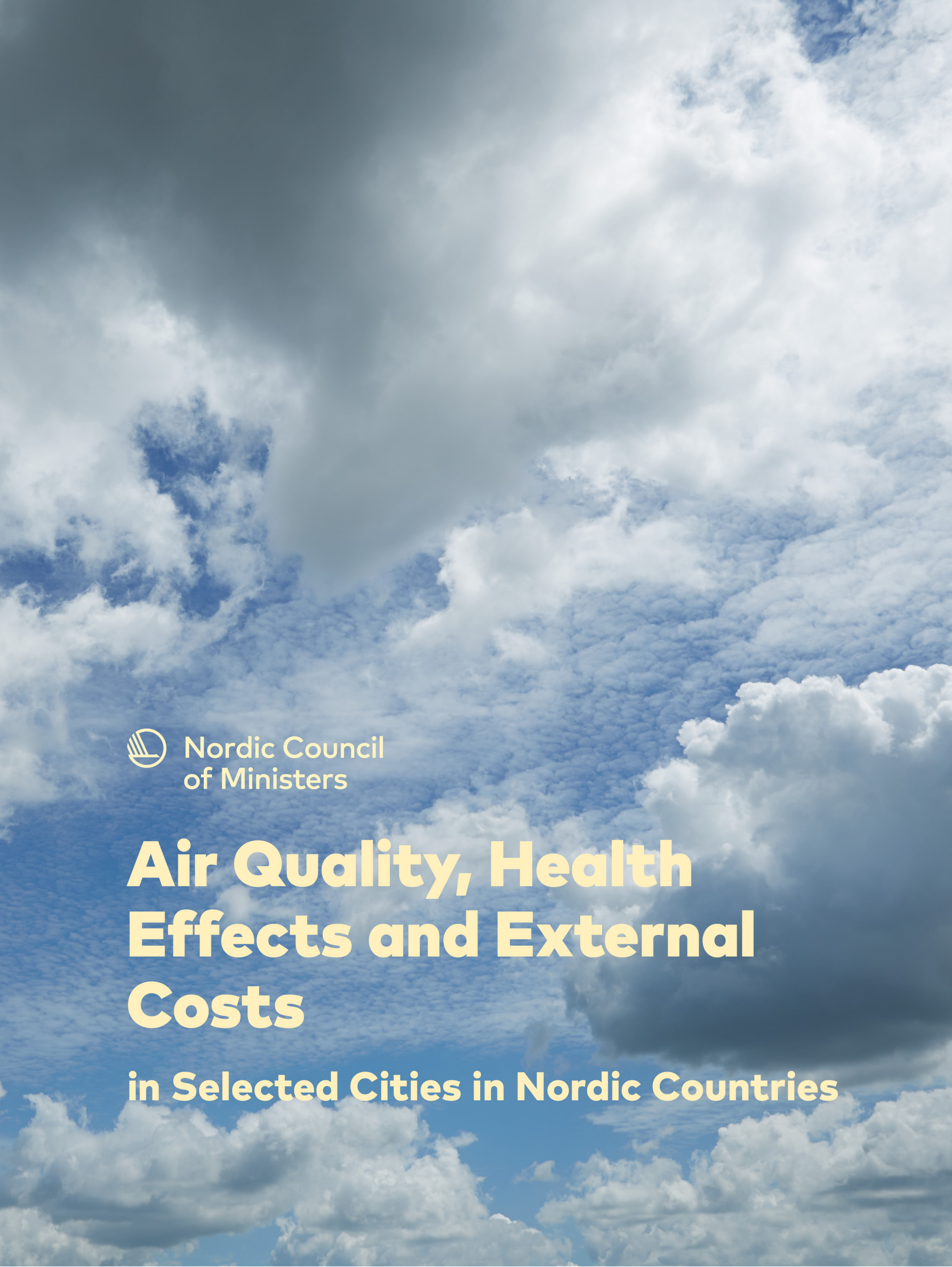


Nordic Council of Ministers

Air Quality, Health Effects and External Costs

in Selected Cities in Nordic Countries

Contents

Foreword 5

1. Summary 7

1.1 Background and purpose 7

1.2 Methodology and assumptions 7

1.3 Main conclusions and results 8

2. Overall methodology 17

2.1 Regional scale air quality modelling (DEHM) 17

2.2 Urban scale air quality modelling (UBM) 18

2.3 Modelling health effects and related external costs of air pollution (EVA-system) 19

2.4 Selection of cities and model boundaries 21

2.5 WHO AQG 2021 22

2.6 Evaluation of air quality monitoring in Nordic countries 22

3. Selected Nordic cities and model grids 24

3.1 Selected cities 24

3.2 City boundaries 27

3.3 City grids and upstream grids 28

4. Evaluation of air quality monitoring 31

4.1 WHO AQ guidelines and the EU Air Quality Directive 31

4.2 Present air quality in Nordic countries and WHO guidelines 34

4.3 NO_2 and $PM_{2.5}$ in the selected Nordic cities in 2021 44

4.4 General implications of proposed AQ Directive 48

5. Regional Air Quality in 2019 and 2030 54

5.1 DEHM model domain setups 54

5.2 High-resolution emissions in 2019 and 2030 58

5.3 Regional concentrations compared with WHO AQG 64

6. Urban background concentrations in selected cities in 2019 and 2030 73

6.1 Evaluation of model results against measurements in 2019 73

6.2 Modelled average concentrations over selected cities in 2019 and 2030 77

6.3 Concentration maps for selected cities in 2019 and 2030 78

7. Emission sector contributions to air quality in 2030 95

7.1 København 95

7.2 Stockholm 98

7.3 Helsinki 101

7.4 Reykjavík 104

7.5 Summary of contributions to air quality in 2030 107

8. Emission sector contributions to health effects and external costs in 2030 110

8.1 Assumptions 110

8.2 Health effects and sector contributions in København 118

8.3 External costs and sector contributions in København 127

8.4 Health effects and sector contributions in Stockholm 129

8.5 External costs and sector contributions in Stockholm 138

8.6 Health effects and sector contributions in Helsinki 140

8.7 External costs and sector contributions in Helsinki 149

8.9 Health effects and sector contributions in Reykjavík 151

8.10 External costs and sector contributions in Reykjavík 160

8.11 Health effects in Oslo 162

8.12 External costs in Oslo 164

8.13 Summary of health effects and costs for capital cities 164

References 166

Appendix 1 City boundaries of selected cities 171

Appendix 2 Sector emissions in Nordic countries 175

Appendix 3 Description of measurement stations in selected cities 178

About this publication 185

This publication is also available online in a web-accessible version at:
https://pub.norden.org/temanord2023-548

Foreword

The Nordic Working Group for Climate and Air (NKL) under Nordic Council of Ministers has initiated this project with a specific tender, and Aarhus University, Department of Environmental Science (ENVS) has conducted the research project.

The purpose of the project is to gain a better understanding of the implications of the new WHO guidelines in a Nordic setting. The project also looked at how far Nordic countries currently are from complying with the new 2021-guidelines and provide a foundation for the assessment of measures in the Nordic countries to achieve the new recommended WHO levels. This understanding will also serve to provide a Nordic perspective on the proposed new EU Air Quality Directive from October 2022 - both regarding realistic future limit values and to the regulatory approach.

The project focuses on three main tasks:

- Evaluation of air quality monitoring in Nordic countries.
- Projection of air quality for 2030 for Nordic countries and selected cities based on air quality modelling.
- Sector specific contribution to air quality 2030 for Nordic countries and selected cities based on air quality modelling and modelling of health effects and related external costs.

Chapter 1 is the summary.

Chapter 2 outlines the overall methodology, models and assumptions applied, and criteria for evaluation of air quality monitoring.

In **chapter 3**, the selection of three cities in each of the Nordic countries is described with the aim to cover the largest cities, but also to have a good geographical coverage for each country.

In **chapter 4**, a comparison between measurement data and the former and new WHO air quality guidelines is carried out for rural, urban background and street stations in the selected cities in 2021. Further, the proposed new European air quality directive is described and the overall implications for the Nordic countries are outlined. National experts within air quality monitoring have been sub-contracted from Swedish Environmental Protection Agency, Sweden (Matthew Ross-Jones), NILU, Norway (Claudia Haka), FMI, Finland (Katriina Kyllönen), Environmental Agency of Iceland, Iceland (Þorsteinn Jóhannsson) for the evaluation of air quality monitoring.

Chapter 5 describes the application of the regional scale air quality model used to predict the background air quality in 2019 and 2030. Results are compared with the new WHO guidelines.

In **chapter 6**, the application of the local scale air quality model is used to predict urban background air quality in the selected cities in 2019 and 2030. Results are compared with the new WHO guidelines.

Chapter 7 describes the estimation of the emission sector specific contribution to the air quality in 2030 as shares of transboundary-, country-, and city pollution for the selected cities. This is based on regional and local scale modelling.

In **chapter 8**, the sector contribution of health effects and external costs in 2019 and 2030 is described with focus on the five capital cities in the Nordic countries.

1. Summary

1.1 Background and purpose

The Nordic Working Group for Climate and Air (NKL) under the Nordic Council of Ministers has initiated this project with a specific tender, and Aarhus University, Department of Environmental Science (ENVS) has conducted the research project.

The purpose of the project is to gain a better understanding of the implications of the new WHO guidelines in a Nordic setting. The project also looked at how far Nordic countries currently are from complying with the new 2021-guidelines, and provide a foundation for assessment of measures in the Nordic countries to achieve the new recommended WHO levels. This understanding will also serve to provide a Nordic perspective on the new proposed EU Air Quality Directive from 2022 - both regarding realistic future limit values and to the regulatory approach. The project focuses on three main tasks (1) Projection of air quality for 2030 for Nordic countries and selected cities, (2) Sector specific contribution to air quality in 2030 and health effects and related external costs, and (3) Evaluation of air quality monitoring in Nordic countries based on measurements from 2021 with comparison to WHO guidelines and EU limit values for the Nordic countries as well as for the selected cities, and general implications of the new proposed EU Air Quality Directive for the Nordic countries.

1.2 Methodology and assumptions

The evaluation of predicted air quality in 2030 in relation to the new WHO guidelines from 2021 is focused on a selection of cities in the Nordic countries. Based on the number of inhabitants in the largest cities in the Nordic countries three cities in each country were selected to cover the largest cities, but also to have a good geographical coverage. However, for Iceland only one city is selected but including the greater metropolitan area of Reykjavík. The cities are:

- Sweden: Stockholm, Göteborg and Malmö;
- Denmark: København, Aarhus and Odense;
- Finland: Helsinki, Tampere and Oulu;
- Norway: Oslo, Bergen and Trondheim;
- Iceland: Greater Reykjavík (here after just Reykjavík).

To be able to model air quality in 2030 for the Nordic countries as well as the contribution of emission sectors to air quality, Aarhus University has setup and applied the regional scale air quality model (DEHM) and the local scale urban air quality model (UBM) for the selected cities in the Nordic countries. Further, to address health impacts and related external costs we set up and applied the integrated modelling system – EVA (Economic Valuation of Air Pollution). Aarhus University has developed all these models.

Emissions for Europe and the rest of the Northern Hemisphere are based on emission data from the EMEP database with 0.1 x 0.1 degrees resolution and the ECLIPSE v6b database with 0.5 x 0.5 degrees resolution. Furthermore, global ships emissions are based on the STEAM model with 0.1x0.1 degrees spatial resolution and monthly time resolution.

Projected emissions for 2030 are drawn from existing international emission databases. For EU countries, emissions reflect national projections if targets are met in the NEC directive (National Emission Ceilings), otherwise they reflect reduction targets set out in the NEC directive for 2030 for the country. For non-EU-countries, the national projections are used.

Emissions for the Nordic countries are based on the emission dataset from the research project NordicWelfAir (funded by NordForsk) that for the first time established a high-resolution geographically distributed emission inventory of 1 km x 1 km for the Nordic countries for selected years from 1990 to 2014. The emission inventory for 2014 has been scaled to 2019 and 2030 based on the total of the country specific emission sectors and assuming a geographic distribution as in 2014.

The year 2019 serves as a reference year where model results are compared with measurements from monitoring stations in the selected cities to evaluate the performance of the air quality models.

Meteorological data are obtained from the Weather Research and Forecasting model (WRF), operated at Aarhus University.

1.3 Main conclusions and results

1.3.1 Evaluation of air quality monitoring in 2021

WHO AQ guidelines and the EU AQ Directive

WHO has tightened their air quality guidelines from 2005 to 2021 for the three pollutants that pose the largest health burden ($PM_{2.5}$, NO_2 and O_3). The WHO Air Quality Guidelines (AQG) are much lower than in the present EU Air Quality Directive, and also lower than the proposed revised EU Air Quality Directive from October 2022. However, the proposed EU Air Quality Directive will eventually align with WHO guidelines for annual $PM_{2.5}$ (5 µg/m^3) and annual NO_2 (10 µg/m^3) for the *average exposure concentration* measured at urban background stations. This is to be achieved with continuous requirement for reduction in concentrations until the target is met. In 2030, a 25% reduction has to be met over a ten-year period, and the same the following years until the target is met.

Present air quality in Nordic countries and WHO guidelines

A comparison between measurement data from 2021 (extracted from the EEA database European Air Quality Portal) and the former and new WHO AQG, has been carried out for each of the Nordic countries where the *maximum* value at any measurement station within the country is compared with the WHO guidelines. This provides an overview of exceedances of the new WHO guidelines in the Nordic countries. Furthermore, it also describes how the exceedances have changed between the former and new WHO guidelines.

The health impacts of air pollution are by far the largest for long-term exposure to $PM_{2.5}$ then followed by NO_2, both as annual means, and then exposure to elevated levels of ozone. All five Nordic countries exceed the 2021 WHO AQG for annual means of $PM_{2.5}$ and NO_2, and also ozone (8h peak season) based on the highest measured values in 2021 (except Iceland for peak ozone as data is not available). More exceedances were observed in 2021 compared with 2005 as the WHO guidelines were tightened from 2005 to 2021.

Present air quality in selected cities

An analysis was carried out based on available measurements of NO_2 and $PM_{2.5}$ in 2021 from rural, urban background and street stations in the selected cities and the new WHO guidelines and the proposed EU Air Quality Directive. This analysis gives an indication of the concentration contribution of the cities (difference between urban background and rural concentrations) and further the contributions of hotspots (difference between street concentrations and urban background concentrations). For each of the selected cities the one station with the *highest* concentration measured, is representing that particular city.

In general, the measurements of NO_2 and $PM_{2.5}$ in 2021 are following the expected concentration pattern with the highest values represented by the traffic stations and the lowest seen at rural background stations with suburban/urban background in-between.

In all the selected cities in the five Nordic countries, annual NO_2 and $PM_{2.5}$ in 2021 are well below the annual limit values (40 µg/m^3 and 25 µg/m^3, respectively) of the current EU Air Quality Directive. In relation to the newly proposed EU Air Quality Directive limits of 20 µg/m^3 and 10 µg/m^3 for NO_2 and $PM_{2.5}$, respectively, 9 out of 13 traffic stations are exceeding the proposed annual limit value for NO_2 and only one for PM

$_{2.5}$. None of the urban or rural background stations are exceeding the annual limit values of NO_2 and $PM_{2.5}$ of the newly proposed directive.

When it comes to the new 2021 WHO guidelines for annual NO_2 (10 µg/m^3), all the traffic stations show higher concentrations than the guideline levels. The same applies to annual $PM_{2.5}$ (5 µg/m^3). For the urban background stations, 6 out of 12 are exceeding the NO_2 guideline levels. For $PM_{2.5}$, 8 out of the 10 are exceeding the guideline levels. For NO_2 measured in the rural background, all the stations with measurements are well below the guideline levels. For $PM_{2.5}$, however, for the rural background stations 3 out of 9 with measurements are exceeding the guideline levels.

General implications of proposed AQ Directive

The overall implications for the Nordic countries of the proposed new EU Air Quality Directive have been analysed.

Measurements

In relation to the present EU Air Quality Directive and the general improvements in the air quality in the Nordic countries over the past 10 years, a comprehensive reorganization would be expected to take place of the air monitoring programmes with cheaper methods and fewer measuring points. However, the new proposal for the EU Air Quality Directive radically changes this possibility, since the tightening of the limit values is accompanied by more stringent assessment thresholds used to determine the number of measuring points and the requirements for the measurement methods.

It is further a requirement to measure ultrafine particles (UFP) and the size distribution of UFP.

There are also increased requirements for documentation of spatial representativeness of measurements and design of the measurement program.

Establishment of supersites

The new proposal for the EU Air Quality Directive requires the establishment of supersites with the aim to increase knowledge about particle pollution at EU level. Supersites require the measurement of a large number of new particle components, of which a requirement to measure the oxidative potential of PM is something completely new in the context of air quality monitoring.

New requirements for average exposure concentrations

The proposed new EU Air Quality Directive introduces a strengthening of the requirements for reducing the average exposure concentration for $PM_{2.5}$ based on measured urban background concentrations and introduces similar requirements for NO_2 that gradually will align with the WHO AQG.

Requirement for air quality modelling

The new proposal for the EU Air Quality Directive includes model calculations as an obligatory element where concentrations of pollutants exceed limit values, or target values. Furthermore, short-term air quality forecasts shall be carried out. Additionally, designated reference model institutions have to be appointed and participate in periodical model reviews and international model intercomparison exercises.

Public information on actual air quality and an Air Quality Index

The proposal for a new air quality directive imposes significantly stricter requirements on information on current air quality including obligatory hourly updates. It is also a requirement to establish an air quality index, and provide short-term air quality forecasts based on modelling.

1.3.2 Regional concentrations compared with the WHO AQG

Nordic emissions in 2019 and 2030

SNAP7 (road transport) contributes the most to NO_x emissions in 2019 but decreases towards 2030 where other sectors also contribute significantly. SNAP2 (residential combustion=wood stoves) is an important contributor to $PM_{2.5}$ emissions, except for Iceland. The combined sectors of SNAP1 (energy), 3 (industrial combustion) and 4 (industrial processes) are the emission sectors that contribute the most to SO_x, except for Iceland where it is the combined sector of SNAP5 (extraction etc.), 6 (solvents) and 9 (waste) where SOx from geothermal energy and power production contributes by far the most allocated to SNAP5. The majority of SO_x in Iceland is hydrogen sulfide (H_2S).

There is a downward trend for emissions for all countries and pollutants from 2019 to 2030.

Regional concentrations in 2019 and 2030

The DEHM model was used to model regional background concentrations in 2019 and 2030 in the model domain of the Nordic countries in order to compare with the WHO AQG from 2021.

For annual NO_2, there is a gradient from south to north with higher concentrations in Denmark and Southern Sweden. It is clear that the concentrations in most areas of the domain are lower than the WHO guideline (10 µg/m^3), except for a few big cities. Ship emissions are also shown to cause elevated concentrations along ship lines, and at big harbors. There is a general decrease in NO_2 concentrations from 2019 to 2030. Five of the selected cities are exceeding the WHO guideline in 2019: København, Trondheim, Stockholm, Oslo and Reykjavík, and only Reykjavík in 2030.

For annual $PM_{2.5}$, the concentration gradient also shows a decrease from south to north in the domain. There is also a decrease in concentrations from 2019 to 2030. There are significant exceedances of the WHO guidelines (5 µg/m^3) in 2019 for Denmark and Southern Sweden, however, these exceedances are much smaller in 2030. Four of the selected cities exceeding the WHO guideline in 2019 were located in Denmark (København, Aarhus, Odense) and Southern Sweden (Malmö) which is reduced to three in 2030 in the same countries, as concentrations in Aarhus no longer exceed the guideline in 2030. In line with other regional scale models, the DEHM model tends to underestimate the mass concentration of $PM_{2.5}$ due to the so-called "mass-closure problem". Probably part of the "missing mass" in the model is water in the particles, which is measured, but not modelled. Also processes and sources that are not fully described in the regional model such as re-suspended dust and mineral dust (to a lesser extent) could be contributing to the measurements, but not included completely in the model.

For peak ozone, the WHO guideline (60 µg/m^3) is exceeded in most part of the domain both in 2019 and 2030. Peak ozone concentrations show a very slight decrease towards 2030, especially for Iceland and Finland. Concentrations of ozone are not higher in big cities, but actually lower compared with rural areas, due to the titration effects of NO_x where NO_x emissions from e.g. traffic convert ozone to NO_2. All selected cities are exceeding the WHO guideline in both 2019 and 2030.

A similar analysis as above has been carried out for the pollutants PM_{10}, CO and SO_2. All selected cities are below the WHO guideline in 2019 and 2030 for annual PM_{10} (15 µg/m^3) and peak PM_{10} (45 µg/m^3 as annual 99th percentile of 24h-mean). All selected cities are below the WHO guideline for CO in 2019 and 2030 (4 mg/m^3 as annual 99th percentile of 24h-mean). All selected cities are below the WHO guideline for peak concentration of SO_2 in both 2019 and 2030 (40 µg/m^3 as annual 99th percentile of 24h-mean).

As there is uncertainty on model results, there is also uncertainty associated with the above assessment when modelled concentrations are compared with a threshold and stated to be either above or below, especially when predicted concentrations are close to the thresholds.

1.3.3 Urban background concentrations in selected cities

Observed versus model concentrations in 2019

Observed concentrations at urban background stations were compared with modelled urban background concentrations based on DEHM/UBM for 2019.

As expected the model results for the urban background concentrations of $PM_{2.5}$ and NO_2 with UBM are generally higher than the DEHM results due to the higher resolution of UBM of 1 km x 1 km compared with the resolution of DEHM of 5.6 km x 5.6 km. Consequently the model results for O_3 are lower with UBM than with DEHM due to previously described reactions with NOx.

The comparison between observations of NO_2 at urban background measuring stations and UBM model results in 2019 shows that the model predicts a higher range in concentration levels than shown in the observations and the model tends to overestimate the concentration. The comparison for O_3 shows that the model tends to underestimate, which is expected if NO_2 is overestimated. The comparison is best for $PM_{2.5}$ where the UBM modelled concentration levels are in agreement with the observed levels. Taking the mass-closure problem mentioned above into account, this means that the model most like overestimates the $PM_{2.5}$ concentrations.

The UBM model results show descreasing urban background concentrations from 2019 to 2030, which can be explained by the decreasing urban emissions. Part of the decrease in urban background concentrations is also due to decreasing regional concentrations modelled with DEHM serving as input to UBM from the regional background, due to decreasing emissions from the country in which the city is located as well and from abroad.

Geographic distribution of modelled concentrations over selected cities in 2019 and 2030

The geographic distribution of concentrations in the cities are depending on population density and associated emission density, large road transport corridors as well as ship traffic. Concentrations of NO_2 and $PM_{2.5}$ are decreasing from 2019 to 2030 whereas concentrations of O_3 are slightly increasing.

Estimates of urban background concentrations in 2030 versus WHO AQG

Emission projections and model results are subject to uncertainties, and since the UBM model also generally overestimates NO_2 concentrations, caution should be taken when comparing modelled concentrations with WHO AQG. Therefore, an estimate of compliance with the WHO AQG in 2030 is based on current observation levels and modelled changes from 2019 to 2030 with focus on the capital cities.

Based on this analysis for NO_2 it is likely that the urban background stations in København, Stockholm, Helsinki and Reykjavík will be under the WHO AQG of 10 $\mu g/m^3$ in 2030. For $PM_{2.5}$ København may be slightly over the WHO AQG of 5 $\mu g/m^3$ in 2030 whereas other cities are likely to be below the guideline.

Concentrations in all selected cities are exceeding the WHO guideline in both 2019 (observations, except Reykjavík with no data) and 2030 (model results) for peak ozone. Modelled peak ozone concentrations show a very slight decrease towards 2030.

1.3.4 Sector contributions to air quality in capitals in 2030

Information for each of the Nordic capital cities on the contribution to air quality from different emission sectors given as the contribution from the city, from the country of the city (disregarding emissions from the city) and sources from abroad is provided based on model results. The analysis focuses on 2030 to illustrate the potential benefits of regulation of the different emission sectors in the future. Furthermore, the focus is on $PM_{2.5}$ and NO_2 as they are the largest contributors to health effects.

The contribution to air quality of $PM_{2.5}$ in 2030 for the Nordic capital cities ranges from 10% to 26% from city emissions, 16% to 23% from country emissions and 51% to 76% from emissions originating abroad. The similar numbers for NO_2 are 18% to 35%, 18% to 42% and 23% to 55%, respectively.

