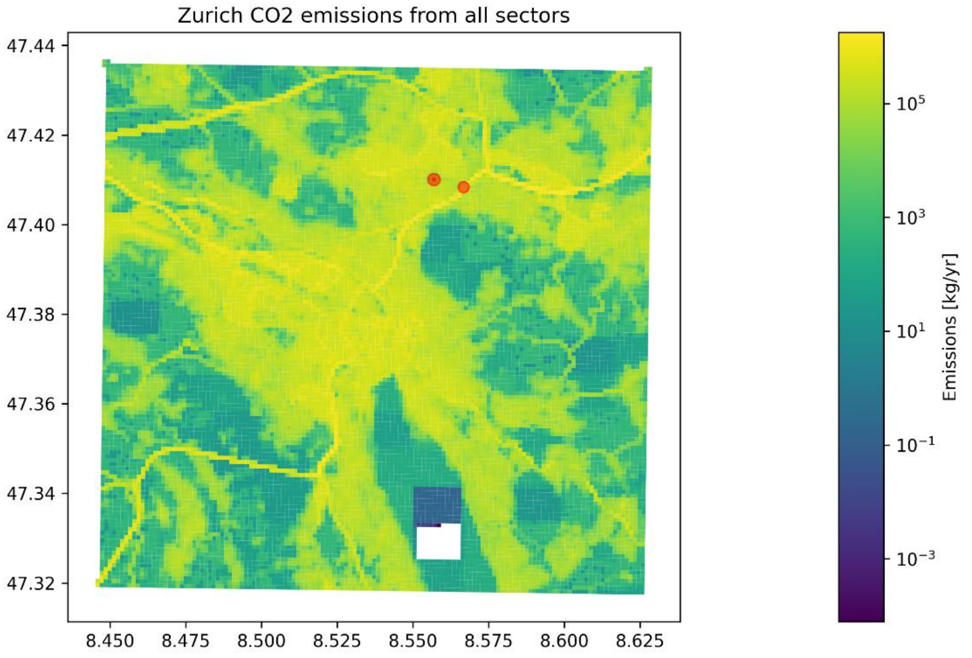

Figure 38. Emission map of CO_2 for Zurich.

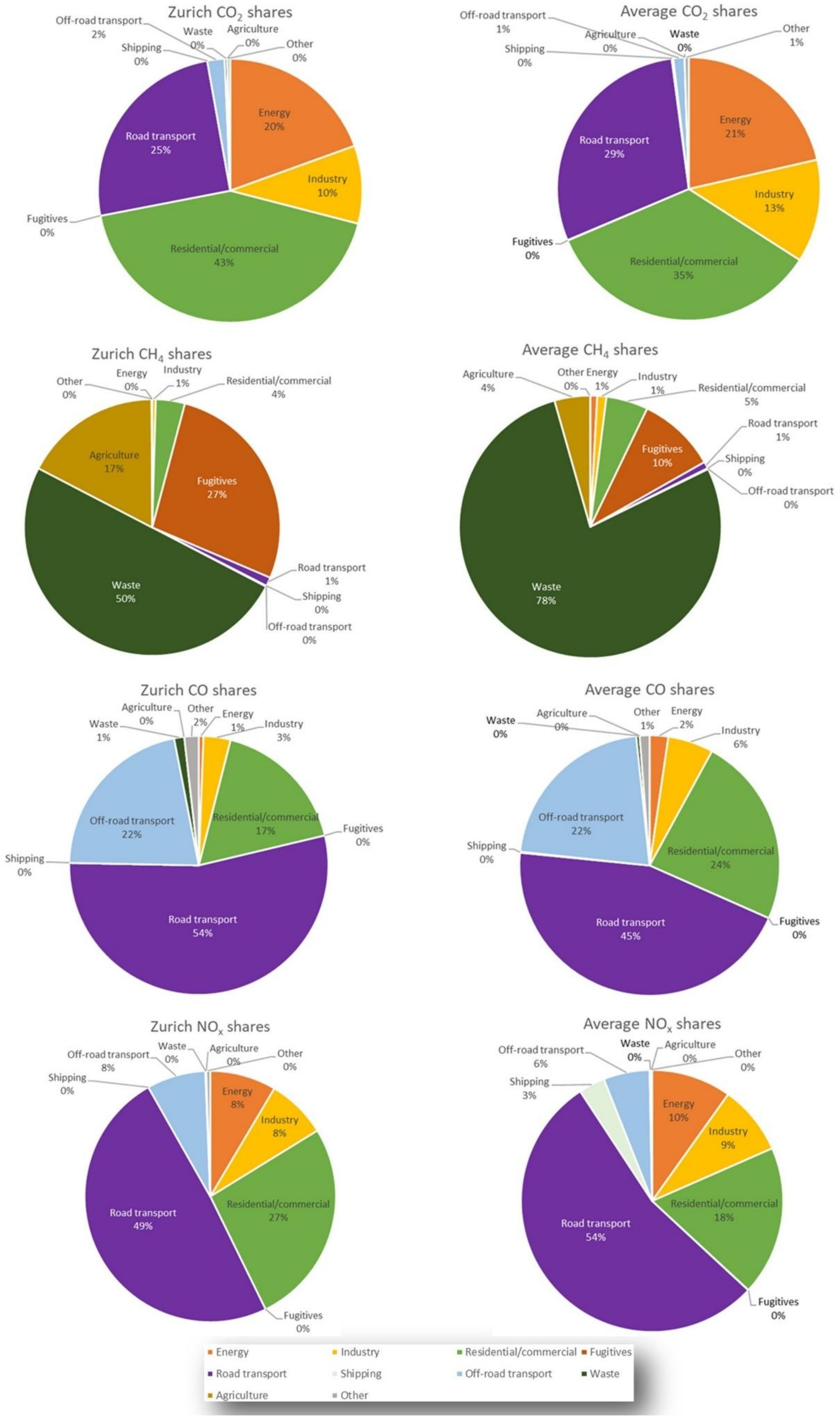

Figure 39. Pie charts showing the relative contribution of each source sector to the total emissions of CO_2, CH_4, CO and NO_x for Zurich (left) and the average of all selected cities (right).