København stands out with the highest contribution from abroad and relative low contributions from city and country emissions to air quality of $PM_{2.5}$ in this case due to its location close to Central Europe.

In the comparison, Reykjavík has a relatively large $PM_{2.5}$ contribution from abroad despite its location in the North Atlantic Ocean. However, the absolute $PM_{2.5}$ concentrations are the lowest compared with the other cities. Possible explanations could be the influence of ship emissions, long-range transport and sea salt. Moreover, Reykjavík and Iceland have a relatively small population further adding to the relative importance of emissions from abroad.

The three largest sectors contributing to urban background concentrations of $PM_{2.5}$ in 2030 from city emissions are road transport (SNAP7), residential wood combustion (SNAP2) and the combined sector of energy, industrial combustion and industrial processes (SNAP134), except for Reykjavík where the contribution from residential wood combustion is insignificant and off-road (SNAP8) plays a larger role due to the fishing fleet. For NO_2 the three largest sectors are road transport (SNAP7), the combined sector of energy, industrial combustion and industrial processes (SNAP134) and off-road (SNAP8) but all other sectors with combustion emissions also contribute.

The largest sectors contributing to urban background concentrations of $PM_{2.5}$ in 2030 from country emissions are residential wood combustion (SNAP2), road transport (SNAP7), the combined sector of energy, industrial combustion and industrial processes (SNAP134) and off-road (SNAP8) but also agriculture

(SNAP10). For NO_2 the largest sectors are off-road (SNAP8), road transport (SNAP7), and the combined sector of energy, industrial combustion and industrial processes (SNAP134).

The contribution from abroad has not been broken down in emission sectors as it is computationally very demanding and time consuming to analyse results.

1.3.5 Sector contributions to health effects and external costs in capitals in 2030

A summary of the number of predicted premature deaths in the Nordic capital cities due to air pollution is given in Table 1.1.

Key factors in determination of premature mortality are air quality levels of $PM_{2.5}$, NO_2 and O_3 and the number of inhabitants exposed, which is also evident from Table 1.1. It is also seen that although populations are expected to grow from 2019 to 2030, premature deaths are predicted to decrease as air quality improves except for Iceland where number of premature deaths is the same in 2019 and 2030 as a combined effect of a relatively high population growth and decreasing pollution levels. Data for 2030 for Oslo are missing due to erroneous geographic distribution of the emissions from oil and gas production for 2030 allocated to land areas.

Table 1.1. Number of premature deaths in capital cities in 2019 and 2030.

	Area (km^2)	Inhabitants in 2019	Inhabitants in 2030	2019	2030	Difference
København	95	594,679	610,810	410	310	-22%
Stockholm	207	1,064,033	1,154,401	620	510	-19%
Helsinki	195	687,693	687,865	390	330	-15%
Reykavik	173	226,661	264,756	39	39	1%
Oslo	262	664,000	697,526	450	n.a.	n.a.

The distribution of premature deaths caused by emissions from the city, from the country and from abroad for the Nordic capital cities is shown in Table 1.2.

The contribution from the city emissions range from 15% to 43%, from emissions in the rest of the country from 18%-27% and from emissions from abroad from 30% to 60%. Reykjavík has the highest contribution from the city and lowest from abroad. The opposite picture is seen for København with the lowest contribution from the city and highest from abroad.

Table 1.2. Percentage of premature deaths in Nordic capital cities in 2030 distributed on emission contributions from city to city, from country and from abroad

	From city	From country	From abroad	Total
København	15%	23%	63%	100%
Stockholm	35%	18%	47%	100%
Helsinki	25%	21%	53%	100%
Reykavík	43%	27%	30%	100%
Oslo	n.a.	n.a.	n.a.	n.a.

Table 1.3. Total external costs for air pollution in capitals in 2019 and 2030 (Billion EUR).

	2019	2030	Difference
København	1.1	0.9	-21%
Stockholm	1.6	1.3	-20%
Helsinki	1.2	0.9	-16%
Reykavík	0.14	0.14	-2%
Oslo	1.2	n.a.	n.a.

The external costs follow the premature mortality as the costs of morbidity plays a minor role, and hence the distribution on emission sectors and on the contribution from city, country and abroad also follows the number of premature deaths presented earlier.

2. Overall methodology

In this chapter, the overall methodology for addressing the three main tasks of the project is presented: (1) Projection of air quality for 2030 for the Nordic countries and selected cities, (2) Sector specific contribution to air quality in 2030 and health effects and related external costs, and (3) Evaluation of air quality monitoring in Nordic countries.

To address the analyses in (1) and (2), the regional scale air quality model (DEHM) and the urban scale air quality model (UBM) have been set up and applied, and to address health impacts and related external costs the integrated modelling system - EVA (Economic Valuation of Air Pollution) was used. A brief description of these model tools is provided below, followed by a description of the selection of cities and model boundaries. Aarhus University has developed all the models. Finally, a description of the methodologies for addressing task (3) is outlined.

2.1 Regional scale air quality modelling (DEHM)

The Danish Eulerian Hemispheric Model (DEHM) is a state-of-the-art, three-dimensional, atmospheric chemistry transport model (CTM) developed to study long-range transport of air pollution across the Northern Hemisphere. DEHM was originally developed in the early 1990s in the modelling group of ENVS in order to study atmospheric transport of sulphur-dioxide and sulphate into the Arctic (Christensen, 1997). The model has been modified, extended and up-dated continuously since then (Frohn et al., 2001; Brandt et al., 2012). The original simple sulphur-dioxide-sulphate chemistry has been replaced by a more comprehensive chemical scheme, including 80 chemical species, 9 primary particles and 158 chemical reactions. The DEHM model has also been used for studies of additional components, including POPs, mercury, pollen, CO_2 and ultrafine particles.

The model includes descriptions of the atmospheric transport and mixing, the chemical processes as well as the removal by rain and the deposition/removal to land and water surfaces. Natural emissions of e.g. sea salt and biogenic VOCs are calculated on-line in the model, while anthropogenic emission input data are based on a number of international (e.g. EMEP) and national inventories. For Denmark the high-resolution (1 km x 1 km) emissions from the SPREAD model is applied (Plejdrup et al., 2021). The driving meteorological data are obtained from the Weather Research and Forecasting model (WRF, Skamarock et al., 2008), also run routinely at ENVS, or from the ECMWF Integrated Forecasting System (IFS, http://dx.doi.org/10.21957/zw5j5zdz5).

The model domain covers most of the Northern Hemisphere, discretized on a polar stereographic projection true at 60°N, and includes a two-way nesting procedure with several nests, allowing for higher spatial resolution over selected areas. The setup is flexible and can change from study to study.

The most commonly applied setup includes three nested domains with higher resolution over Europe, Northern Europe and Denmark. Currently the finest resolution is 5.56 km x 5.56 km for a domain covering Denmark. The vertical discretization is defined on an irregular grid with 29 layers up to ~18 km. The thickness of the lowest layer is 15–25 m and varies with meteorological conditions.

The DEHM model has been developed and applied as a part of the Danish Air Quality Monitoring Programme (NOVANA) for more than 15 years – with focus both on chemical species important for human health (ozone, NO_2, particles, etc.) and on deposition of reduced and oxidized nitrogen to marine and terrestrial eco-systems (Ellermann et al., 2022).

The model has also been applied for more than 30 years in the Arctic Monitoring and Assessment Programme (AMAP) in several assessments to study the atmospheric transport to and deposition within the Arctic of sulphur, sulphate, ozone, NOx, VOC's, lead, Hg, Black Carbon, POPs and other components and is a reference model in AMAP.

The DEHM model has through the years been included in a number of international model intercomparison exercises together with similar state-of-the-art models from both Europe and North America (latest e.g. AQMEII phase 1 and 3) and for different areas (Europe, North America and Arctic).

DEHM is one of 11 European models of the EU-funded CAMS2-40 'Regional production' (an extension of CAMS-50). CAMS2-40 is part of the Copernicus Atmosphere Monitoring Service (CAMS), providing air quality forecasts and analysis for Europe on a daily basis.

2.2 Urban scale air quality modelling (UBM)

The Urban Background Model (UBM) (Brandt et al., 2012; 2013a,b) is a high-resolution Gaussian plume-in-grid model for prediction of background concentrations with a 1 km x 1 km resolution. It is in its standard setup for Denmark, capable of calculating hourly values of 17 health related chemical components for a period covering 1979 to present. The emissions for this setup are obtained from the SPREAD model that provides spatially distributed national emissions from all sectors on a 1 km x 1 km grid for Denmark based on various geographic variables applied for the different emission sectors (Plejdrup et al., 2021).

The model is coupled to the long-range chemical transport model, DEHM, for chemical boundary conditions and to the WRF model for meteorology. UBM is developed for downscaling air pollution at high resolution using a Gaussian plume-in-grid model applying high-resolution emission data (1 km x 1 km) and includes simplified chemistry for the reactions governing O_3, NO_2 and NO. The coupled model DEHM/UBM includes the gaseous air pollution components nitrogen-oxides (NO_x, NO_2), ozone (O_3), carbon monoxide (CO), sulphur dioxide (SO_2) and ammonia (NH_3) and the particulate matter fractions PM_{10} and $PM_{2.5}$, as well as the individual components of $PM_{2.5}$ and PM_{10}: mineral dust, black carbon (BC), organic matter (OM), nitrate (NO_3^-), sulphate (SO_4^{2-}), ammonium (NH_4^+), (and the sum of the latter three; Secondary Inorganic Aerosols (SIA)), Secondary Organic Aerosols (SOA) and sea salt.

The model is continuously evaluated against observations from the Danish monitoring network, but also from other measuring campaigns and observations in other countries (see e.g. Hvidtfeldt et al., 2018; Kumar et al., 2019; Khan et al., 2019, Raaschou-Nielsen et al., 2020). In the just finalized research project NordicWelfAir, UBM has been setup and evaluated for a domain covering continental Scandinavia (Frohn et al., 2022)

The model has been used for air pollution forecasting at high resolution for cities since 1998 and is a central part of the Danish Air Quality Monitoring Programme for calculating air pollution levels and trends as well as input to the EVA model system for performing assessments of health impacts and related external costs (Ellermann et al., 2022). UBM has been used in many advisory projects for Governmental decision support. The model also forms the basis for a large number of epidemiological and health impact assessment research projects.

2.3 Modelling health effects and related external costs of air pollution (EVA-system)

The integrated model system EVA (Frohn et al., 2022, Andersen et al., 2007, 2008, Brandt et al., 2013a,b), is based on the impact-pathway approach (Friedrich and Bickel, 2001) and is used for assessment of health impacts from air pollution, including both health effects and related external costs (sometimes also referred to as "indirect costs"), which can be attributed to air pollution exposure. Air pollution components important for health impacts and included in the EVA system are: NO_2, SO_2, O_3 and $PM_{2.5}$, where the individual constituents of $PM_{2.5}$ are: mineral dust, BC, OC, SIA, SOA and sea salt.

The EVA model is coupled to the air pollution models DEHM and UBM for regional-scale and local-scale health impact assessments, respectively. EVA includes gridded population data, exposure-response functions for health impacts in terms of a number of morbidity endpoints and mortality, and economic valuation of the health impacts from air pollution.

To calculate the impacts of the total air pollution levels or of emissions from a specific source or sector, concentrations and population data are combined to estimate human exposure. Then the health effect response is calculated using an exposure-response function, and applying economic valuation for the different health effects provides the estimation of the external costs.

The different elements of the EVA-system are illustrated in Figure 2.1.

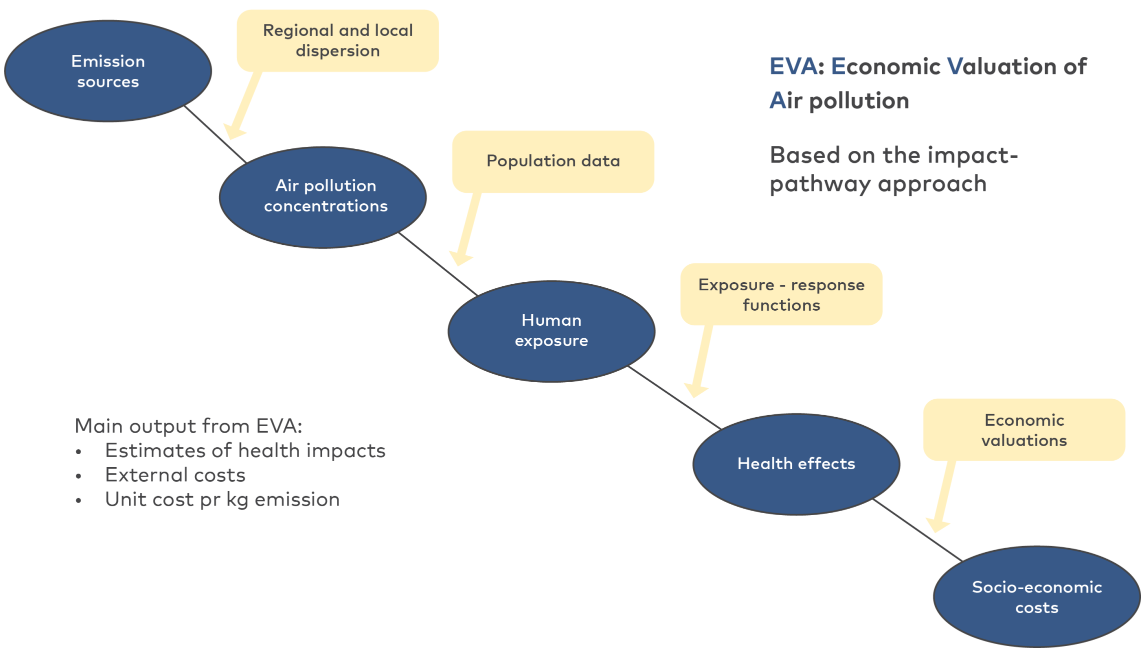


Figure 2.1. Illustration of the elements (yellow boxes) and data/results of the EVA-system (blue ovals).

The EVA model system can be used at different scales – e.g. for Europe based on DEHM, or for Denmark with high geographic resolution (1 km x 1 km) based on UBM.

The EVA-system is part of the Danish national air quality monitoring program, where annual estimates for health effects and related external costs of air pollution are carried out for Denmark. The EVA-system has also been applied to estimate the contributions of Nordic anthropogenic emissions to air pollution and premature mortality over the Nordic region and in the Arctic (Im et al., 2019) and it has been compared with other state-of-the-art assessment tools (Anenberg et al., 2016; Lehtomaki et al., 2020).

The EVA model system applies a set of standard costs for acute and chronic mortality, derived for Denmark (Andersen et al., 2019). To apply the EVA system for other countries, we transformed the costs data to represent other countries using the OECD benefit transfer methodology formula (OECD 2012: 138).

Population data for 2030 has been established for the Nordic countries based on data from Eurostat.

2.4 Selection of cities and model boundaries

A national expected average exposure concentration in 2030 for selected cities in the Nordic countries must be calculated. The task is to model the sector specific contribution to the air quality in 2030 as the total share of transboundary, country, and city pollution for the Nordic countries and for the selected cities.

Based on the number of inhabitants in the largest cities in the Nordic countries, cities were selected in each country to cover the largest cities, but also to have a good geographical coverage.

Model boundaries of cities and country

The definition of city boundaries is not trivial as it depends on what is considered to belong to the city.

To use a standardized approach across the Nordic countries, the geographic datasets that contain the boundaries of cities, greater cities and functional urban areas were used as defined according to the EC-OECD city definition and used for the Eurostat Urban Audit data collection. The data was used as GIS files downloaded from https://ec.europa.eu/eurostat/data/database. These datasets are used as the starting point for demarcation of the geographic extend of the city areas for each of the selected cities. The selected cities and model boundaries are described in chapter 3.

The country boundary is given by the borders of each Nordic country and the transboundary contribution is defined as everything arising from sources outside each country border.

Given these boundaries, the requested average exposure concentration can be calculated using the models described above and the share of the emission sectors' contribution to the air pollution concentrations as well as to the health impacts and related external costs can be calculated by applying the EVA-system.

2.5 WHO AQG 2021

In chapter 4, there is a summary of the WHO AQG from 2005 and 2021 together with the air quality limit and target values of the present and proposed EU Air Quality Directive (from 2008 and 2022 respectively).

WHO has tightened their recommendations significantly from 2005 to 2021, based on the new knowledge and better documentation of the harmful effects of air pollution, especially at lower concentration levels as is the case in the Nordic countries (WHO 2006; 2021). The present EU limit values are significantly higher than the WHO guidelines in both 2005 and 2021 (EU, 2008).

In October 2022, the European Commission published proposals for revised air quality limit values in the draft revision of the Air Quality Directive (European Commission, 2022). This is a proposal and therefore not the final revised limit values. The final limit values will only be available once they have been negotiated and adopted by the European Parliament and the Council. The EU Commission's proposal for revised limit values is lower than the current limit values for 2008, but not as low as the WHO guidelines from 2021.

An important difference between the WHO guidelines and EU limit values is that WHO guidelines are recommendations and EU limit values are legally binding for the EU member states and the countries have to prepare action plans to comply within a reasonable time, if exceedances are observed.

The EU Air Quality Directive requires limit values to be complied with by certain years at the latest. The WHO guidelines do not operate with similar year of compliance, as they are recommendations, so there are no specific objectives that the guidelines should be complied with at specific years.

As the purpose of the project is to gain a better understanding of the implications of the new WHO guidelines in a Nordic setting, the following analysis will focus on comparison of model results with the new WHO guidelines from 2021.

2.6 Evaluation of air quality monitoring in Nordic countries

An analysis is carried out of available measurements in 2021 from rural, urban background and street stations in the selected cities and compared with the new WHO guidelines. This analysis gives an indication of the concentration contribution of the cities (difference between urban background and rural concentrations) and further the contributions of hotspots (difference between street concentrations and urban background concentrations). The latter complements the modelling activities that only include rural and urban back-ground concentrations.

Additionally, a comparison between measurement data from 2021 and the former and new WHO AQG is carried out for each of the Nordic countries where the maximum value of any measuring station within the country is compared with the WHO guidelines. This provides an overview of exceedances of the new WHO guidelines in the Nordic countries. Furthermore, it also describes how the exceedances have changed between the former and new WHO guidelines.

Further, the proposed new European air quality directive is described and the overall implications for the Nordic countries as well as general recommendations for the revision are outlined. National experts within air quality monitoring have been sub-contracted from Swedish Environmental Protection Agency (Sweden), NILU (Norway), FMI (Finland) and Environmental Agency of Iceland (Iceland) for the evaluation of the air quality monitoring.

3. Selected Nordic cities and model grids

This chapter includes a description of the selected Nordic cities, their city boundaries and related model grids.

3.1 Selected cities

Based on the number of inhabitants in the largest cities in the Nordic countries, three cities were selected in each country except for Iceland as shown in Table 3.1. The number of inhabitants is from Eurostat data based on a 1 km x 1 km grid and selected within the city boundaries. As a starting point the three largest cities were selected. However, it has also been an objective to ensure larger cities in different parts of the countries.

For Finland the second (Espoo) and fourth (Vanta) largest cities are part of the Helsinki urban region and hence Tampere (3rd) and Oulu (5th) were chosen.

Reykjavík urban region is considered one urban area consisting of six contiguous municipalities, Reykjavík, Kópavogur, Garðabær, Hafnarfjörður, Seltjarnarnes and Mosfellsbær. It could be considered as Greater Reykjavík. Other cities on Iceland are small, and for small cities, the urban background concentration over the city will be almost entirely dominated by the regional background concentrations and sources in the city will have very limited influence on urban background concentrations. Therefore, only Greater Reykjavík has been chosen for Iceland.

Table 3.1. Selection of largest cities in each of the Nordic countries. Inhabitants based on Eurostat within city boundaries.

Country	City	City type	Inhabitar	Year	Comments
SE	Stockholm	Capital	960000	2018	
SE	Göteborg	2nd largest	605000	2018	
SE	Malmö	3rd largest	338000	2018	
DK	København	Capital	548000	2018	
DK	Aarhus	2nd largest	339000	2018	
DK	Odense	3rd largest	201000	2018	
FI	Helsinki	Capital	634000	2018	
FI	Tampere	3rd largest	229000	2018	Espoo (2nd) and Vantaa (4th) in Helsinki region
FI	Oulu	5th largest	196000	2018	
NO	Oslo	Capital	664000	2018	
NO	Bergen	2nd largest	279000	2018	
NO	Trondheim	3rd largest	194000	2018	
IS	Reykjavík	Capital	222000	2018	Here Rekjavík is Greater Reykjavík that includes six contiguous municipalities: Reykjavík, Kópavogur, Garðabær, Hafnarfjörður, Seltjarnarnes and Mosfellsbær.

For the Danish cities the population by Eurostat was compared with population data from Statistics Denmark. Eurostat estimates 548,000 inhabitants in 2018 based on the gridded data for København following the administrative boundaries. Statistics Denmark indicates 718,000 inhabitants for the municipalities of København and Frederiksberg or a difference of 24%. It was unexpected to find such large difference adding to the uncertainty on estimation of health effects and related external costs. For Aarhus and Odense the differences were within 2%. The data from Eurostat was chosen for all Nordic cities for consistency throughout the project.

The location of the selected cities is seen in Figure 3.1.

Figure 3.1. The location of the selected Nordic cities.

3.2 City boundaries

The definition of city boundaries is not well-defined as it depends on what is considered to belong to the city.

A standardized approach was used across the Nordic countries to define the boundaries of cities based on the EC-OECD city definition used for the Eurostat Urban Audit data collection. These datasets include boundaries for cities, greater cities and functional urban areas defined in the following way. A City is a local administrative unit (LAU) where the majority of the population lives in an urban centre of at least 50,000 inhabitants. The Functional Urban Area consists of a city and its commuting zone, formally known as larger urban zone (LUZ). The Greater City is an approximation of the urban centre when this stretches far beyond the administrative city boundaries.

The different city boundaries are illustrated in Figure 3.2.

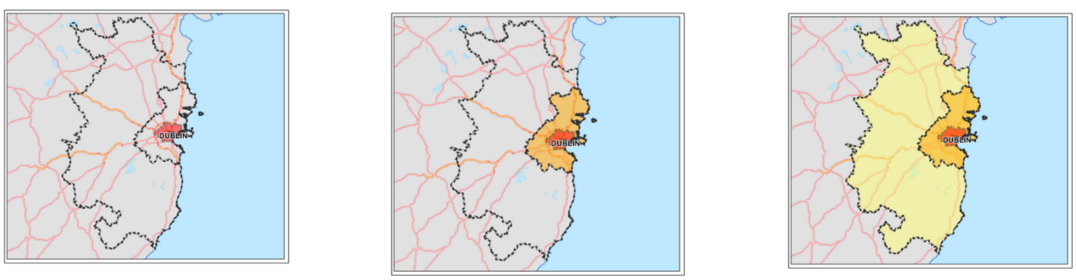


Figure 3.2. Illustration of different city boundaries with the case of Dublin (Source: Eurostat).

Based on an analysis of the three different types of city boundaries, the most suitable type of boundary is the city boundary for the selected cities. The city boundaries are based on administrative boundaries of the city.

Although the same city boundary type was chosen for all cities, they are still quite different with respect to geographical extend and how much is built-up urban area and how much is rural/natural area. In Appendix 1 the city boundaries are shown on aerial photos. Examples of cities that are almost entirely composed of built-up urban areas are København, Stockholm, Helsinki and Malmö where the rest of the cities have larger rural/natural areas outside the urban built-up area within the administrative city boundary.

One of the outcomes of the modelling is an average concentration in 2030 over the area defined by the city boundaries. It is obvious that an area with a city boundary which almost entirely includes built-up area will have higher concentrations than an area with a city boundary that includes large rural/natural areas, due to the differences in emission density. This should be kept in mind when comparing results from different cities.

It is also evident that Eurostat doesn't characterize suburban areas as a specific part of cities. Therefore, it has not been possible to e.g. analyse the average concentration over suburban areas or their contribution to city concentrations.

3.3 City grids and upstream grids

It is necessary to define receptors for the UBM model over the selected cities to be able to calculate the average concentration over the areas defined by the city boundaries, and to be able to calculate the contribution to the average concentration of the emissions within the city boundaries.

The regional model (DEHM) provides the background concentrations to the cities and the urban background model (UBM) calculates the local contribution taking into account the upstream background concentration from 25 km upstream and the emissions 25 km upstream and to the receptor point in question. The upstream area is illustrated in Figure 3.3 for København.

The EEA reference grid on a 1 km x 1 km resolution is used for the Nordic countries. The coordinate reference system (CRS) for the EEA reference grid is ETRS89/LAEA Europe. The Geodetic Datum is the European Terrestrial Reference System 1989. The Lambert Azimuthal Equal Area (LAEA) projection is centred at 10E, 52N. Being based on an equal area projection, the EEA reference grid is suitable for generalising data, statistical mapping and analytical work whenever a true area representation is required (EEA, 2011).

The upstream area for København is illustrated in Figure 3.3.

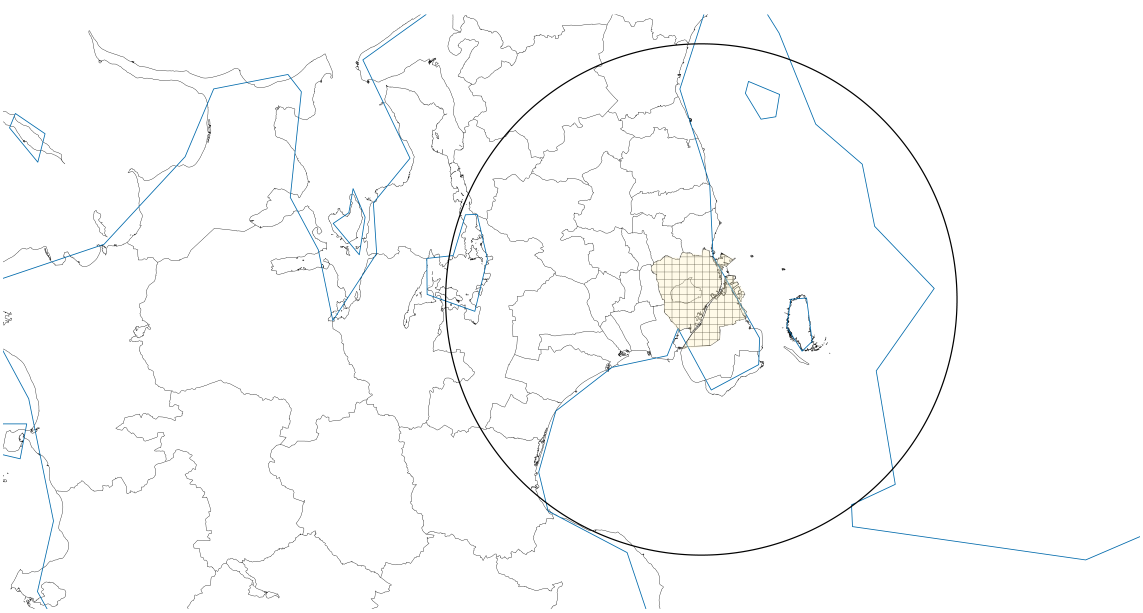


Figure 3.3. Upstream area for København shown as a schematic 25 km circle around København. Municipal boundaries are shown for part of Zealand in Denmark. Schematic country boundaries are also shown. The city grid for København is also shown (beige area).

The city grid for København is illustrated in Figure 3.4.

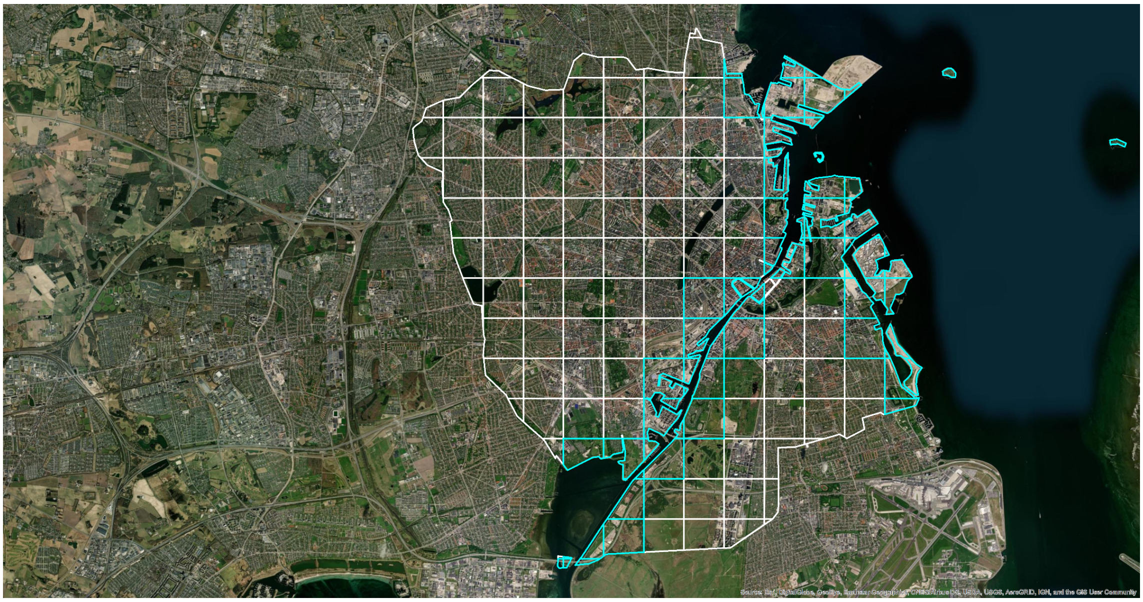


Figure 3.4. City grid for København. Grid size as rectangle 13 km x 15 km. Grid cells are visualized and those bordering water are highlighted.

The city grid serves both as receptor grid, emission grid and population grid. The receptor grid includes the receptor points for the UBM calculations as the centre point of each grid cell (centre in 1 km x 1 km cell). The grid cell is also used to calculate the number of inhabitants for health impact calculations based on the share of the area of the cell that is within the city boundaries as information of inhabitants are based on the 1 km x 1 km grid cells. Similar for emissions where the share of the area of the cell that is within the city boundaries is used to assign emissions to the cell. In the case that a grid cell is bordering water, then the entire emission and inhabitants of the grid cell are used.

For each of the selected cities the receptor grid and emission grid has been prepared and the shares of areas of the cells within the city boundaries as well as cells bordering water have been identified using GIS techniques.

In Table 3.2, a description of the extend of city grid size and upstream grid as rectangles is shown.

Table 3.2. Description of the extend of each city, the grid size and the upstream grid as rectangles.

Count-ry	City	Xcenter of upper left city cell (m)	Ycenter of upper left city cell (m)	X city Distance (km)	Y city Distance (km)	Upper left grid cell of up-stream grid (x-centre) (m)	Upper left grid cell of up-stream grid (y-centre) (m)	Up-stream grid size (x) (km)	Up-stream grid size (y) (km)
SE	Stockholm	4761500	4062500	28	23	4731500	4092500	88	83
SE	Göteborg	4416500	3864500	40	41	4386500	3894500	100	101
SE	Malmö	4503500	3618500	17	16	4473500	3648500	77	76
DK	København	4475500	3628500	13	15	4445500	3658500	73	75
DK	Aarhus	4317500	3691500	28	38	4287500	3721500	88	98
DK	Odense	4332500	3597500	26	22	4302500	3627500	86	82
FI	Helsinki	5137500	4223500	23	25	5107500	4253500	83	85
FI	Tampere	5038500	4375500	29	46	5008500	4405500	89	106
FI	Oulu	5028500	4803500	82	83	4998500	4833500	142	143
NO	Oslo	4348500	4115500	27	37	4318500	4145500	87	97
NO	Bergen	4054500	4166500	29	36	4024500	4196500	89	96
NO	Trondheim	4323500	4483500	35	18	4293500	4513500	95	78
IS	Reykjavík	2807500	4924500	43	38	2777500	4954500	103	98

4. Evaluation of air quality monitoring

A comparison between measurement data from 2021 and the former and new WHO AQG is carried for each of the Nordic countries where the maximum value of any measurement station within the country is compared with the WHO guidelines. This provides an overview of exceedances of the new WHO guidelines in the Nordic countries. Furthermore, it also describes how the exceedances have changed between the former and new WHO guidelines.

Additionally, an analysis is carried out based on available measurements in 2021 from rural background, suburban/urban background and traffic stations in the selected cities and the results are compared with the new WHO guidelines and the proposed EU Air Quality Directive. This analysis gives an indication of the concentration contribution of the cities (the difference between urban background and rural concentrations) and further the contributions of hotspots (the difference between traffic concentrations and urban background concentrations). The latter complements the modelling activities that only include rural and urban background concentrations.

Further, the proposed new European air quality directive is described and the overall implications for the Nordic countries are outlined.

4.1 WHO AQ guidelines and the EU Air Quality Directive

The current EU Directive (EU, 2008) and the Fourth Daughter Directive (EU Directive 2004/107/EC of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air (EU, 2004)), will in the future be merged into one directive, following the adoption of the newly proposed EU Directive on ambient air quality (EU, 2022).

A comparison of the levels in the 2005 and 2021 WHO AQG (WHO, 2006; WHO 2021) with the corresponding limit and target values of the current and the proposed EU Directive on ambient air quality and cleaner air for Europe (AQD) of October 2022 is shown in Table 4.1. The pollutants presented here is limited to particulate matter ($PM_{2.5}$ and PM_{10}), ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and carbon monoxide (CO), which are the pollutants treated by WHO (2021). It should therefore be noticed that pollutants included in the EU Directive 2004/107/EC of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air (EU, 2004), often mentioned as the so-called Fourth Daughter Directive, are not described here. It should also be remarked that limits and targets in relation to protection of vegetation and natural ecosystems are not included either as the focus is solely on air pollutants with the potential of affecting human health.

Table 4.1. Overview of the different concentration levels mentioned in the 2005 and 2021 WHO AQG compared with the corresponding limit and target values of the current directive (2008) and in the October 2022 proposed EU Directive (P2022) on ambient air quality and cleaner air for Europe (AQD). Numbers not marked are simple mean values of the averaging times given. Numbers that are marked with a superscript are explained in the notes below the table.

Pollutant	**Averaging time**	**Unit**	**WHO AQG** 2005	**WHO AQG** 2021	**EU AQD[c1]** 2008	**EU AQD[c2]** P2022
$PM_{2.5}$	Annual	µg/m^3	10	5	25	10
	24-hour	µg/m^3	25[a]	15[a]	n.a.	25[d]
PM_{10}	Annual	µg/m^3	20	15	40	20
	24-hour	µg/m^3	50[a]	45[a]	50[e]	45[f]
O_3	Peak season	µg/m^3	n.a.	60[b]	n.a.	n.a.
	8-hour	µg/m^3	120[a]	100[a]	120[g]	120[h]
NO_2	Annual	µg/m^3	20	10	40	20
	24-hour	µg/m^3	n.a.	25[a]	n.a.	50
	1-hour	µg/m^3	200	200	200[i]	200[j]
SO_2	Annual	µg/m^3	n.a.	n.a.	n.a.	20
	24-hour	µg/m^3	20	40[a]	125[k]	50[L]
	1-hour	µg/m^3	n.a.	n.a.	350[m]	350[n]
	10-minutes	µg/m^3	500	500	n.a.	n.a.
CO	24-hour	mg/m^3	n.a.	4[a]	n.a.	4[o]
	8-hour	mg/m^3	10	10	10[p]	10[p]
	1-hour	mg/m^3	35	35	n.a.	n.a.
	15-min	mg/m^3	100	100	n.a.	n.a.

Notes to the recommended levels in the WHO AQG

[a] 99th percentile (i.e. 3–4 exceedance days per year)

[b] Average of daily maximum 8-hour mean O_3 concentrations in the six consecutive months with the highest six-month running-average O_3 concentration.

Notes to the limit and target values in the EU Directives on ambient air quality and cleaner air for Europe (AQD) in relation to human health

NB. Except for ozone which are Target values, all other numbers are Limit values.

[c1] EU Directive 2008/50/EC on ambient air quality and cleaner air for Europe (AQD)

[c2] Proposal for a revision of the EU Directives on ambient air quality, 26 October 2022

[d] Limit value. 25 µg/m^3 not to be exceeded more than 18 times a calendar year

[e] Limit value. 50 µg/m^3 not to be exceeded more than 35 times a calendar year

[f] Limit value. 45 µg/m^3 not to be exceeded more than 18 times a calendar year

[g] Target value. 120 µg/m^3 not to be exceeded on more than 25 days per calendar year averaged over three years

[h] Target value. 120 µg/m^3 not to be exceeded on more than 18 days per calendar year averaged over three years

[i] Limit value. 200 µg/m^3 not to be exceeded more than 18 times a calendar year

[j] Limit value. 200 µg/m^3 not to be exceeded more than 1 time a calendar year

[k] Limit value. 125 µg/m^3 not to be exceeded more than 3 times a calendar year

[L] Limit value. 50 µg/m^3 not to be exceeded more than 18 times a calendar year

[m] Limit value. 350 µg/m^3 not to be exceeded more than 24 times a calendar year

[n] Limit value. 350 µg/m^3 not to be exceeded more than 1 time a calendar year

[o] Limit value. 4 mg/m^3 not to be exceeded more than 18 times a calendar year

[p] Limit value. Maximum daily eight hour mean

General comments to the WHO AQG

The 2005 WHO AQG mentions 12 parameters in total and the 2021 AQG mentions 15 parameters. The recommended concentration levels in the WHO AQG as can be seen in Table 4.1 have generally been reduced considerably from the WHO 2005 to the WHO 2021. The perhaps most pronounced differences are $PM_{2.5}$ annual average and NO_2 annual average where the recommended levels have been decreased to 50% of the former levels.

Of the in total 15 parameters, 6 have had their concentration levels reduced without changing the statistical calculation of the parameter, that is PM_{10} and $PM_{2.5}$ annual, PM_{10} and $PM_{2.5}$ 24-hours, ozone 8-hours, and NO_2 annual.

Only 1 out of the 15 parameters have had the statistical calculation of the parameter changed, that is SO_2 24-hour where the calculation has changed from a simple average to the 99^{th} percentile.

Out of the 15 parameters, 5 remain unchanged that is NO_2 1-hour, SO_2 10-min., CO 8-hour, CO 1-hour and CO 15-min.

Out of the 15 parameters in the WHO 2021 AQG, 3 new parameters have been introduced, that is ozone peak season, NO_2 24-hour, and CO 24-hour.

When comparing the WHO AQG levels and the EU AQD values it should be noted that there is not one to one correspondence from the WHO AQG to the EU AQ Directive values and the statistical calculation of the concentration levels / values are different in most cases.

General comments to the proposed EU Air Quality Directive

In the proposal for the new Air Quality Directive (EU, 2022) a tightening of the current requirements for the exposure concentration (also known as AEI – Average Exposure Indicator) of $PM_{2.5}$ is suggested and similar requirements for the exposure concentration of NO_2 are introduced. The new proposal to reduce the exposure concentration for $PM_{2.5}$ states that the exposure concentration should decrease by 25% over a ten-year period. The reduction requirement will apply from 2030 and every year thereafter. For example, this means that the exposure concentration in 2030 (average of the three years 2028–2030) should be 25% lower than measured in 2020 (average of 2018–2020). The reduction requirement applies until the average exposure concentration is in line with the proposed exposure concentration target set at 5 µg/m^3 for $PM_{2.5}$, i.e. similar to the air quality guideline established by WHO (WHO, 2021). If for example the mean exposure concentration for $PM_{2.5}$ was 10 µg/m^3 in 2020, it should thus be reduced to 7.5 µg/m^3 by 2030, and thereafter until the target of 5 µg/m^3 is achieved. For NO_2, completely new requirements related to exposure concentration have been suggested in the proposal for a revised Air Quality Directive. As for $PM_{2.5}$, it is proposed that the exposure concentration for NO_2 should decrease by 25% over a ten-year period. The reduction requirement will apply from 2030 until the proposed exposure concentration target is reached. For NO_2, a target of 10 µg/m^3 has been proposed, i.e. similar to the air quality guideline established by WHO (WHO, 2021).

4.2 Present air quality in Nordic countries and WHO guidelines

In this section, measurements from 2021 in the Nordic countries are compared with the former 2005 WHO AQG WHO (2006) and the new WHO AQG for 2021 (WHO, 2021).

Index values representing the percentage of annual concentration measured levels for 2021 with respect to the 2005 WHO AQG (WHO, 2006) are compared with corresponding index values with respect to the 2021 WHO AQG (WHO, 2021). A set of two figures is shown per country so the differences between the two sets of WHO guidelines are displayed for each of the five Nordic countries.

General comments to the measurement data

The source of the data is the database at EEA - European Air Quality Portal where annual statistics of air quality values originating both from AirBase and AQ e-Reporting can be extracted. The European Air Quality Portal contains only quality-approved data reported to the EU. Only datasets with a data coverage of more than 85% has been extracted following the general recommendations for reporting air quality data in the EU.

The year 2021 is the latest year with full data reporting and it has therefore been chosen as the year for comparing the two different WHO AQG sets described respectively in WHO (2006) and WHO (2021). The year 2021 can be regarded as a measuring year where the societies after the Covid-19 lock-down have returned to more normal conditions compared with the preceding year 2020 which could be believed to have been affected much more by the Covid-19 lock-down. The first one to two months of 2021 were still, however, affected e.g. by reduced traffic. For the year 2022 the deadline for the EU data reporting is in the autumn 2023 which means that 2022 is not a possibility to use either. This leaves the year 2021 perhaps as the best compromise compared with going back to before the Covid-19 lock-down e.g. to 2019 where air pollution levels would be less relevant than 2021.

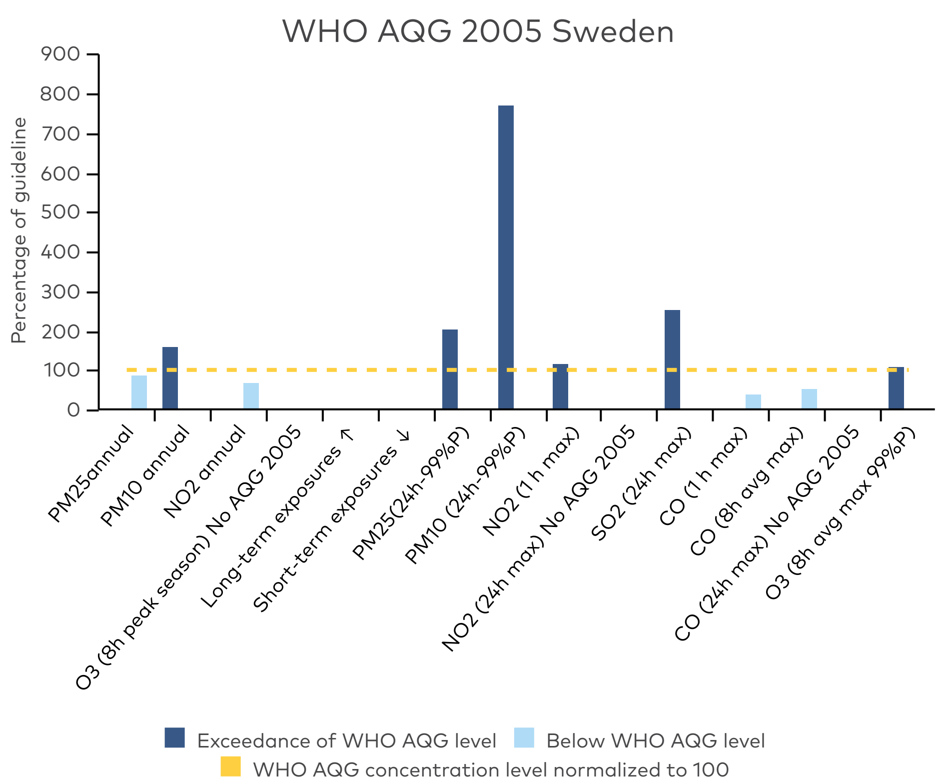
For each of the pollutants listed in Table 4.1 under the WHO columns *the highest values* fulfilling the data coverage criteria of 85% has been selected for each country. As an example, the highest value for $PM_{2.5}$ annual average is simply the highest average value measured at all the stations in the country in question in 2021 regardless of station type and can e.g. also include the site category Industrial. These stations can also be outside the selected cities. Another example is the highest value for $PM_{2.5}$ 24-hour average, which is defined as the highest 99th percentile (i.e. 3–4 exceedance days are allowed per year) measured at all the stations in the country in question in 2021 regardless of station type. The index values presented in the following figures are thus displaying the highest values for the year 2021 for the parameters according to the WHO AQG statistics but for the short-term exposure, it is not necessarily the same as an exceedance of the WHO AQG levels. The 99th percentile short-term exposures are representing index values in relation to the highest calculated 99th percentile value alone, but strictly speaking there is only an exceedance of the WHO AQG levels, when there are more than 3–4 exceedance days of the 99th percentile per year.

In the 10 figures for the five Nordic countries, all the axes are kept at the same scale for the sake of comparison although index values vary a lot. The first figure for each country is indexing the 2021 measurements according to the WHO 2005 guideline levels and the second figure is indexing the 2021 measurements according to the WHO 2021 guideline levels. Index values of very short averaging times for SO_2 (10 min.) and CO (15 min.) the WHO AQG concentrations levels have been omitted due to lack of reporting these measurements. The statistical definitions of the WHO AQG concentration levels when these differ from simple average values will appear from the notes following Table 4.1. WHO guideline values for O_3 8-hour max peak season, NO_2 24-hour max, and CO 24-hour max were defined in the 2021 WHO AQG but not in the 2005 version. This is the reason why these data are not presented in the WHO 2005 figures but are presented in the WHO 2021 figures.

Figures 4.1.-4.5 present the results for the Nordic countries.

Sweden

In Figure 4.1 is the index values in relation to the 2005 and 2021 WHO AQG for measurements of 2021 in Sweden.



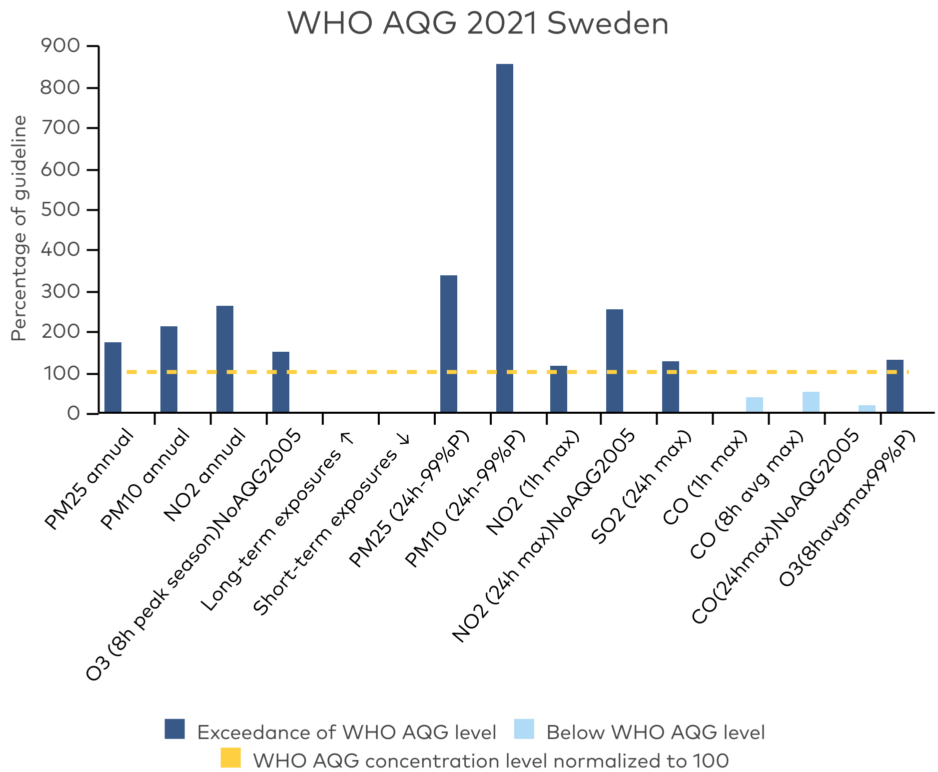
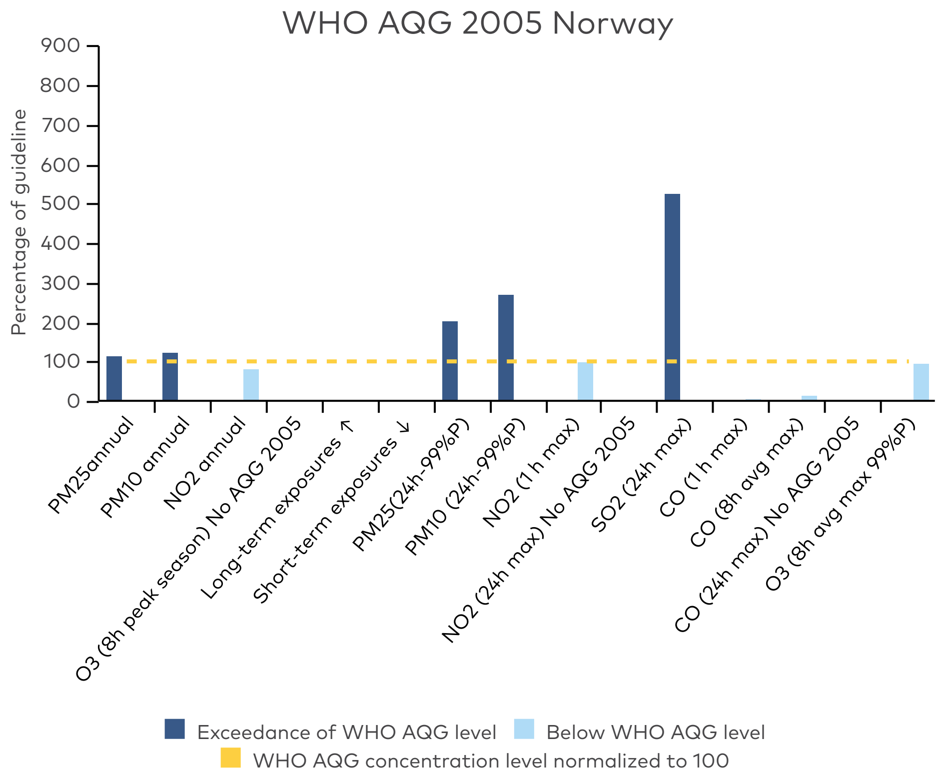


Figure 4.1. Index values in relation to 2005 and 2021 WHO AQG) for concentration levels for 2021 measurements in Sweden. The index value for each parameter has been calculated from the highest measured concentration with a data coverage > 85%. It should be pointed out that the 99th percentile short-term exposures are representing index values in relation to the highest calculated 99th percentile value alone, but strictly speaking there is only an exceedance of the WHO AQG levels, when there are more than for 3–4 exceedance days of the 99th percentile per year.

The relatively high levels of SO_2 were due to emissions from sulphite pulp production at an industrial plant. This was discontinued at the end of 2021 and concentrations during 2022 have been much lower.

Norway

In Figure 4.2 is the index values in relation to the 2005 and 2021 WHO AQG for measurements of 2021 in Norway.



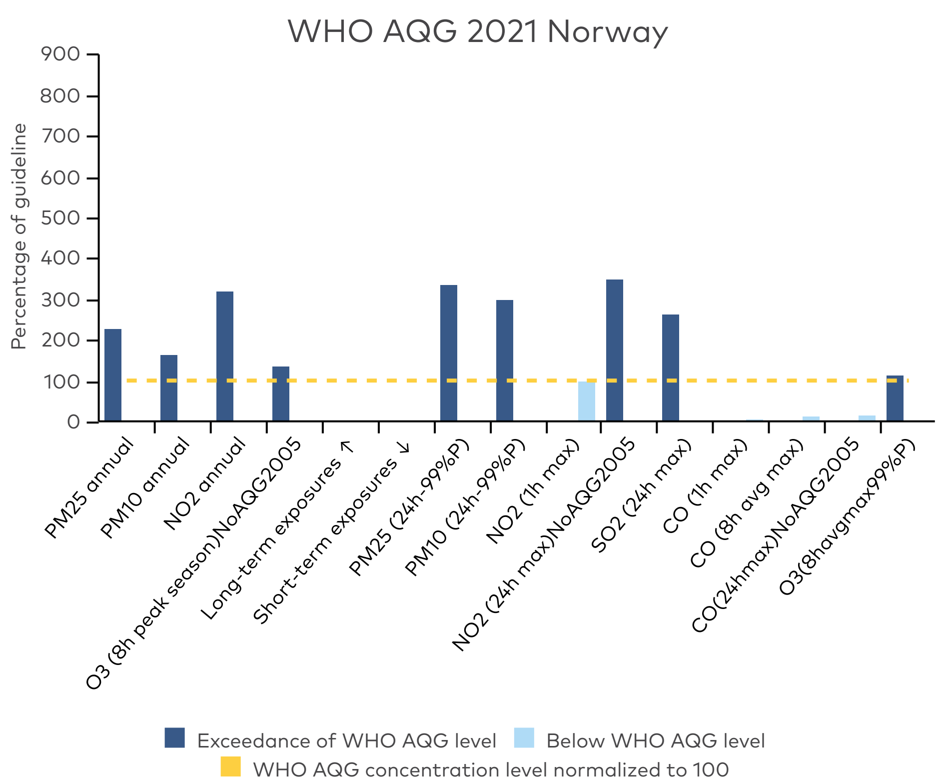
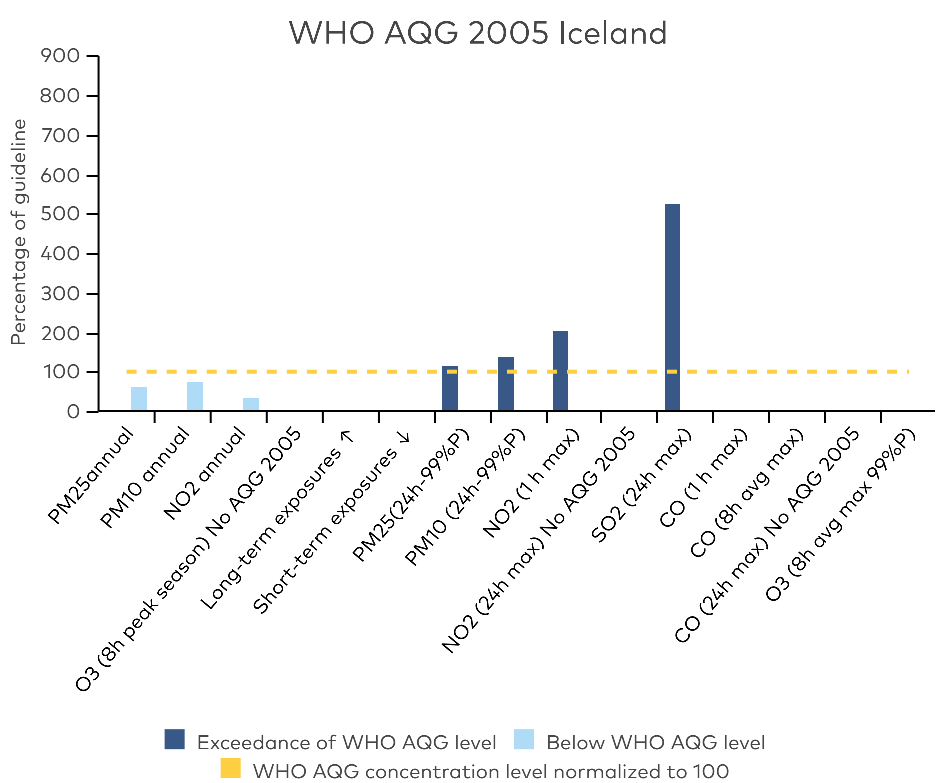


Figure 4.2. Index values in relation to 2005 (top panel) and 2021 (bottom panel) WHO AQG for concentration levels for 2021 measurements in Norway. The index value for each parameter has been calculated from the highest measured concentration with a data coverage > 85%. It should be pointed out that the 99th percentile short-term exposures are representing index values in relation to the highest calculated 99th percentile value alone, but strictly speaking there is only an exceedance of the WHO AQG levels, when there are more than for 3–4 exceedance days of the 99th percentile per year.

Iceland

In Figure 4.3 is the index values in relation to the 2005 and 2021 WHO AQG for measurements of 2021 in Iceland.

Data for ozone and carbon monoxide have according to the EEA - European Air Quality Portal seemingly not been reported for Iceland for 2021 which is the reason why these two parameters cannot be found in the figures for Ice-land. The high values for SO_2 especially for 2005 are due to volcanic eruptions that is a natural source of SO_2 therefore fluctuating from year to year.



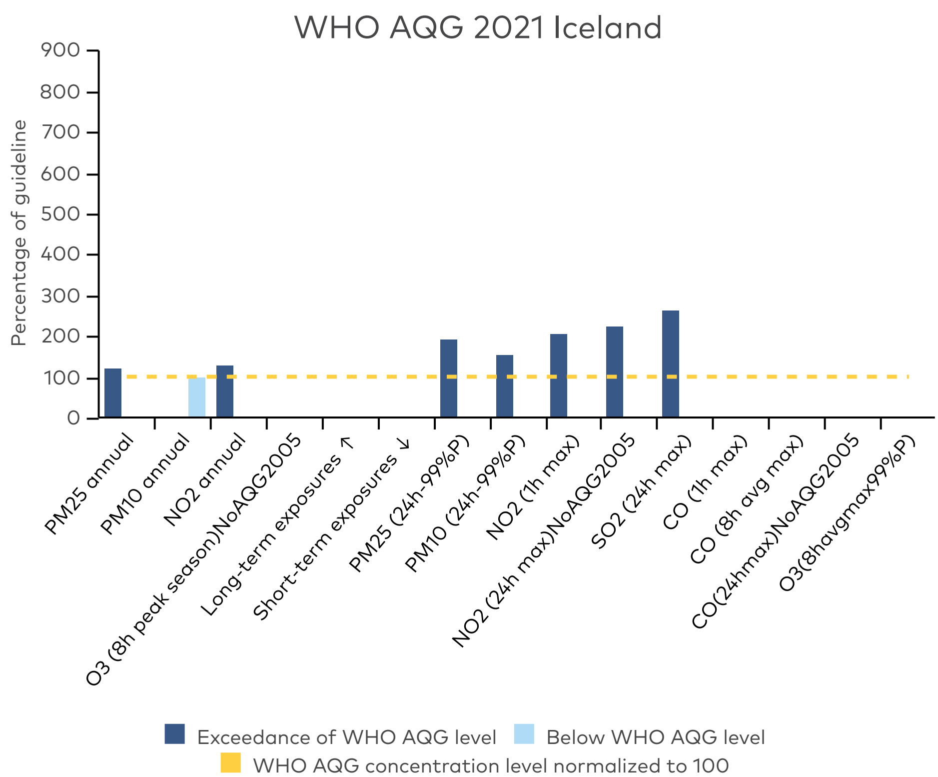


Figure 4.3. Index values in relation to 2005 (top panel) and 2021 (bottom panel) WHO AQGAQG (AQG) for concentration levels for 2021 measurements in Iceland. The index value for each parameter has been calculated from the highest measured concentration with a data coverage > 85%. Ozone and carbon monoxide is not reported for Iceland 2021. It should be pointed out that the 99th percentile short-term exposures are representing index values in relation to the highest calculated 99th percentile value alone, but strictly speaking there is only an exceedance of the WHO AQG levels, when there are more than for 3–4 exceedance days of the 99th percentile per year.

Finland

In Figure 4.4 is the index values in relation to the 2005 and 2021 WHO AQG for measurements of 2021 in Finland. The urban CO measurements have been ceased due to concentration levels well below the lower assessment threshold of European legislation (Directive 2008/50/EC). In 2021, Finland used indicative reporting for CO based on satellite measurements. Based on this the CO concentrations are well below both 2005 and 2021 WHO guideline levels (pers.com, K. Kyllönen, FMI).

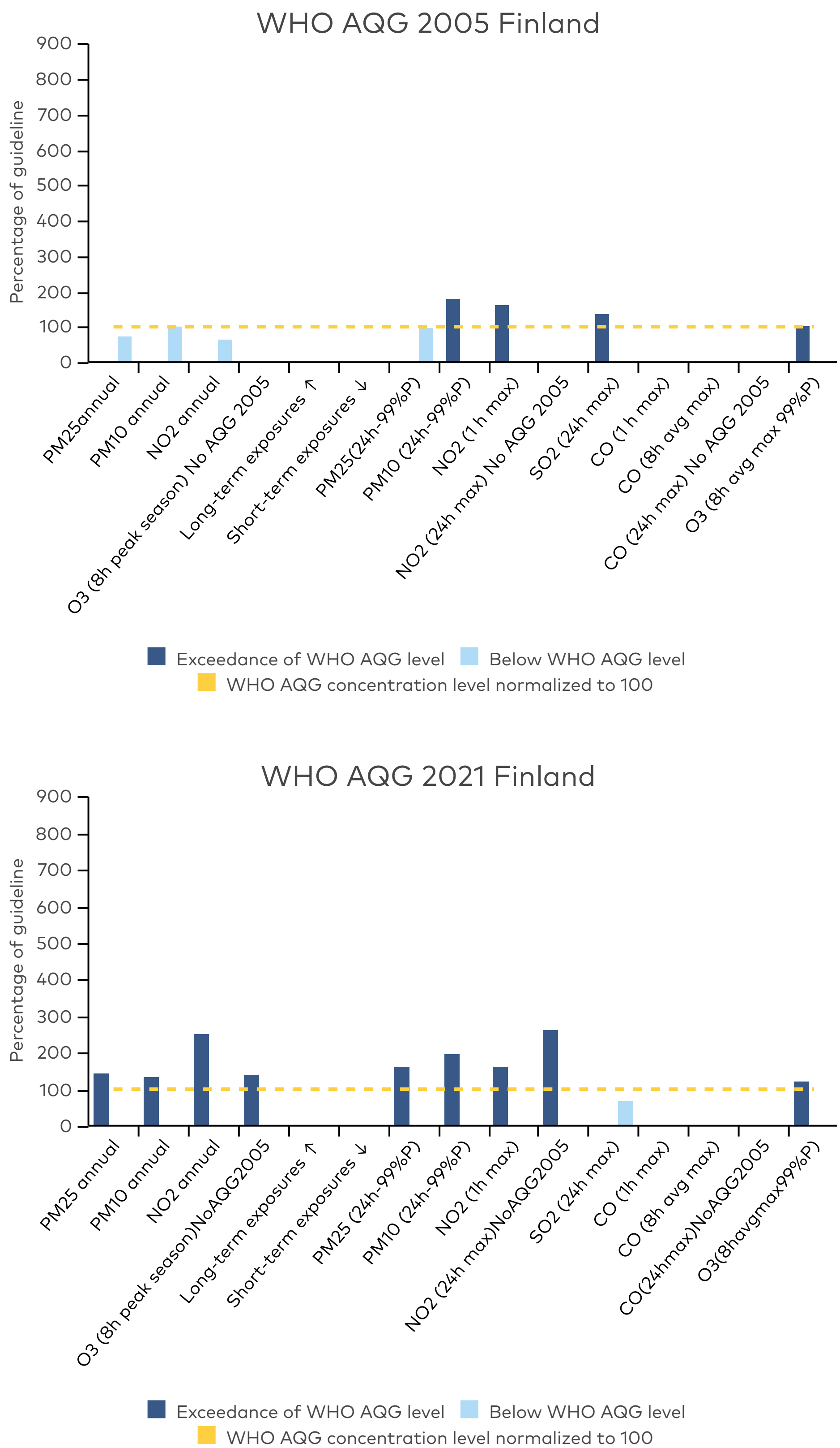
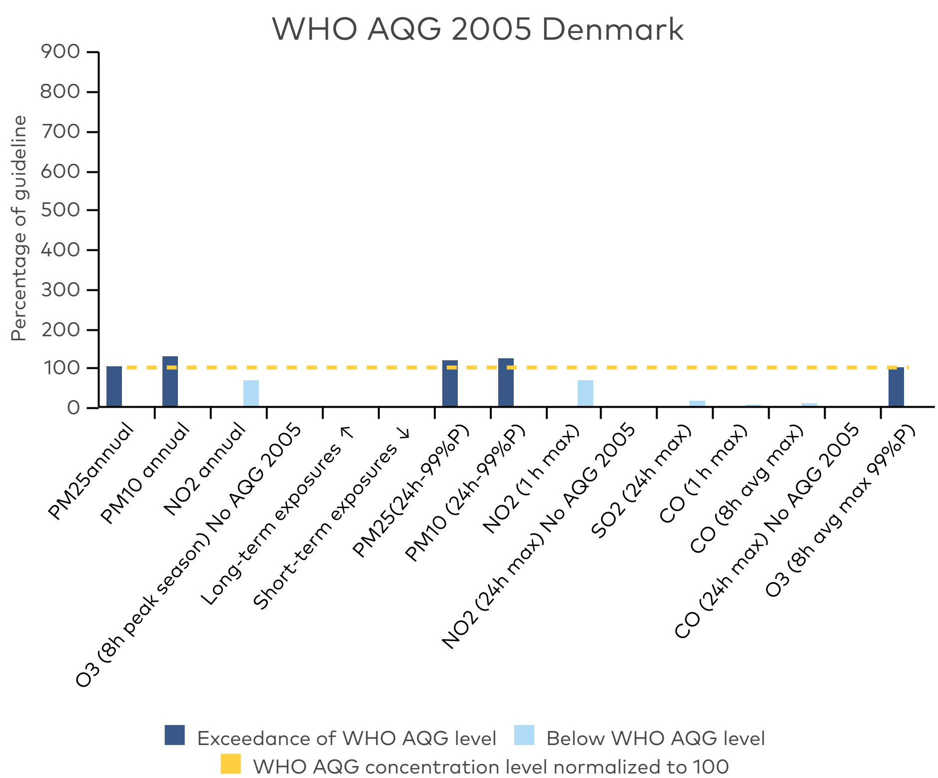


Figure 4.4. Index values in relation to 2005 (top panel) and 2021 (bottom panel) WHO AQG for concentration levels for 2021 measurements in Finland. The index value for each parameter has been calculated from the highest measured concentration with a data coverage > 85%. Carbon monoxide is not reported for Finland 2021. It should be pointed out that the 99th percentile short-term exposures are representing index values in relation to the highest calculated 99th percentile value alone, but strictly speaking there is only an exceedance of the WHO AQG levels, when there are more than for 3–4 exceedance days of the 99th percentile per year.

Denmark

In Figure 4.5 is the index values in relation to the 2005 and 2021 WHO AQG for measurements of 2021 in Denmark.



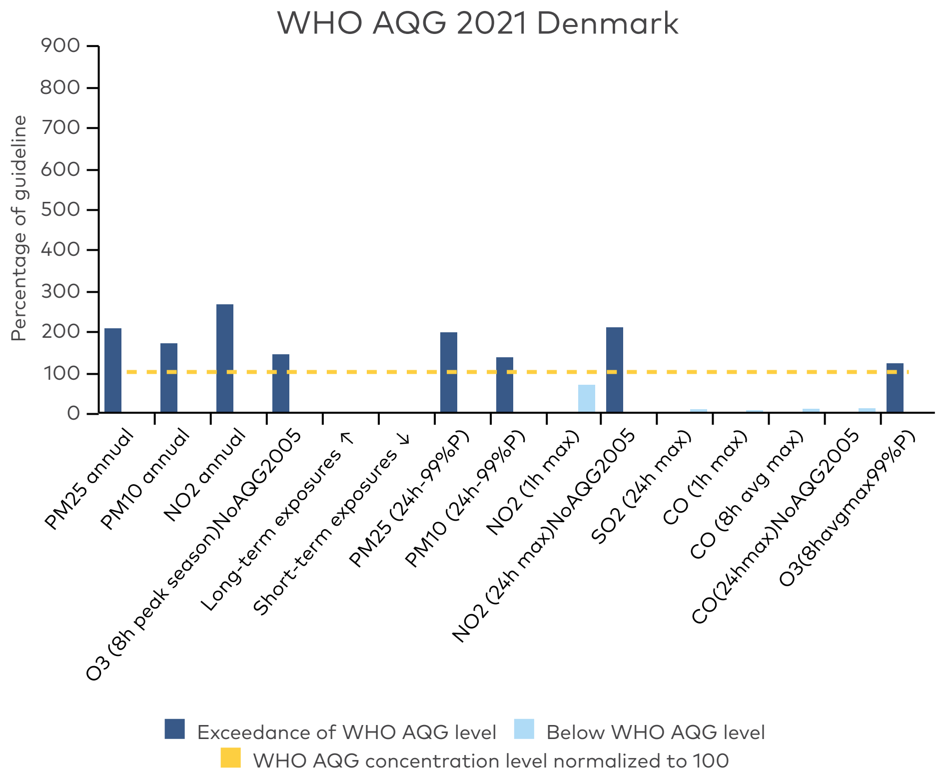


Figure 4.5. Index values in relation to 2005 (top panel) and 2021 (bottom panel) WHO AQG) for concentration levels for 2021 measurements in Denmark. The index value for each parameter has been calculated from the highest measured concentration with a data coverage > 85%. It should be pointed out that the 99th percentile short-term exposures are representing index values in relation to the highest calculated 99th percentile value alone, but strictly speaking there is only an exceedance of the WHO AQG levels, when there are more than for 3–4 exceedance days of the 99th percentile per year.

All Nordic countries

The health impacts of air pollution are by far the largest for long-term exposure to $PM_{2.5}$ then followed by NO_2, both as annual means, and then exposure to elevated levels of ozone. All five Nordic countries exceed the 2021 WHO AQG for annual means of $PM_{2.5}$ and NO_2, and ozone (8h peak season) (except Iceland with no data) based on highest measured values in 2021.

4.3 NO_2 and $PM_{2.5}$ in the selected Nordic cities in 2021

Measurements of annual average concentrations of NO_2 and $PM_{2.5}$ for 2021 for the selected cities in the five Nordic countries in relation to the 2022 proposed EU Air Quality Directive (EU, 2022) and the 2021 WHO Guidelines (WHO, 2021), are presented in the following. It should be noted that for each of the selected cities *only the one station with the highest concentration measured, is representing that particular city*. The three selected cities for each of the five Nordic countries have been mentioned in chapter 2 but for the sake of completeness they are given here as well. For Iceland, only one city has been selected.

- Sweden: Stockholm, Göteborg and Malmö;
- Denmark: København, Aarhus and Odense;
- Finland: Helsinki, Tampere and Oulu;
- Norway: Oslo, Bergen and Trondheim;
- Iceland: Greater Reykjavík.

For each of the selected Nordic cities, the highest measured concentration levels of NO_2 and $PM_{2.5}$ have been found for each of the three site categories: A) Traffic, B) Urban-/suburban background, and C) rural background and are presented in Figure 4.6 and 4.7.

Traffic: Urban traffic stations or street stations (shortened in the figure to 'traffic'). **Urban/suburban background**: Urban background and suburban stations. No distinction has in this connection been made between these two categories (shortened in the figure to 'sub/urb'). **Rural and rural background**: Rural and rural background stations. No distinction in this connection have been made between these two categories (shortened in the figure to 'rural'). It should be noted that no industrial sites are included in this section because the focus is to complement the modeling data in the other chapters of the above mentioned three site categories with actual measurements.

The source of the data is as in the above, the EEA database, European Air Quality Portal, where annual statistics of air quality values originating both from AirBase and AQ e-Reporting can be extracted. The European Air Quality Portal contains only quality-approved data reported to the EU. Only datasets with a data coverage of more than 85% have been extracted following the general recommendations for reporting air quality data in the EU.

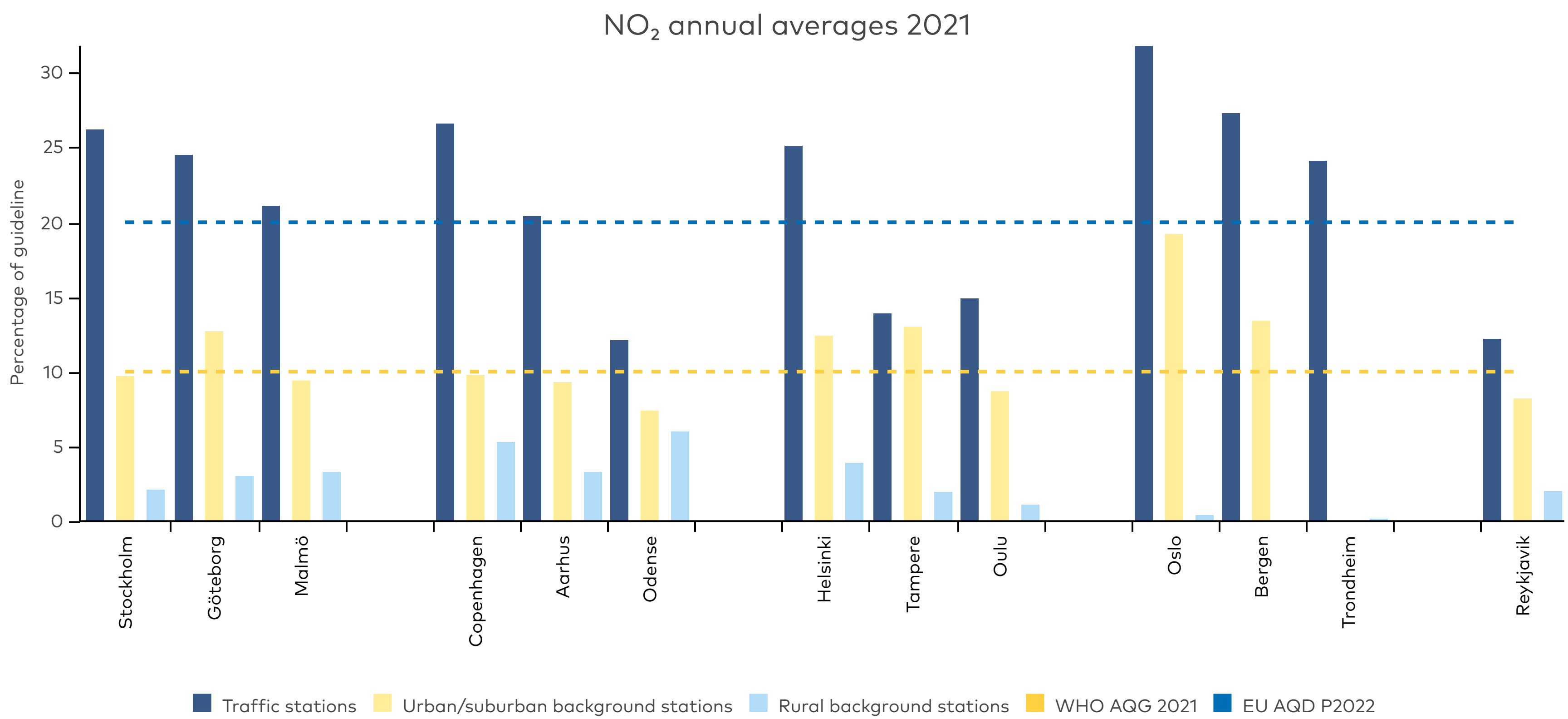


Figure 4.6. Highest measured annual average NO_2 concentrations for 2021 fulfilling the data coverage criteria of 85% for each of the selected cities for each category of measuring station in relation to the WHO AQG) concentration levels for 2021 (10 µg/m^3) and in relation to the suggested limit value (20 µg/m^3) in the newly proposed EU Directive (EU, 2022). For the numbers used and comments to these, see Appendix 3. It should also be noticed that rural background stations are not necessarily located within the immediate vicinity of the city it is supposed to represent, see text and Appendix 3.

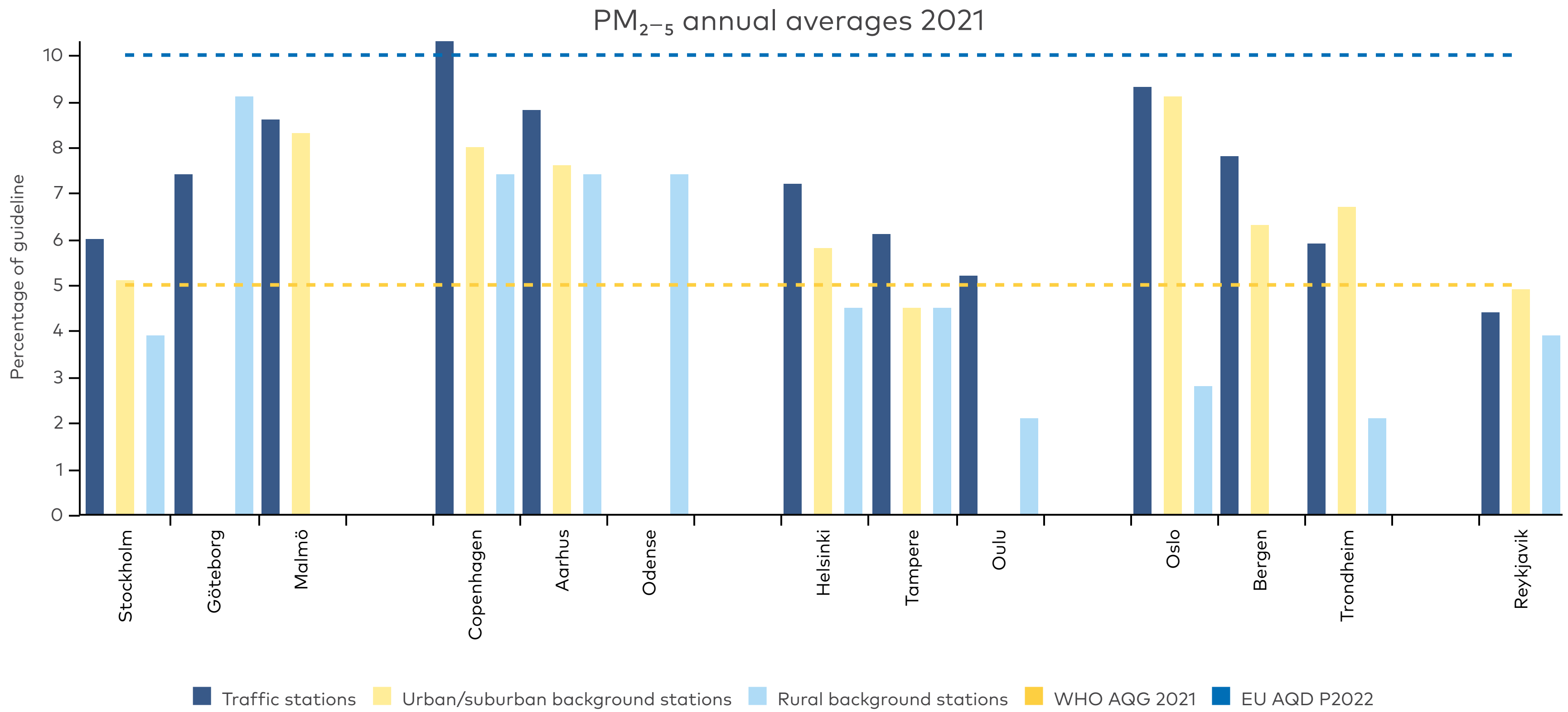


Figure 4.7. Highest measured annual average $PM_{2.5}$ concentrations for 2021 fulfilling the data coverage criteria of 85% for each of the selected cities for each category of measuring station in relation to the WHO AQG concentration levels for 2021 (5 µg/m^3) and in relation to the suggested limit value (10 µg/m^3) in the newly proposed EU Directive (EU, 2022). Dashed red line: Proposed EU AQD limit value; Dashed black line: 2021 WHO AQG concentration level. For the numbers used and comments to these, see Appendix 3. It should also be noticed that rural background stations are not necessarily located within the immediate vicinity of city it is supposed to represent, see text and Appendix 3.

Some reservations, however, should be taken when linking rural background measurements of NO_2 and $PM_{2.5}$ to specific cities as in Figure 4.6 and 4.7. Although rural or rural background stations are supposed to spaciously represent larger geographical areas, the distance between a rural station and a city can be so large, that the representativeness of this station for the immediate rural or rural background level for that particular city can be questionable because of eventual regional concentration gradients. The most pronounced examples are e.g. for the city Oulu (Finland), where the distance between the rural station representing the background for Oulu and the city itself is 230 km for the station measuring NO_2 and 330 km for the station measuring $PM_{2.5}$. For Bergen (Norway), the distance to the nearest rural or rural background station is about 280 km SE of Bergen (Birkenes observatoriet, 30 km NE of Kristiansand), to the second nearest it is about 310 km E of Bergen (Hurdal25, 50 km NE of Oslo), and to the third nearest it is about 320 km NE of Bergen (Kårvatn), but none of these were found suitable to represent the rural or rural background for the oceanic climate influenced location of Bergen, which is why Bergen was left without representative rural or rural background measurements in Figure 4.6 and 4.7. A third example is Denmark, where $PM_{2.5}$ representing rural or rural background only is measured at one station (Risø about 30 km W of København). The $PM_{2.5}$ measurements at Risø are thus representing all the three selected stations in Denmark i.e. it is the same value for København, Aarhus and Odense rural that is presented in Figure 4.7. Modelling estimates of the regional background $PM_{2.5}$ concentration levels for Denmark indicate a weak southern to northern gradient with the highest levels in the South. The three selected cities in Denmark are located in the central-south part of the country within a rather limited band not extending more than about 80 km north-south, supporting the assumption that Risø to a reasonable extent, can represent the rural background level of the three selected Danish cities.

In all the selected cities in the five Nordic countries annual NO_2 and $PM_{2.5}$ (see Figure 4.6 and 4.7) are well below the annual limit values (40 µg/m^3 and 25 µg/m^3, respectively) of the present Air Quality Directive (EU, 2008) in 2021. In relation to the annual limit values in the newly proposed EU Air Quality Directive (EU, 2022) of 20 µg/m^3 and 10 µg/m^3 for NO_2 and $PM_{2.5}$, respectively, 9 out of 13 traffic stations are exceeding the proposed annual limit value for NO_2 and only one for $PM_{2.5}$. None of the urban or suburban background nor the rural or rural background stations, are exceeding the annual limit values of NO_2 and $PM_{2.5}$ of the newly proposed directive. It should be emphasised here that for each of the selected cities only the one station with the highest concentration measured, is representing that particular city, and especially for traffic sites there often exists more than one station in the same city.

When it comes to the new 2021 WHO guidelines (WHO, 2021) for NO_2 all the traffic stations shown with valid measurements have concentrations higher than the guideline levels. The same applies to $PM_{2.5}$ (except for Reykjavík). For the urban or suburban background stations, 5 out of 12 are exceeding the NO_2 guideline levels. For $PM_{2.5}$, 8 out of the 10 are exceeding the guideline levels. For NO_2 on the rural or rural background stations all the stations with measurements are well below the guideline levels. For $PM_{2.5}$ however on the rural or rural background stations 4 out of 11 with measurements are exceeding the guideline levels. Again, it should be emphasised that for each of the selected cities only the one station with the highest concentration measured, is representing that particular city, and especially for traffic sites there often exists more than one station in the same city.

In general the measurements of NO_2 and $PM_{2.5}$ in 2021 are following the expected concentration levels and the expected pattern with the highest values for the traffic stations and the lowest at rural background with sub-/urban in-between and there is only two exceptions from this: In Trondheim (Norway) where the measurement of $PM_{2.5}$ at the urban background station shows higher values than the measurement at the traffic station. And in Göteborg where the $PM_{2.5}$ concentration measured at the rural background station (Råö) is higher than the concentration measured at the traffic station. For both of these cases it is indicated (by the commenting of the text by the representatives of the two countries) that the automatic PM measurement methods used, might play a role.

4.4 General implications of proposed AQ Directive

On October 26, 2022, the European Commission published its proposal for a revised Air Quality Directive (EU, 2022). The proposal for the new directive brings together the current EU Directive, Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe (EU, 2008) and the so-called Fourth Daughter Directive, EU Directive 2004/107/EC of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air (EU, 2004). This section will try to give an overview of the essential changes of the newly proposed Air Quality Directive and its implication for the air quality programs and measuring networks in the Nordic countries in general. To analyze in detail all the implications including e.g. the economic consequences for each of the Nordic countries, will include analysis of e.g. the zone or agglomeration classifications and assessment thresholds for the different pollutants, however, this will be beyond the scope of this analysis. Therefore, only the most essential and general implications that are found to be of common interest for the Nordic countries have been analyzed. Because it is an overview of only the essential changes for the Nordic countries in general, the actual conditions for the air quality program in the single country might deviate due to e.g. the concentration levels of the pollutants, assessment thresholds and number of zones.

Implications for requirements on measurements

General improvements in the air quality in the Nordic countries over the past 10 years have influenced the commitments in relation to the EU air quality directives regarding the fixed measurements of regulated air pollution components that have been significantly reduced. To estimate the level of monitoring in the EU Member States, the measure of the assessment thresholds is used to determine the level of monitoring in the Member States. If the concentration of a pollutant is above the upper assessment threshold, fixed measurements of high quality shall be applied, while at concentrations below the lower assessment threshold it is possible only to use indicative methods (EU, 2004, 2008). With the general improvements in the air quality in the Nordic countries in relation to the present EU air quality directive (EU, 2008) for some pollutants it would in principle be possible only to estimate concentration levels using indicative methods.

In relation to the present EU Air Quality Directive and the general improvements in the air quality in the Nordic countries over the past 10 years, a comprehensive reorganization would be expected to take place of the air monitoring programmes with cheaper methods and fewer measuring points. However, the new proposal for the EU Air Quality Directive radically changes this possibility, since the tightening of the limit values is accompanied by more stringent assessment thresholds used to determine the number of measuring points and the requirements for the measurement methods. At the same time, the system is simplified so that the two previous assessment thresholds (upper and lower assessment thresholds) are replaced by a single assessment threshold.

In addition to the above major changes in the requirements of the new proposal for the air quality directive, there are also several minor adjustments to the main text of the directive and to the many appendices. An example is e.g. when an exceedance of a limit value is calculated by modelling, then one year of fixed high quality measurements shall be carried out (if the area covered by the modelling is not already represented by fixed measurements).

The assessment thresholds establish the minimum level of the extent of measurements of the various air pollution components and the quality of the measurements. If the concentrations are above the assessment threshold, then the AQ Directive specifies the number of measurements to be carried out in the individual zones based on the number of inhabitants living in the zone. If the assessment threshold is exceeded, then fixed measurements with the reference methods specified in the AQ Directive or by equivalent methods need to be carried out. If the concentrations are below the assessment threshold requirements for the measurements are not as strong. In these cases, only indicative measurements or objective estimations are needed.

In cases where concentrations are above the assessment threshold, there is still the possibility of reducing the number of fixed measurements that should be carried out by the reference methods or by equivalent methods to the half, if the fixed measurements are supplemented by other methods. The new proposal for the air quality directive sets out four conditions to be met, of which one tightening is of particular importance: "The number of indicative measurements shall be the same as the number of fixed measurements, which they replace, and the indicative measurements shall have a duration of at least two months per calendar year" (EU, 2022, Article 9(3)). This is a significant tightening in relation to the current air quality directive (EU, 2008), which does not require one-to-one replacement of fixed measurements with indicative measurements, and this is of great importance for the cost of the measurement program in question.

Requirements for the establishment of monitoring supersites

The new proposal for the Air Quality Directive requires the establishment of supersites in all EU Member States with the aim of increasing knowledge about particle pollution at EU level. For Denmark as an example, this means that a supersite needs to be established at an urban background site and at a rural background site. Supersites require the measurement of a large number of new particle components, of which the requirement to measure the oxidative potential of PM is something completely new in the context of air quality monitoring. The background for the requirement to measure PM's oxidative potential is that the latest research indicates that PM's oxidative potential can be a better measure of the harmful effect of particle pollution than the particle mass (Gao et al., 2020). There are many different types of measurement methods for measuring the oxidative potential of PM and the proposed new Air Quality Directive does not specify how it should be measured. Another new feature is that measurements of total deposition of arsenic, cadmium, mercury, nickel, benzo(a)pyrene and selected polycyclic aromatic hydrocarbons (PAHs) shall in the example of Denmark be carried out at an urban background measuring station as well. In the Danish example, this type of measurement so far has only been done at a rural background station. In connection with the deposition measurements, the wording around the deposition measurements has been tightened, as "bulk deposition" has been sharpened to "total deposition" (EU, 2022). This may have implications for how the measurements of these components are carried out in each country.

Requirements for public information on actual air quality

The proposal for a new air quality directive imposes significantly stricter requirements on information on current air quality including obligatory hourly updates. However, the proposal is not entirely precise in all respects. The text of the directive itself states that informing the public about current air quality should be provided for all regulated air pollution components in outdoor air (EU, 2022;

paragraph 35). This could e.g. include information of the public on air quality of benzo(a)pyrene or cadmium, which would not be possible to carry out on an hourly basis. In the revised Annex IX to the Directive it is required only that information (on an hourly up-date) should be provided on current air quality levels for $PM_{2.5}$, PM_{10}, nitrogen dioxide, ozone, sulphur dioxide, and carbon monoxide. On the other hand, there is a requirement that there must be hourly up-date information on air quality at least for the minimum number of required measuring points indicated in Annex III (EU, 2022).

Requirements for the establishment of Air Quality Index

In the proposed directive it is stated that: Member States shall establish an air quality index covering sulphur dioxide, nitrogen dioxide, particulate matter (PM_{10} and $PM_{2.5}$) and ozone, and make it available through a public source providing an hourly update. The air quality index shall consider the recommendations by the WHO and build on the air quality indices at European scale provided by the European Environmental Agency.

Monitoring of ultrafine particles

The proposal for a new Air Quality Directive requires measurements of ultrafine particles (UFP) and on the size distribution of ultrafine particles, but there are not defined limit values, target values or similar other regulation included in the proposal (EU, 2022). In the previous directive, there were no requirements for measuring ultrafine particles (EU, 2008). In the new proposal for the Air Quality Directive there are requirements in connection with supersites and there is a requirement for measurements in areas where high concentrations of ultrafine particles can be expected. The purpose of the latter is to obtain more information on the concentrations of ultrafine particles in areas which may be affected by emissions from for example airports, ports, road traffic, industrial sites or domestic heating (EU, 2022). The new air quality directive proposal requires at least one fixed location measurements of ultrafine particles (EU, 2022). The proposal for a new Air Quality Directive calls for cooperation with ACTRIS in relation to the implementation of the measurements (EU, 2022). ACTRIS has requirements on measuring size range that the instruments should be able to measure e.g. particles with diameters up to 800 nm, which might be different from the measuring range of the instruments already in use in the networks.

Requirement for air quality modelling

The new proposal for the Air Quality Directive includes model calculations as an obligatory element where concentrations of pollutants exceed limit values, or target values. There are also a large number of requirements in relation to the modelling calculations (EU, 2022, Annex IV, Section F): "

a. (a) that the designated reference institutions participate in the European network of air quality modelling set up by the Commission's Joint Research Centre;
b. that best practices in air quality modelling identified by the network through scientific consensus are adopted in relevant applications of air quality modelling for the purposes of fulfilling legal requirements pursuant to Union legislation, without prejudice to model adaptations necessitated by singular circumstances;
c. that the quality of relevant applications of air quality modelling is periodically checked and improved through intercomparison exercises organised by the Commission's Joint Research Centre;
d. that the European network of air quality modelling be responsible for the periodic review, at least every 5 years, of the ratio of modelling uncertainties listed in the final columns of Tables 1 and 2 of this Annex and subsequent proposal of any necessary changes to the Commission."

In addition to this, there is also a requirement to implement model calculations in cases where the limit values are exceeded in a zone. Also, it is proposed that, in connection with the notification of the public where there are episodes of high concentrations of ozone, nitrogen dioxide, $PM_{2.5}$ and PM_{10}, short-term air quality forecasts shall be carried out. If the prognosis indicates a risk of exceeding the information threshold, the population should be notified of this. This is supposedly already being done in the Nordic countries, but this will need to be extended to include the proposed information thresholds for $PM_{2.5}$ and PM_{10}.

New requirements for average exposure concentrations, AEI

In the proposal for the new Air Quality Directive a strengthening of the requirements for reducing the average exposure indicator concentration for $PM_{2.5}$ (AEI) is introduced together with similar requirements for NO_2 (EU, 2022). The new air quality directive appears to impose the same requirements on the number of urban background measuring stations where the average exposure concentration is to be measured.

Increased requirements for documentation of spatial representativeness

The wording regarding documentation of the monitoring carried out has generally been tightened. An example of this is that there are comprehensive requirements for the documentation of the geographical representativeness of the measurements at the measuring stations, where, among other things, there are requirements for the use of model calculations.

Increased requirements for documentation of monitoring network

There are extensive requirements for documentation of the design of the measurement program and the network of measuring stations. Annex IV, Section D (EU, 2022) sets out following: "

D. Site selection, its review and documentation

1. The competent authorities responsible for air quality assessment shall for all zones fully document the site-selection procedures and record information to support the network design and choice of location for all monitoring sites. The design of the monitoring network shall be supported at least by either modelling or indicative measurements.
2. The documentation shall include the location of the sampling points through spatial coordinates, detailed maps and shall include information on the spatial representativeness of all sampling points. "

The above quotation indicates the first two requirements out of 10 listed in Annex IV, section D. They illustrate the tightening of the documentation requirements set out in the proposal for the new air quality directive.

5. Regional Air Quality in 2019 and 2030

5.1 DEHM model domain setups

In the project, five different model domain setups have been made i.e. for the Danish cities together with Göteborg and Malmö, for Stockholm, for the Norwegian cities, for the Finnish cities and finally for Iceland. Each model domain covers the Northern Hemisphere in a polar stereographic projection true at 60°N with a spatial resolution of 150 km x 150 km, and high resolution is obtained over the five Nordic areas using a two-way nesting technique, increasing the resolution over Europe (50 km x 50 km), Northern Europe/Nordic Countries (16.67 km x 16.67 km) and specific Nordic area (5.56 km x 5.56 km).

In the vertical direction, 29 levels resolve the lowest approx. 15 km of the atmosphere in the model. The regional air quality model, DEHM, is driven by meteorological input from the numerical weather prediction model WRF v4.1 (Skamarock et al., 2008), where the spatial setup of the WRF model system is identical to the setup of the DEHM model system both horizontally and vertically, which means that the 2D and 3D WRF data are not interpolated spatially to the similar DEHM grid points, but directly available with the correct resolution. The WRF model is driven by global data from the ERA5 reanalysis from ECMWF (Hersbach et al., 2018). The WRF data were archived with 1-hour resolution and interpolated in time inside the DEHM model. The WRF model was run for the period 30/11 2018 to 1/1 2020, and DEHM was run for 1/12 2018 to 1/1 2020, where the simulations for December 2018 were carried out to initialise the model system.

In Table 5.1 the five DEHM domains and cities involved in each domain are listed.

Table 5.1. Five DEHM Domains and cities involved in each domain.

Domain	Cities
Denmark–Sweden	København, Aarhus, Odense, Malmö, Göteborg
Stockholm	Stockholm
Norway	Oslo, Bergen, Trondheim
Finland	Helsinki, Tampere, Oulu
Iceland	Greater Reykjavík

In Figures 5.1–5.5 the geographical extend of the five model domain setups are shown.

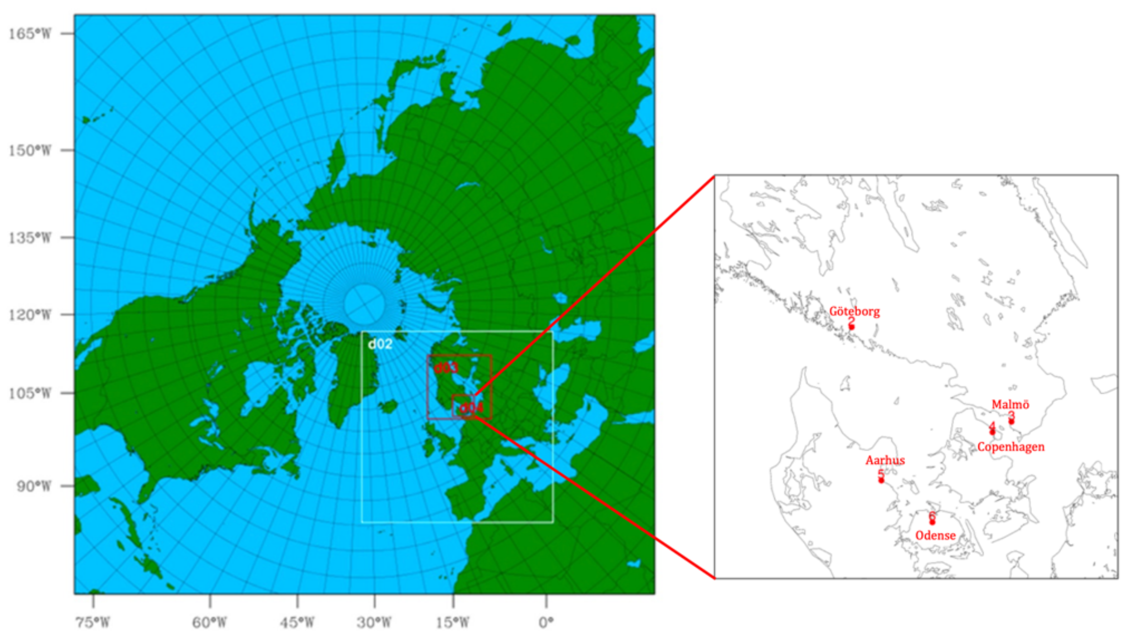


Figure 5.1. Model domain setup for the Danish cities, Göteborg and Malmö.

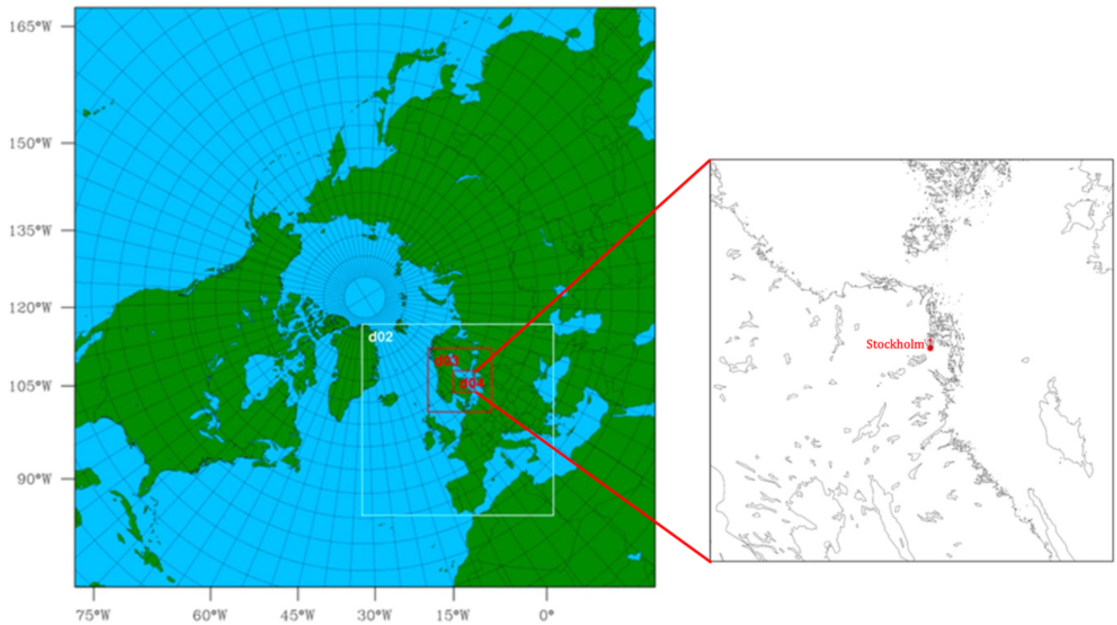


Figure 5.2. Model domain setup for Stockholm.

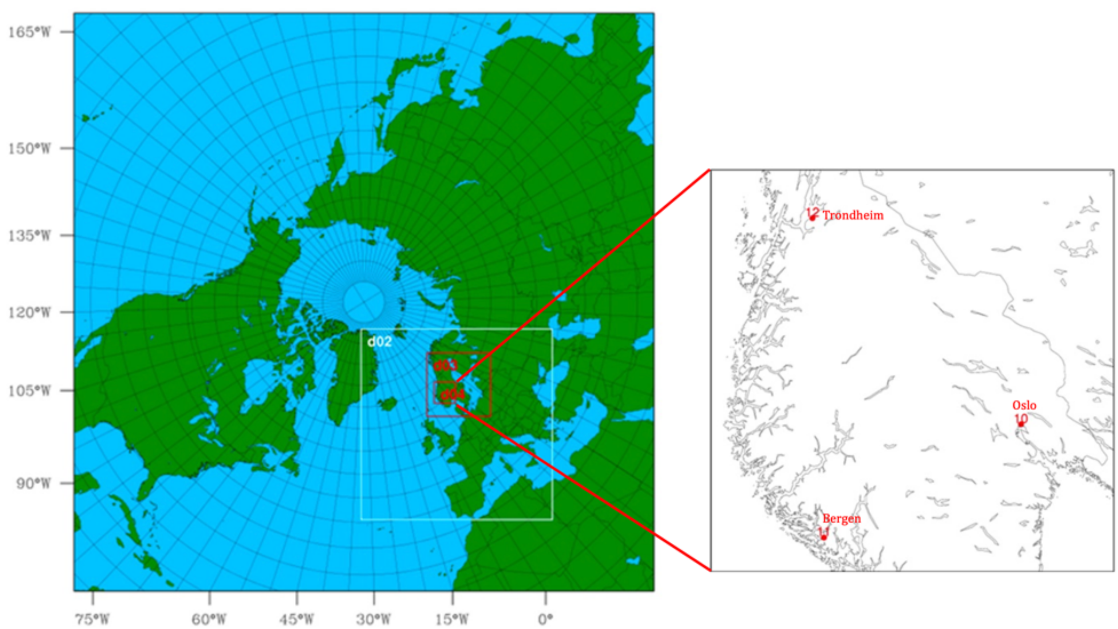


Figure 5.3. Model domain setup for the Norwegian cities.

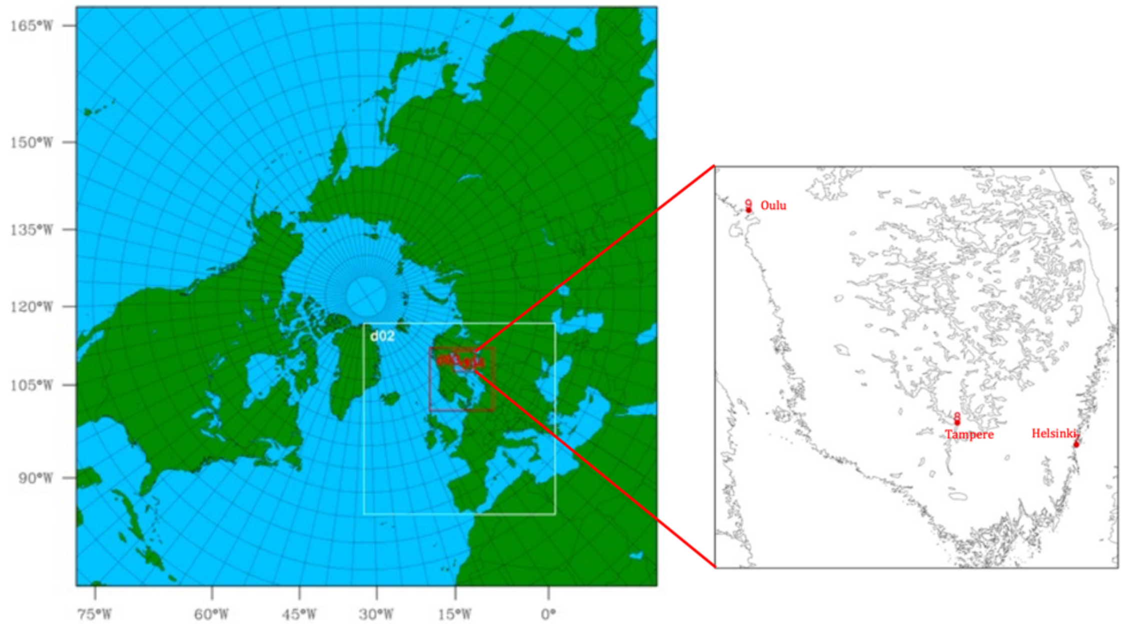


Figure 5.4. Model domain setup for the Finnish cities.

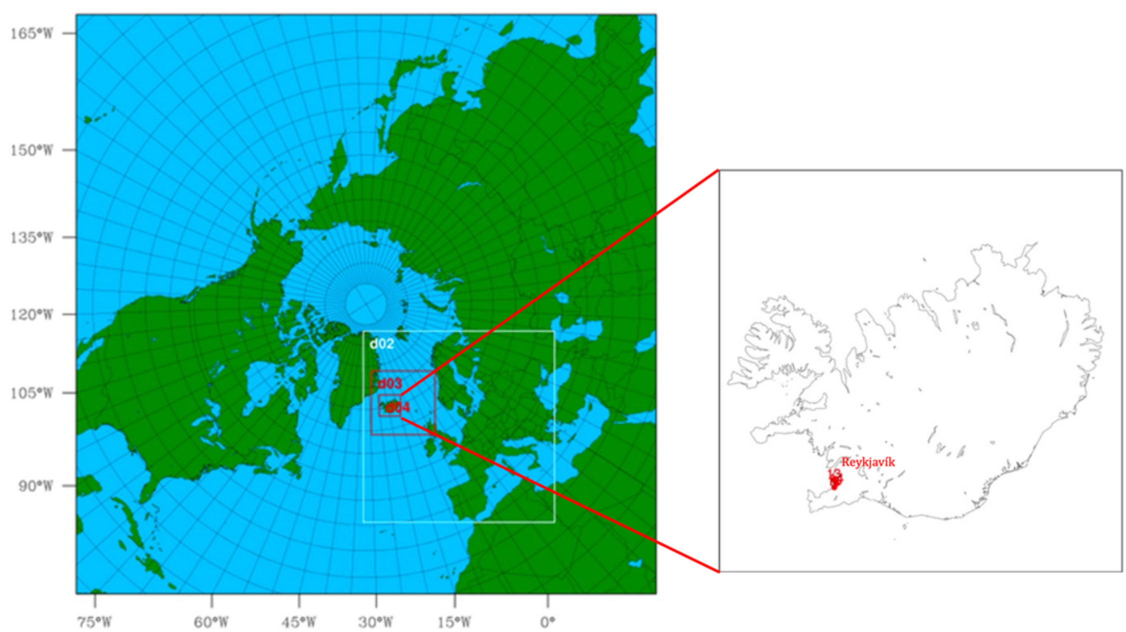


Figure 5.5. Model setup for Iceland.

5.2 High-resolution emissions in 2019 and 2030

Emissions for Europe and the rest of the Northern Hemisphere are based on emission data from the EMEP database with 0.1° x 0.1° spatial resolution and the ECLIPSE v6b database with 0.5° x 0.5° spatial resolution. Furthermore, global ships emissions based on the STEAM model with 0.1° x 0.1° resolution and monthly time resolution were used.

Projected emissions for 2030 are drawn from existing international emission databases. For EU countries, emissions reflect national projections if targets are met in the NEC directive (National Emission Ceilings), otherwise reduction targets set out in the NEC directive for 2030 for the country. For non-EU-countries, the national projections are used. Emissions of CO and PM_{10} are included in the national emission inventories but are not mandatory for projections, and hence there are limitations for obtaining projections of emissions of CO and PM_{10} for 2030 for all countries.

The countries' projection of emissions for 2030 are given as total emissions on NFR (Nomenclature for Reporting) Code level for each component. These emissions on NFR code level are converted to the country specific GNFR (Gridded NFR) sectors given in the gridded EMEP emissions. Finally, the gridded country specific GNFR sectors for 2019 are scaled in order to establish gridded EMEP emissions. This is done by requiring that the total gridded country specific GNFR sectors are equal the countries' projection in the same GNFR sectors for 2030 and by assuming that the spatial distribution in 2030 is similar to the spatial distribution in 2019.

Emissions for the Nordic countries (except Iceland) are based on the emission dataset from the research project NordicWelfAir (funded by NordForsk) where a high-resolution geographically distributed emission inventory of 1 km x 1 km for the Nordic countries was established for selected years from 1990 to 2014. The emission inventory for 2014 was in a similar way as for the EMEP data scaled to 2019 and 2030 based on the total country specific GNFR sectors and the national total emissions for 2019/the projection of emissions for 2030 respectively. The emission sector system applied in the NordicWelfAir emissions is based on the old SNAP (Selected Nomenclature for Air Pollution) , and since SNAP does not exactly match the GNFR sectors, these scalings to 2019 and 2030 were based on fewer, aggregated sectors, which have an exact match. See Table 5.2.

Table 5.2. Matching sector correspondence between SNAP and GNFR.

SNAP	GNFR
1 (Energy) 3 (Industrial comb.) 4 (Industrial proc.)	A_PublicPower B_Industry
2 (Residential combustion)	C_OtherStatComb
5 (Extraction etc.) 6 (Solvents) 9 (Waste)	D_Fugitive E_Solvents J_Waste
7 (Road transport)	F_RoadTransport
8 (Off-road, without shipping)	I_Off-road H_Aviation
10 (Agriculture)	K_AgriLivestock L_AgriOther

The calculations for Iceland are different from the other countries because the high-resolution (1kmx1km) NordicWelfAir emissions was the first high-resolution emission inventory made and it has not been evaluated in detail yet. Therefore, only EMEP emissions (0.1° x 0.1° approx. 11 km x 6 km) are used in both DEHM and UBM for Iceland. The differences between the approach for handling emissions in DEHM and UBM include the distribution in the vertical, where DEHM has a vertical distribution profile depending on SNAP/GNFR category, whereas UBM does not. For the other Nordic countries, where NordicWelfAir emissions were available, the emissions from high stacks were given in separate point-source files, including the stack height, and this has been treated in a special way in UBM (plume-in-grid approach) to account for the vertical distribution. However, for Iceland these data are not available, and all emissions are gridded and emitted at surface level in the model.

Another issue with the Icelandic emissions is that the emissions from SNAP8 (national fishing fleet) has been reported (by Iceland) to EMEP with a geographic distribution, where all emissions occur in the harbours, not on the ocean. This is a choice made by the Icelandic emission authorities, but it means that the sources of SNAP8 emissions are placed very close to the population, as most of the Icelandic population lives close to the harbours and leading to an overestimation of concentration levels in these areas. It is not possible to adjust for this as it would require a redistribution of emissions based on the location of the fishing vessels that is beyond the scope of the present project.

Furthermore, Icelandic emissions of SOx are almost entirely dominated by hydrogen sulphite (H_2S) emissions from geothermal power plants allocated to SNAP5. In these plants, hydrogen sulfide (H_2S) is released during geothermal processing. In the atmosphere it is oxidized to SO_2 and further to sulphate. The chemical lifetime for the chemical reactions that convert H_2S to SO_2 by OH radical is approx. two days and probably longer at Iceland due to the cold climate, so this H_2S will not contribute to SO_2, and definitely not to sulphate over Iceland. All H_2S emissions are included in the SOx emission inventory as SO_2 by assuming that one molecule H_2S is equal one molecule SO_2. In the first version of the air quality and health modelling it was assumed that SOx was 95% SO_2 and 5% sulphate as is standard for combustion related SOx emissions. However, this led to very high modelled SO_2 concentrations and also influenced estimates of $PM_{2.5}$. After becoming aware of the hydrogen sulphide issue the air quality and health estimates were adjusted by post-processing. From the model runs for SNAP 5, 6 and 9 combined with the basic model run an estimate was made of the incorrect contribution from H_2S emissions, which was reported as SO_2 in the official emission inventory for Iceland and therefore treated as SO_2 in the models system, to the concentrations of SO_2, sulphate and nitrate by assuming that 100% of the contributions from SNAP5, 6 and 9 to these three compounds are coming from H_2S emissions and with this assumption it is possible to adjust all model results.

The NordicWelfAir emissions available for Norway for this project, was not complete for the SNAP sectors 1, 3, 4, 5, 8 and 9. Therefore, it was decided to use EMEP GNFR sectors for Norway instead for these specific emission sectors. It should be noted, that the EMEP data are similar, but with a more coarse spatial resolution, compared with the NordicWelfAir data.

In Figure 5.6–5.8 the total emissions of selected pollutants (SO_x, NO_x and $PM_{2.5}$) are shown for the Nordic countries for the aggregated SNAP sectors for 2019 and 2030.

The combined sectors of SNAP1 (Energy), SNAP3 (Industrial combustion) and SNAP4 (Industrial processes) are the emission sectors that contribute the most to SOx except for Iceland, where the combined sector of SNAP5 (Extraction etc,), 6 (Solvents) and 9 (Waste) show the largest contributions to SOx emissions due to geothermal energy production allocated to SNAP5. The largest source of SOx is from geothermal power plants, and SOx emissions are therefore dominated by hydrogen sulphide emissions.

SNAP7 (Road transport) contributes the most to NO_x in 2019 but decreases towards 2030 where other sectors also contribute significantly. SNAP8 (off-road) also contributes significantly to NOx. For Iceland these emissions are dominated by fishing vessels. They are not geographically correct distributed in the EMEP emission inventory as all emission are allocated to harbour areas and not where most of the emissions take place at sea.

SNAP2 (Residential combustion) represents almost entirely emissions from wood burning in wood stoves in Nordic countries and contributes the most to $PM_{2.5}$ emissions except for Iceland since woodstoves are not commonly used in Iceland.

There is a reduction for all countries and pollutants from 2019 to 2030.

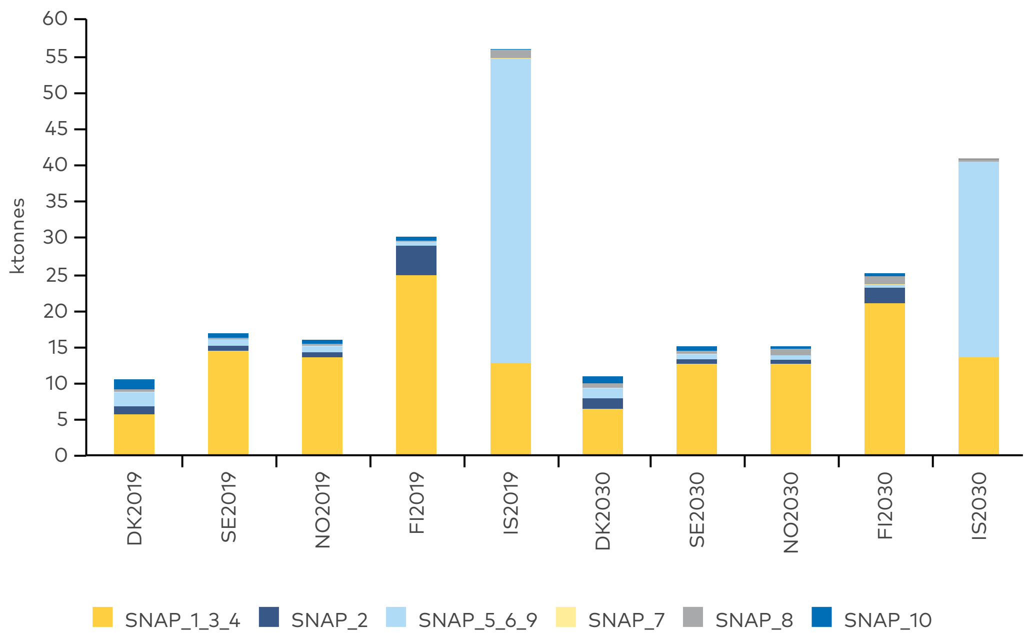


Figure 5.6. Emissions of SO_x in the Nordic countries for the aggregated SNAP sectors for 2019 and 2030.

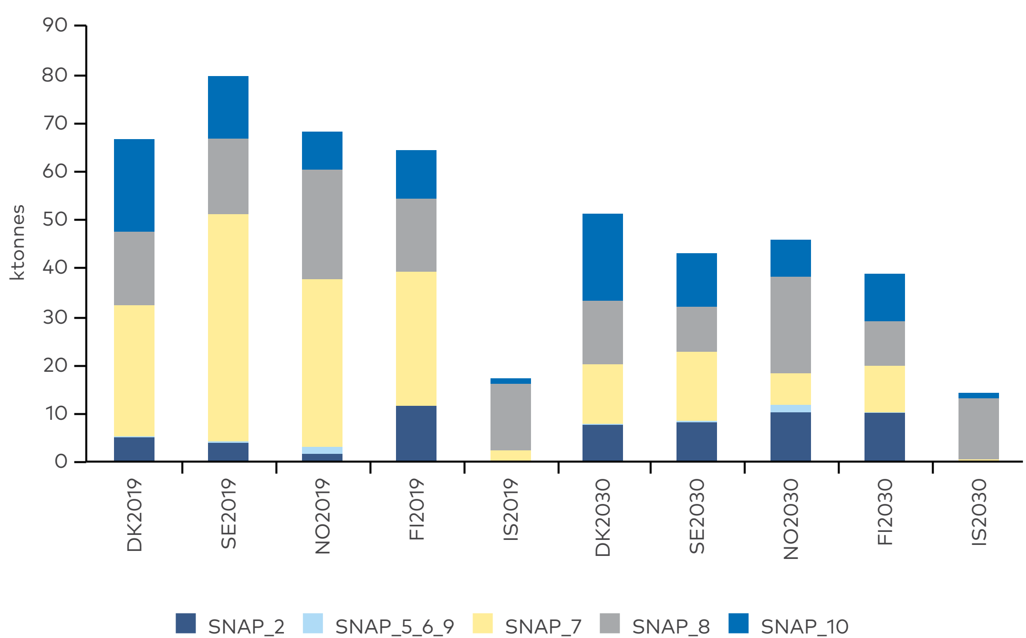


Figure 5.7. Emissions of NO_x in the Nordic countries for the aggregated SNAP sectors for 2019 and 2030.

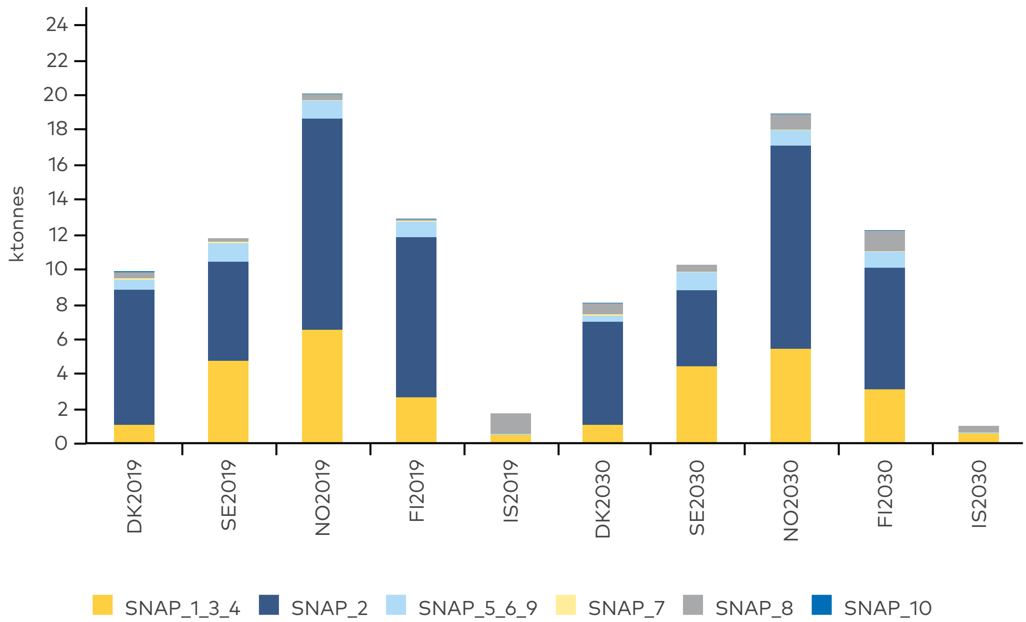


Figure 5.8. Emissions of $PM_{2.5}$ in the Nordic countries for the aggregated SNAP sectors for 2019 and 2030.

In Appendix 2 the numbers behind the figures 5.6–5.8 are given.

An example of the final geographical variation of NO_x emissions is given in Figure 5.9.

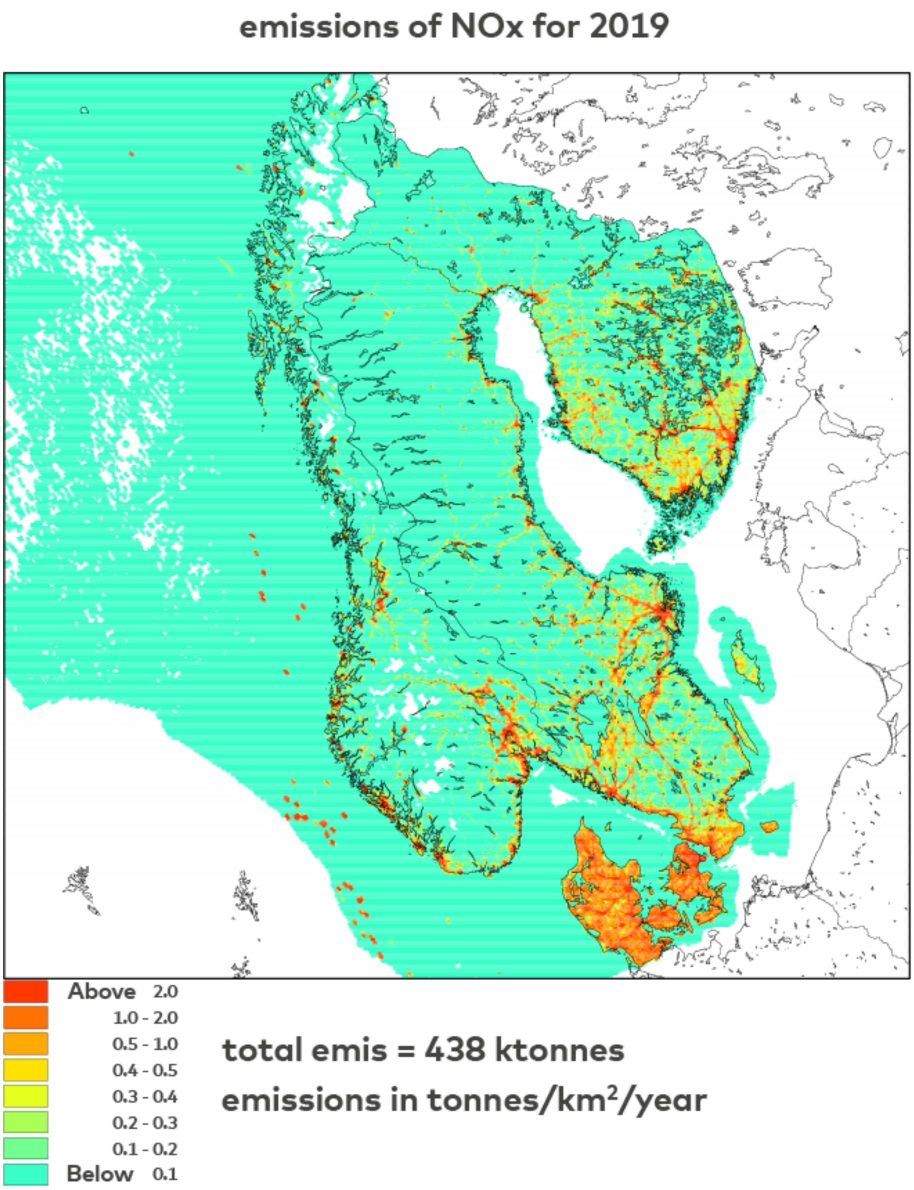


Figure 5.9. An example of the geographical variation of NO_x emissions in Denmark, Norway, Sweden and Finland.

5.3 Regional concentrations compared with WHO AQG

To limit the presentation of pollutants and statistical parameters, the following focuses on pollutants and parameters that pose the largest risk for impacts on human health from air pollution. These pollutants and parameters are annual mean concentrations of $PM_{2.5}$ and NO_2 together with peak season concentrations of ozone, the latter defined as the average of daily maximum 8-hour mean O_3 concentrations in the six consecutive months with the highest six-month running-average O_3 concentration. The new WHO guidelines for annual mean of $PM_{2.5}$ is 5 µg/m^3, for annual mean of NO_2 it is 10 µg/m^3, and for peak ozone it is 60 µg/m^3. In the following figures, concentrations for 2019 and 2030 are visualised side-by-side for each pollutant to present the development in concentrations from 2019 to 2030.

The selected cities are labelled with magenta colour if the concentration at the grid cell of the city is exceeding the WHO guideline, otherwise, labelled with black colour. It is the DEHM interpolated values to the observational site, which can be thought of as the nearest grid cell to the measurement location that represent the city. Further, the WHO guideline values are marked as a black line in the colour bar of the legend.

Note that the results presented in these figures are regional concentrations which represent the background condition of the selected cities. The actual urban background concentrations over the cities will be slightly higher for $PM_{2.5}$ and NO_2 (lower for O_3), and for hotspots like busy streets, concentrations will be even higher for $PM_{2.5}$ and NO_2 (lower for O_3).

Annual mean of NO_2

In figure 5.10, the annual mean concentrations of NO_2 in the model domain are visualised for the model simulation of 2019 and 2030. The WHO guideline for the annual mean concentration of NO_2 is 10 mg/m^3.

There is a general gradient from south to north with higher concentrations in Denmark and southern Sweden. It is obvious that the concentration in most areas of the model domain are below the WHO guideline, and the exception is the few big cities. Ship emissions can also be seen to cause elevated concentrations along ship routes, especially in the inner Danish waters, and at the biggest harbors. There is a general decrease in concentrations from 2019 to 2030.

Five of the selected cities are exceeding the WHO guideline in 2019: København, Trondheim, Stockholm, Oslo and Reykjavík, and only Reykjavík in 2030.

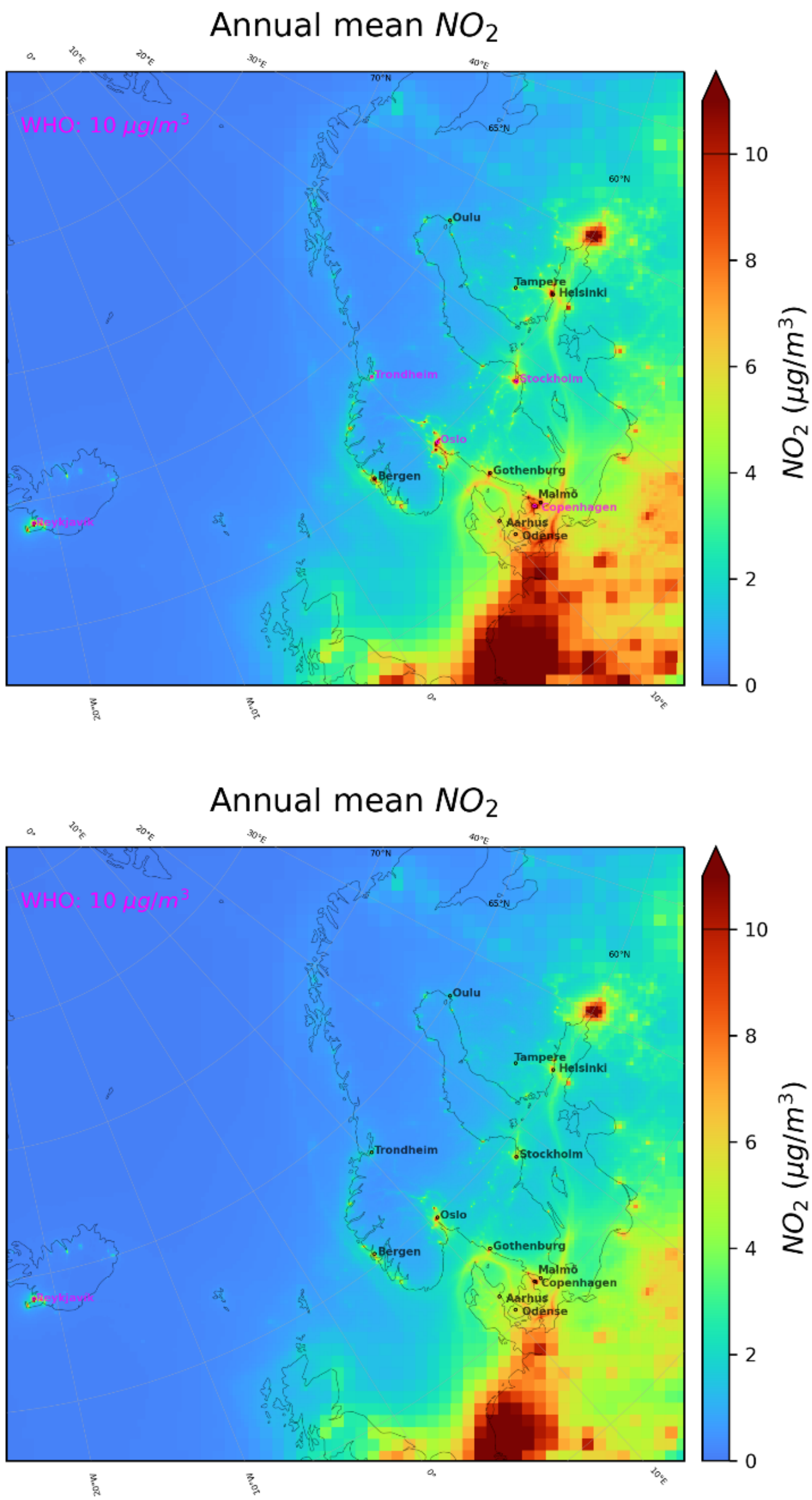


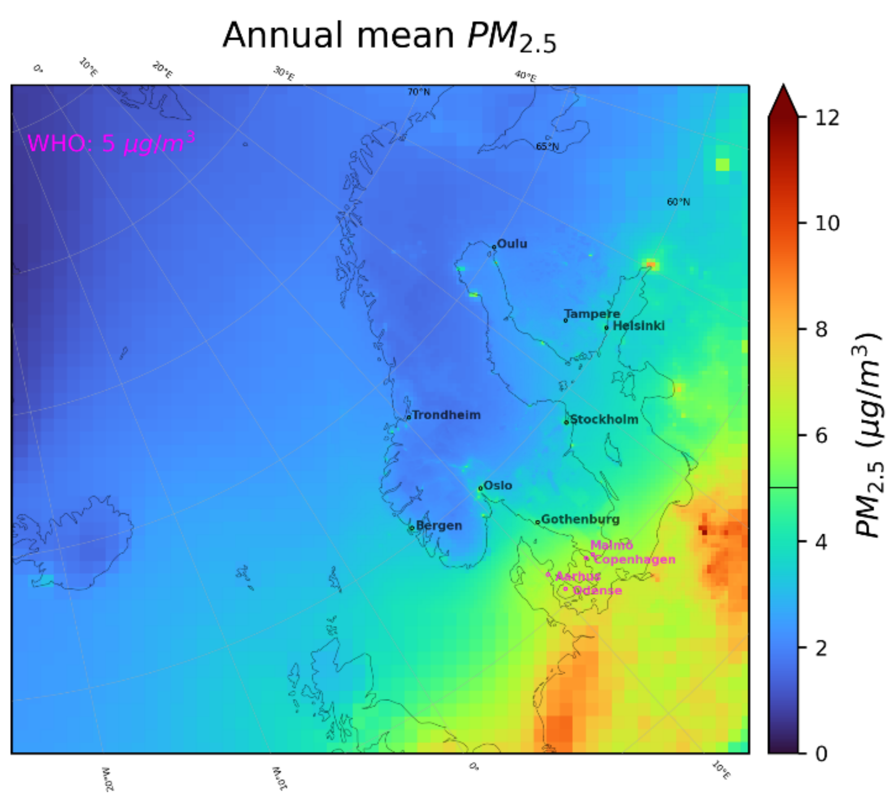
Figure 5.10. Annual mean concentrations of NO_2 for 2019 (left) and 2030 (right). The WHO 2021 guideline value is 10 mg/m^3 and it is exceeded in the selected cities labelled in magenta.

Annual mean of $PM_{2.5}$

In Figure 5.11, the annual mean concentrations of $PM_{2.5}$ in the model domain are visualised for the model simulation of 2019 and 2030. The WHO guideline for the annual mean concentration of $PM_{2.5}$ is 5 mg/m^3. The general concentration gradient also shows a decrease from south to north in the domain, and as for NO_2, there is a decrease in concentrations from 2019 to 2030.

There are significant exceedances of the WHO guidelines in 2019 for Denmark and southern Sweden. There are still exceedances in 2030, but they are much smaller.

In four of the selected cities, the concentrations exceed the WHO guideline in 2019 located in Denmark (København, Aarhus, Odense) and southern Sweden (Malmö). This is reduced to three in 2030 in the same countries as Aarhus no longer exceeds the guideline in 2030 based on the model simulations.



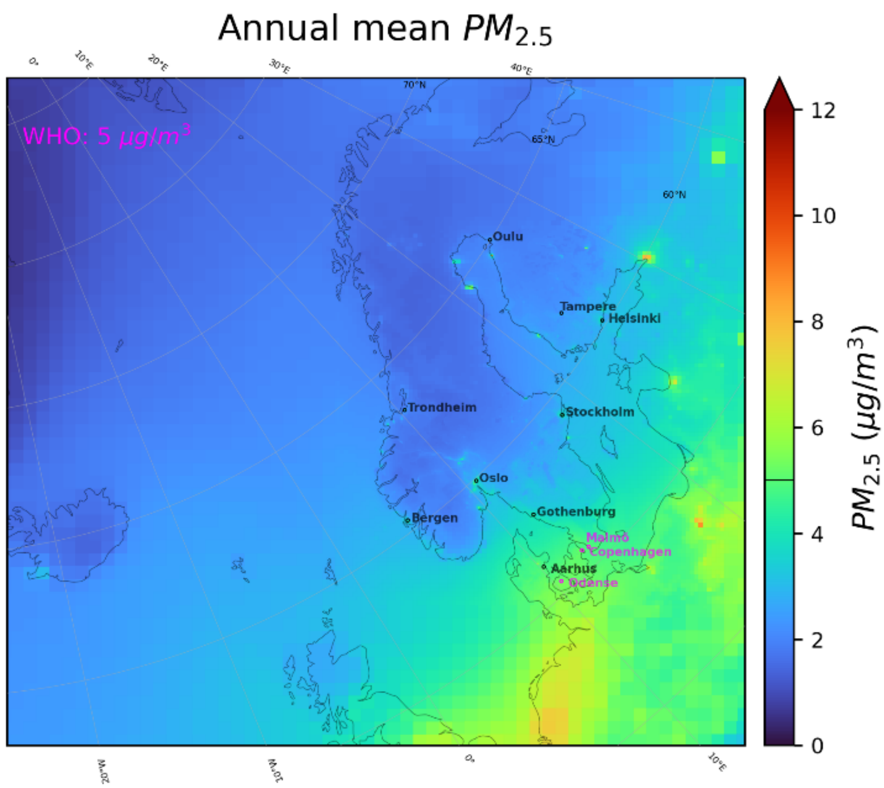


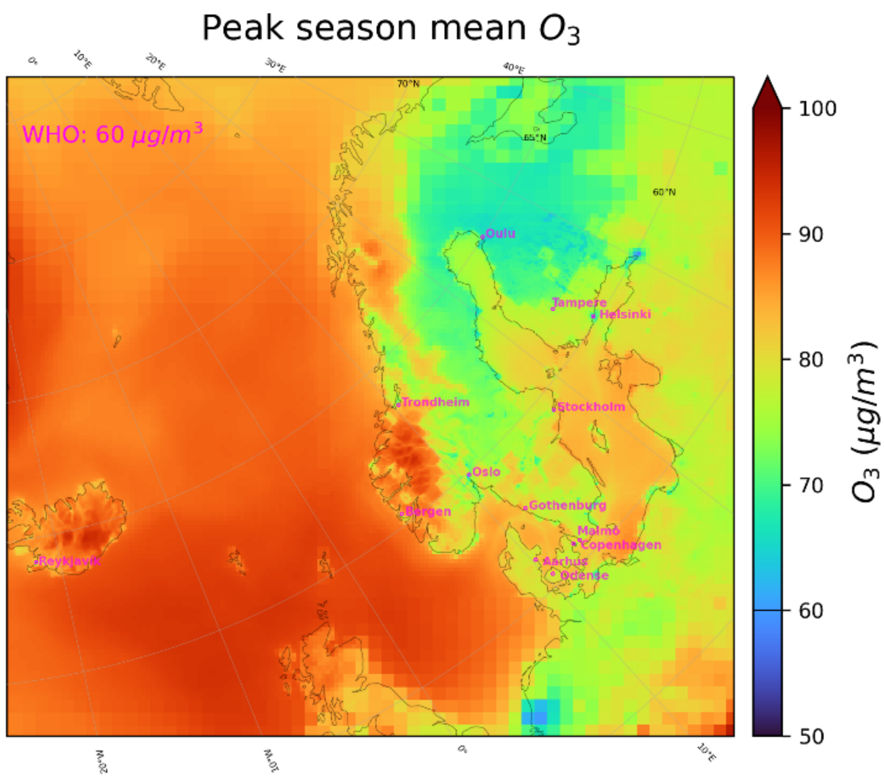
Figure 5.11. Annual mean concentrations of $PM_{2.5}$ for 2019 (left) and 2030 (right). The WHO 2021 guideline value is 5 mg/m^3 and it is exceeded in the selected cities labelled in magenta.

Peak ozone

Figure 5.12 shows the peak seasonal concentrations of O_3. The WHO guideline concentration is 60 mg/m^3, and this is exceeded in the model simulation in most parts of the domain both in 2019 and 2030. Peak ozone concentrations show a very slight decrease towards 2030, especially for Iceland and Finland.

Concentrations of O_3 are not higher in big cities, but actually lower compared with rural areas, due to the titration effects of NO_x where NO_x emissions from e.g. traffic converts ozone to NO_2.

The concentrations in all the selected cities are exceeding the WHO guideline for peak season mean ozone in both 2019 and 2030.



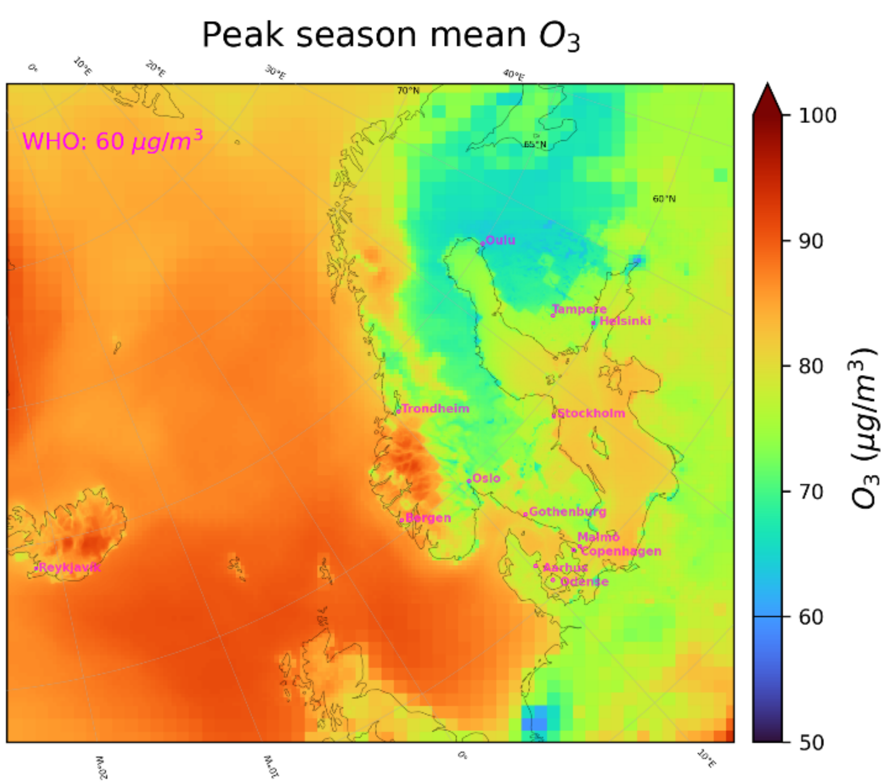


Figure 5.12. Peak season concentrations of O_3 for 2019 (left) and 2030 (right). The WHO 2021 guideline value is 60 mg/m^3 and it is exceeded in the selected cities labelled in magenta.

Other pollutants

A similar analysis as presented above has been carried out for the pollutants PM_{10}, CO and SO_2.

All selected cities have concentration levels that are below the WHO guideline in 2019 and 2030 for annual PM_{10} (15 µg/m^3) and peak PM_{10} (45 µg/m^3 as annual 99th percentile of 24h-mean).

All selected cities have concentration levels that are below the WHO guideline for CO in 2019 and 2030 (4 mg/m^3 as annual 99th percentile of 24h-mean).

All selected cities were below the WHO guideline for peak concentration of SO_2 in both 2019 and 2030 (40 µg/m^3 as annual 99th percentile of 24h-mean).

Modelled annual mean concentrations versus observations in 2019 and modelled annual mean concentrations in 2030

In Table 5.3 the modelled annual mean concentrations of NO_2, O_3 and $PM_{2.5}$ for the selected cities are compared with observations in 2019 at urban background stations. The modelled annual means for 2030 are also shown. The modelled concentrations represent the grid cells (5.6 km x 5.6 km) where the urban background measurement stations are located.

Table 5.3. Annual mean observed (2019) and modelled concentrations of urban background NO_2, O_3, and $PM_{2.5}$ (2019 and 2030). Unit µg/m^3, all model results from the DEHM model.

City	NO_2			O_3			$PM_{2.5}$		
	Observation (2019)	DEHM (2019)	DEHM (2030)	Observation (2019)	DEHM (2019)	DEHM (2030)	Observation (2019)	DEHM (2019)	DEHM (2030)
København	11.9	12.0	8.6	62.3	61.8	63.4	10.9	6.7	5.3
Aarhus	11.4	7.2	5.4	56.3	64.3	64.6	9.4	6.1	4.9
Odense	9.9	6.9	5.3	60.0	64.6	64.6	-	6.5	5.3
Stockholm	10.4	14.4	7.2	54.9	58.7	63.6	4.8	5.4	4.7
Malmö	10.3	10.0	6.5	59.8	64.0	65.8	9.7	6.4	5.2
Göteborg	17.0	10.5	6.1	54.4	63.1	65.5	7.0	5.2	4.4
Helsinki	14.9	9.4	5.6	51.6	56.1	58.1	5.6	4.0	3.4
Tampere	9.9	5.6	3.2	53.7	57.6	58.3	3.9	3.2	2.7
Oulu	10.4	4.0	2.3	48.9	54.2	54.4	-	2.8	2.4
Reykjavík	9.3	13.4	12.9	-	60.5	59.3	7.9	4.3	2.9
Oslo*	19.2	14.9	*7.3*	43.2	52.6	*57.6*	7.6	5.0	*4.4*
Bergen*	18.8	11.0	*5.7*	53.0	62.8	*65.7*	5.8	4.4	*3.9*
Trondheim*	18.2	10.0	*4.7*	-	57.8	*61.0*	6.2	3.9	*3.5*

* See note in text.

As expected, the DEHM model in general underestimates the NO_2 concentrations when compared with observations obtained at urban background stations as the DEHM model has a coarser resolution compared with UBM. The DEHM model predicts a considerable decrease in concentrations from 2019 to 2030 as a result of emission reductions.

As expected, the DEHM model overestimates the O_3 concentrations when compared with observations obtained at urban background stations. Furthermore, the DEHM model predicts a slight increase in concentrations from 2019 to 2030, which can be understood by the decrease in NO_x emissions leading to less NO_x available for depletion of O_3 over the cities.

Finally, also as expected, the regional scale DEHM model underestimates the $PM_{2.5}$ concentrations when compared with observations obtained at urban background stations. Also for $PM_{2.5}$, it is seen that the DEHM model predicts a small decrease in concentrations from 2019 to 2030 as a result of emissions reductions. Note that observed $PM_{2.5}$ level of 7.9 µg/m^3 in 2019 in Reykjavik is relatively high compared with observed levels in 2021 of approx. 5 µg/m^3 probably due to influence of volcanic emissions in 2019.

In general air pollution models tend to underestimate the concentration of $PM_{2.5}$ when comparing with measurements. In international literature, this is referred to as "the mass closure problem" or "the missing mass problem". As the field of air pollution research evolves, more relevant processes are included in the models and natural and anthropogenic emissions are described in higher detail, this mass gap is slowly reduced. It is likely that part of the "missing mass" is water in the particles which is typically not described by the models. Processes that are not fully described in the models, such as the formation of secondary organic particles (SOA) can also contribute to the problem, as can missing sources such as e.g. mineral dust and more importantly for urban areas, re-suspended dust.

Various attempts have been made in recent years to adjust for the lack of mass in the Danish National Air Quality Monitoring Programme, as this has an impact on the estimation of health effects and external costs. Results of analyses of measurements and model results for $PM_{2.5}$ have shown that the gap between the concentrations predicted by the models and obtained with measurements corresponds to a missing mass of approx. 33% of the modelled concentration (Ellermann et al., 2022). This means that based on the available Danish measurements – and assuming that these are representative for the country as a whole - $PM_{2.5}$ concentrations are underestimated by approx. 33% in Denmark on average in space and time. It has not been analysed in this project, whether this is also the difference in the other Nordic countries.

It is important to keep this in mind when comparing model calculated concentrations of $PM_{2.5}$ with the WHO guidelines. In connection with the calculation of future air quality in 2030, it is not known what the underestimation is, as there are no measurements for 2030. However, it is very likely that the modelled concentrations of $PM_{2.5}$ in 2030 are also underestimated.

In the subsequent modelling of urban background concentrations and health effects for Oslo, it became evident that something was wrong with the aggregation of projected emissions for 2030 as well as with the geographic distribution of emissions leading to a large unexpected increase in concentrations and health effects from 2019 to 2030. The official projection of the energy sector includes both public power and emissions from oil and gas production in the Norwegian Sea/North Sea, and it was not possible to split the official projection up into these two subsectors. The latter sector constitutes a very large part in Norway as opposed to all other European countries, and these emissions were allocated with the same geographic distribution as power plants leading to high emissions in Oslo from the public power plant sector. The way DEHM handles elevated point sources (like e.g. power plants) in the energy sector compared with the simpler model UBM, results in less influence on the surface concentrations due to this erroneous distribution of the emissions from oil and gas production, and therefore the regional background concentrations are predicted to decrease from 2019 to 2030 as seen in Table 5.3, even though the energy sector emissions are too high on land. As this introduces an uncertainty on results for 2030 for the Norwegian cities, we have marked the DEHM model results in *italic* in Table 5.3.

6. Urban background concentrations in selected cities in 2019 and 2030

In this chapter, we compare results from the UBM model with observations to indicate the uncertainty on model results. Urban background observations are compared with the UBM model results for 2019 for the selected cities. Further, DEHM model results are also shown as DEHM concentrations are used as input to the UBM calculations. Model results for 2030 are also shown, and the average concentration over the selected city masks are given together with the spatial distribution of concentrations over the selected cities.

6.1 Evaluation of model results against measurements in 2019

In Table 6.1, observed concentrations at urban background stations are compared with modelled concentrations for the stations from DEHM and UBM for 2019. Modelled DEHM and UBM concentrations for 2030 for the stations are also shown. Note that emissions on 1 km x 1 km were not available for Reykjavík as previously described and UBM calculations are based on EMEP emissions that have a coarser resolution. UBM calculations are not available for 2030 for Norwegian cities due to problems on projected emissions as explained in the previous chapter.

Table 6.1. Comparison of observations of NO_2, O_3 and $PM_{2.5}$ and concentrations modelled for the station location with DEHM and UBM for 2019 and 2030. Annual values in µg/m^3.

		NO_2					O_3					$PM_{2.5}$				
City	**Station**	**Obs. 2019**	**DEHM 2019**	**DEHM 2030**	**UBM 2019**	**UBM 2030**	**Obs. 2019**	**DEHM 2019**	**DEHM 2030**	**UBM 2019**	**UBM 2030**	**Obs. 2019**	**DEHM 2019**	**DEHM 2030**	**UBM 2019**	**UBM 2030**
København	DK0045A	11.9	12.0	8.6	22.9	18.1	62.3	61.8	63.4	50.7	52.8	10.9	6.7	5.3	8.7	7.0
Aarhus	DK0056A	11.4	7.2	5.4	13.5	11.1	56.3	64.3	64.6	56.0	56.6	9.4	6.1	4.9	7.5	6.1
Odense	DK0046A	9.9	6.9	5.3	11.3	9.1	60.0	64.6	64.6	58.9	59.4	n.a	6.5	5.3	7.7	6.3
Stockholm	SE0022A	10.4	14.4	7.2	30.7	24.1	54.9	58.7	63.6	43.2	45.7	4.8	5.4	4.7	8.0	7.0
Malmö	SE0001A	10.3	10.0	6.5	18.4	12.6	59.8	64.0	65.8	54.6	58.0	9.7	6.4	5.2	8.0	6.6
Göteborg	SE0004A	17.0	10.5	6.1	19.3	13.2	54.4	63.1	65.5	53.1	56.4	7.0	5.2	4.4	6.7	5.7
Helsinki	FI00425	14.9	9.4	5.6	31.8	27.1	51.6	56.1	58.1	39.7	41.2	5.6	4.0	3.4	6.1	5.4
Tampere	FI00801	9.9	5.6	3.2	12.1	5.1	53.7	57.6	58.3	50.9	55.5	3.9	3.2	2.7	3.9	3.3
Oulu	FI00301	10.4	4.0	2.3	14.7	5.3	48.9	54.2	54.4	43.0	49.6	n.a	2.8	2.4	4.0	3.3
Reykjavík	IS0006A	9.3	13.4	12.9	17.9	15.6	n.a	60.5	59.3	57.4	57.0	7.9	4.3	2.9	3.1	2.7
Oslo	NO0073A	23.0	14.9	*7.3*	27.1	n.a	43.2	52.6	*57.6*	41.4	n.a	7.6	5.0	*4.4*	11.5	n.a
Bergen	NO0120A	18.8	11.0	*5.7*	26.3	n.a	53.0	62.8	*65.7*	49.7	n.a	5.8	4.4	*3.9*	8.2	n.a
Trondheim	NO0089A	18.2	10.0	*4.7*	22.7	n.a	n.a	57.8	*61.0*	49.2	n.a	6.2	3.9	*3.5*	8.6	n.a

The UBM model overestimates the calculated NO_2 concentrations at most of the selected cities, especially for København, Malmö, Helsinki, Reykjavík, Bergen and Stockholm. This also results in an underestimation of O_3 at several of the same cities, due to the chemical reactions involving NO_2 and O_3. For $PM_{2.5}$, there are both examples of overestimation and underestimation, when UBM results is compared with the observations.

The data from Table 6.1 are also presented in Figure 6.1 as scatter plots for easier visualisation of the bias and spatial correlation between observations and model results.

As expected the modelled urban background concentrations of $PM_{2.5}$ and NO_2 from UBM are higher than the corresponding DEHM results due to the higher spatial resolution of UBM of 1 km x 1 km compared with the spatial resolution of DEHM of 5.6 km x 5.6 km. This picture is seen to be opposite for O_3 which is also as expected.

In the scatter plot showing observed and modelled NO_2 (Figure 6.1 left) it can be seen that the model (yellow triangles) predicts a higher range in concentration levels (from ~10–30 $\mu g/m^3$) than shown in the observations (~10–20 $\mu g/m^3$) and that the model in general overestimates the concentration. The comparison for O_3 (Figure 6.1 centre) shows a modelled range (from ~40–60 $\mu g/m^3$) that is comparable to the observed range (from ~45–65 $\mu g/m^3$) but the model tends to underestimate the concentrations. The scatter plot for $PM_{2.5}$ (Figure 6.1 right) shows similar ranges for modelled and measured data points with some overestimation of the lowest observed values and some underestimation of the highest observed values.

The urban background concentrations modelled with UBM show a decrease from 2019 to 2030 for NO_2 and $PM_{2.5}$, resulting from the decreasing emissions, which also can be seen in the DEHM model results.

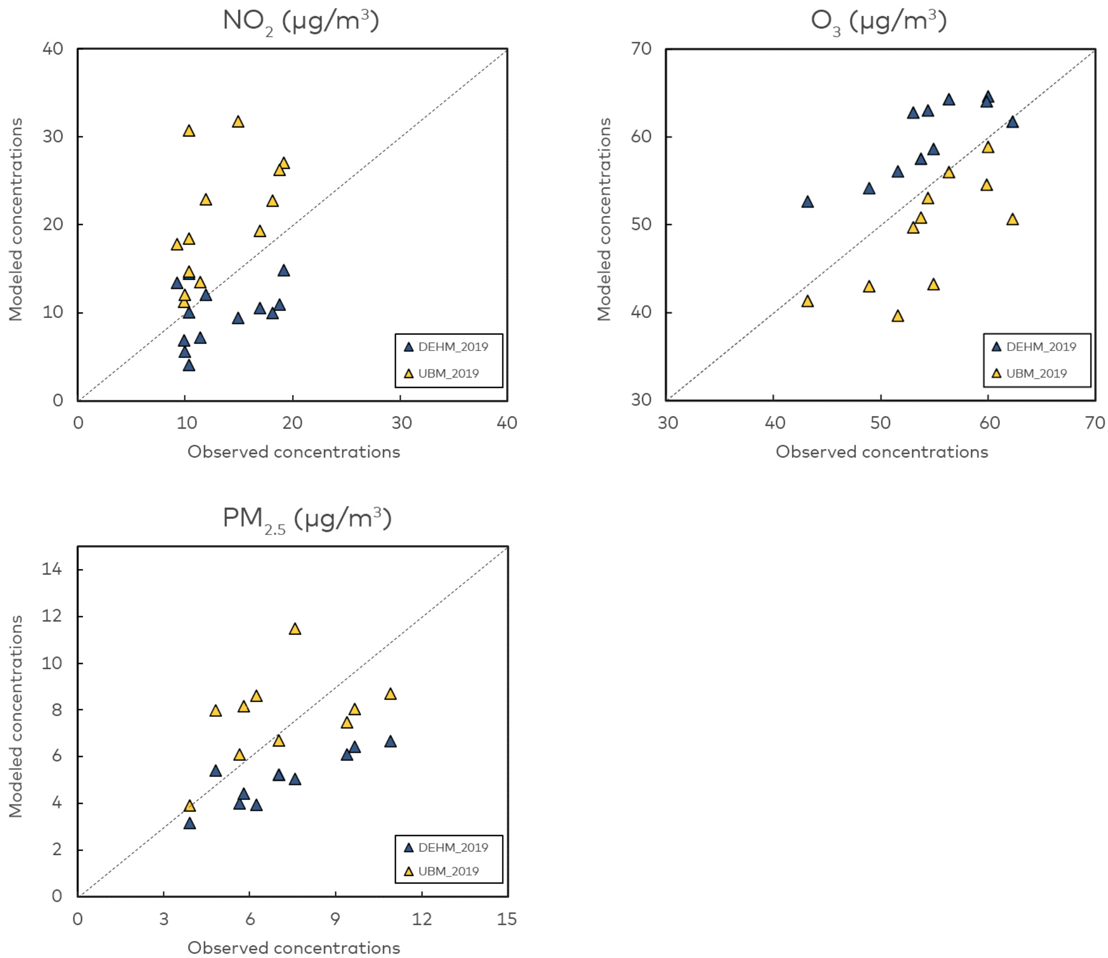


Figure 6.1. Scatter plots showing pairwise comparison of observations and UBM (yellow) and DEHM (blue) model results in 2019. Left is NO_2, centre is O_3 and right is $PM_{2.5}$.($PM_{2.5}$ for Reykjavík not shown due to post-processing).

6.2 Modelled average concentrations over selected cities in 2019 and 2030

The average concentrations of the grid cells included in the city masks are shown in Table 6.2.

Table 6.2. Average concentrations over selected cities in 2019 and 2030 calculated with the UBM model. Units are µg/m^3.

	NO_2		O_3		$PM_{2.5}$	
City	**2019**	**2030**	**2019**	**2030**	**2019**	**2030**
København	21	17	52	54	8.4	6.8
Aarhus	11	9	58	59	7.3	6.0
Odense	11	9	59	60	7.8	6.3
Stockholm	19	14	52	54	6.6	5.7
Malmö	15	11	58	60	7.8	6.3
Göteborg	13	10	58	59	6.1	5.1
Helsinki	24	19	45	47	5.4	4.7
Tampere	5	3	56	57	3.3	2.8
Oulu	3	2	53	53	2.6	2.3
Reykjavík	10	9	64	63	2.6	2.3
Oslo	17	n.a.	50	n.a.	7.6	n.a.
Bergen	10	n.a.	63	n.a.	4.9	n.a.
Trondheim	6	n.a.	63	n.a.	3.7	n.a.

6.3 Concentration maps for selected cities in 2019 and 2030

Concentration maps for the selected cities in each of the Nordic countries for 2019 and 2030 are presented in the following for annual means of NO_2, O_3 and $PM_{2.5}$. The dashed lines displayed in the maps are a rough indication of the extent of the city boundaries as applied in this analysis. Missing maps reflect data limitations as described previously.

General assessment

The geographic distribution of concentrations in the cities is seen to be influenced by population density and thereby associated emission density as well as large road transport corridors and ship traffic. Concentrations of NO_2 and $PM_{2.5}$ are decreasing for all cities from 2019 to 2030, whereas concentrations of O_3 are slightly increasing.

Urban background NO_2 and $PM_{2.5}$ and WHO AQG

The UBM model generally overestimates NO_2 concentrations and caution should be taken when comparing modelled concentrations with WHO AQG. Therefore, an estimate of compliance with the WHO AQG in 2030 also considers the present observed concentrations in 2019. In the following focus is on the capital cities that generally have the highest concentrations levels.

Based on the observed level of NO_2 in 2019 at the urban background station in København (11.9 µg/m^3, 9.8 µg/m^3 in 2021) and the modelled decrease in concentrations towards 2030 of 19%, it is likely that concentrations will be under the WHO AQG of 10 µg/m^3 in 2030 at this station. The average modelled concentration over the mask of København of 17 µg/m^3 in 2030 seems overestimated.

Based on the observed level of NO_2 in 2019 at the urban background station in Stockholm (10.4 µg/m^3, 11.0 µg/m^3 in 2021) and the modelled decrease in concentrations towards 2030 of 26%, it is likely that concentrations will be under the WHO AQG of 10 µg/m^3 in 2030 at this station. The average modelled concentration over the mask of Stockholm of 24 µg/m^3 in 2030 seems overestimated.

Based on the observed level of NO_2 in 2019 at the urban background station in Helsinki (14.9 µg/m^3, 12.4 µg/m^3 in 2021) and the modelled decrease in concentrations towards 2030 of 21%, it is likely that concentrations will be slightly under the WHO AQG of 10 μg/m^3 in 2030 at this station. The average modelled concentration over the mask of Helsinki of 19 μg/m^3 in 2030 seems too high.

Based on the observed level of NO_2 in 2019 at the urban background station in Reykjavík (9.3 μg/m^3, 8.2 μg/m^3 in 2021) and the modelled decrease in concentrations towards 2030 of 13%, it is likely that concentrations will remain under the WHO AQG of 10 μg/m^3 in 2030 at this station. The average modelled concentration over the mask of Reykjavík is 9 μg/m^3 in 2030.

The comparison of observed and modelled concentrations to $PM_{2.5}$ showed some overestimation for the lowest observed values and some underestimation of the highest observed values. Based on the observed level of $PM_{2.5}$ in 2019 at the urban background station in København (10.9 μg/m^3, 8 μg/m^3 in 2021) and the modelled decrease in concentrations towards 2030 of 20%, it is likely that concentrations will be slightly over the WHO AQG of 5 μg/m^3 in 2030 at this station. The average modelled concentration over the mask of København is 7 μg/m^3 in 2030.

Based on the observed level of $PM_{2.5}$ in 2019 at the urban background station in Stockholm (4.9 μg/m^3, 5.1 μg/m^3 in 2021) and the modelled decrease in concentrations towards 2030 of 13%, it is likely that concentrations will be under the WHO AQG of 5 μg/m^3 in 2030 at this station. The average modelled concentration over the mask of Stockholm is 7 μg/m^3 in 2030 seems to be overestimated.

Based on the observed level of $PM_{2.5}$ in 2019 at the urban background station in Helsinki (5.6 μg/m^3, 5.8 μg/m^3 in 2021) and the modelled decrease in concentrations towards 2030 of 15%, it is likely that concentrations will be under the WHO AQG of 5 μg/m^3 in 2030 at this station. The average modelled concentration over the mask of Helsinki is 7 μg/m^3 in 2030.

Based on the observed level of $PM_{2.5}$ in 2019 at the urban background station in Reykjavik (7.9 μg/m^3, 4.9 μg/m^3 in 2021) and the modelled decrease in concentrations towards 2030 of 27%, it is likely that concentrations will be under the WHO AQG of 5 μg/m^3 in 2030 at this station. The average modelled concentration over the mask of Reykjavík is 2.3 μg/m^3 in 2030.

Due to data limitations no modelled concentrations for 2030 are available for Oslo.

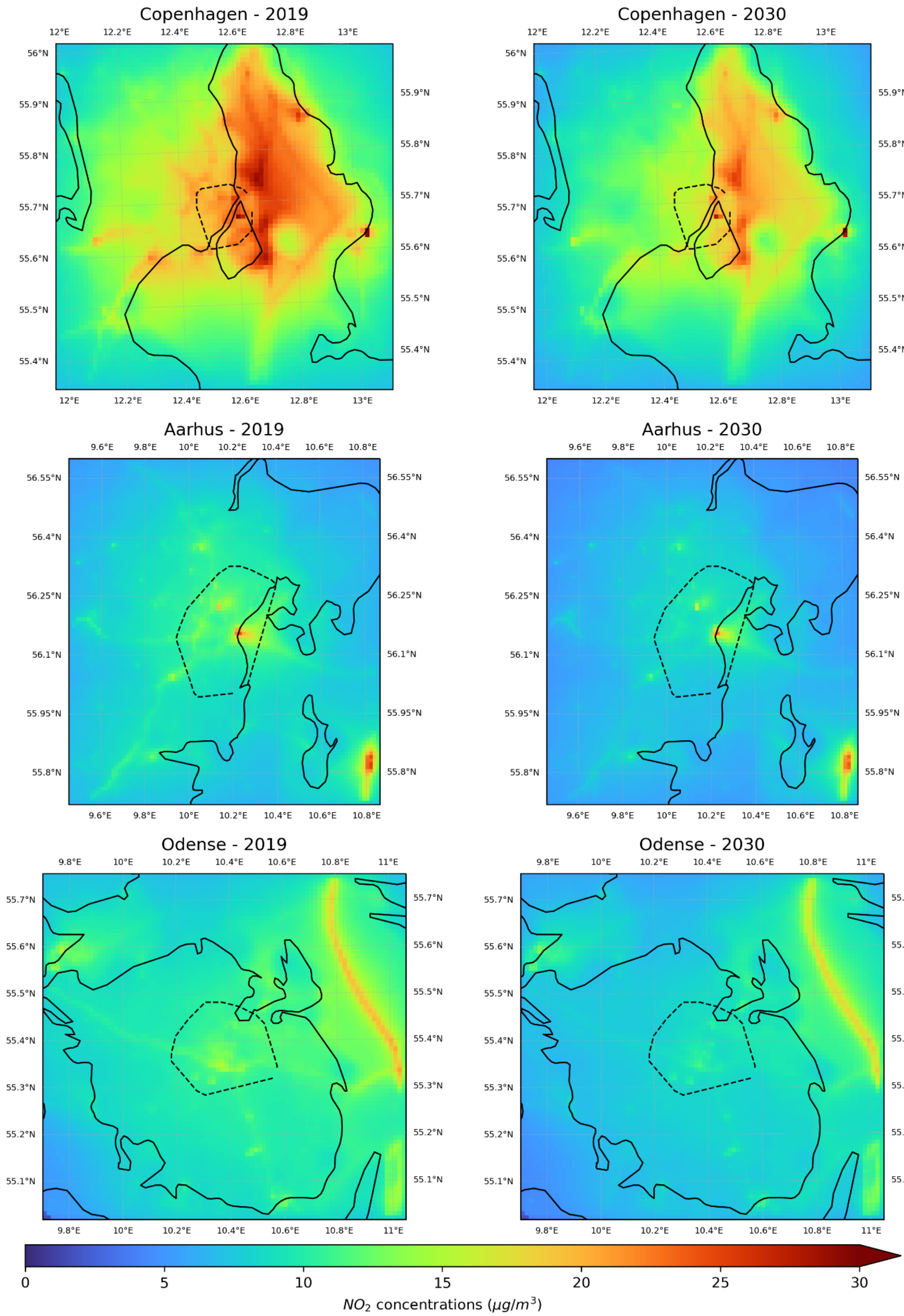


Figure 6.2. Concentration maps showing annual mean values of NO_2 for the Danish cities København (top panel), Aarhus (middle panel) and Odense (bottom panel) for 2019 (left column) and 2030 (right column). Dashed line indicates the extension of the city mask.

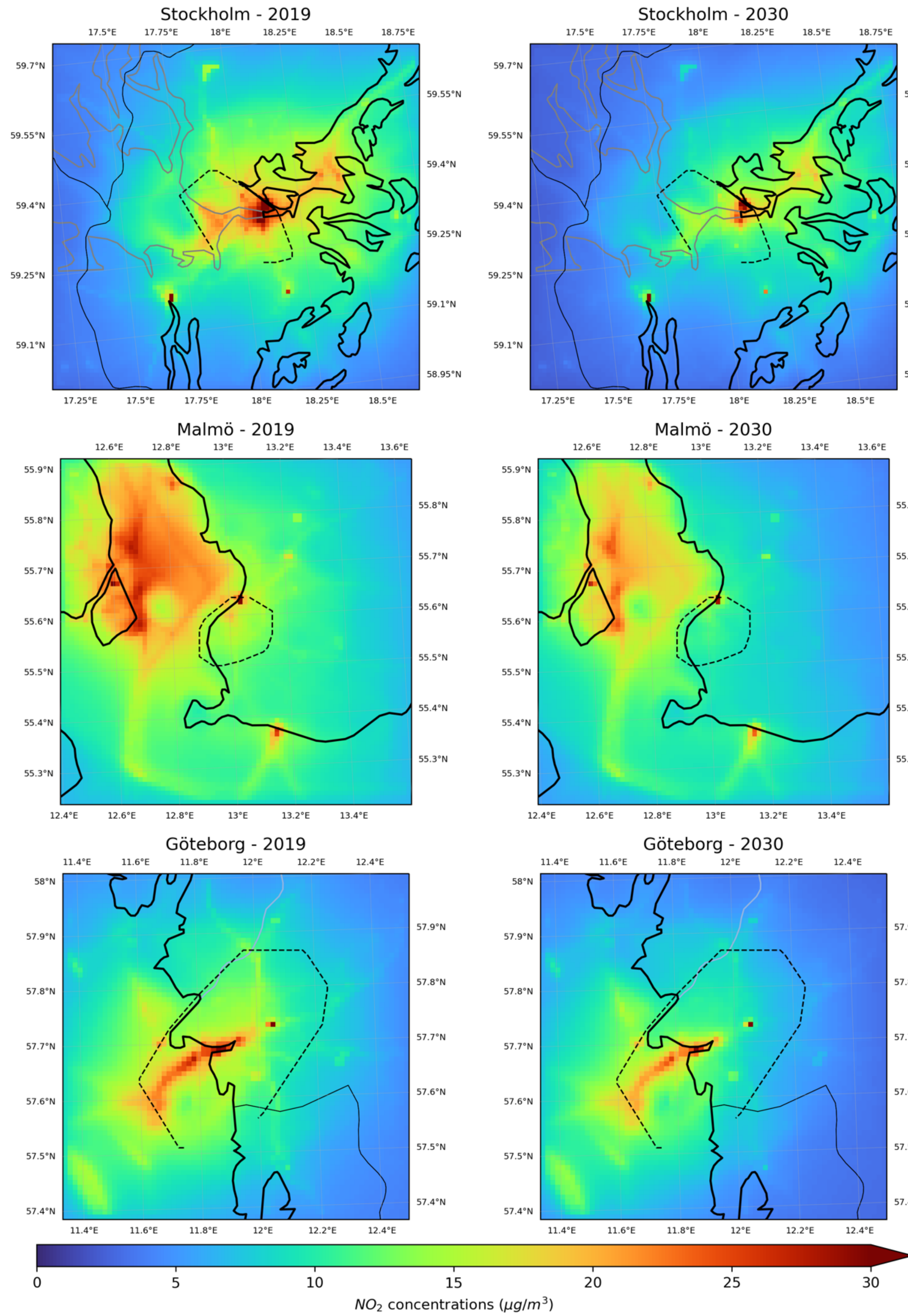


Figure 6.3. Concentration maps showing annual mean values of NO2 for the Swedish cities Stockholm (top panel), Malmö (middle pan-el), and Göteborg (bottom panel) for 2019 (left column) and 2030 (right column). Dashed line indicates the extension of the city mask.

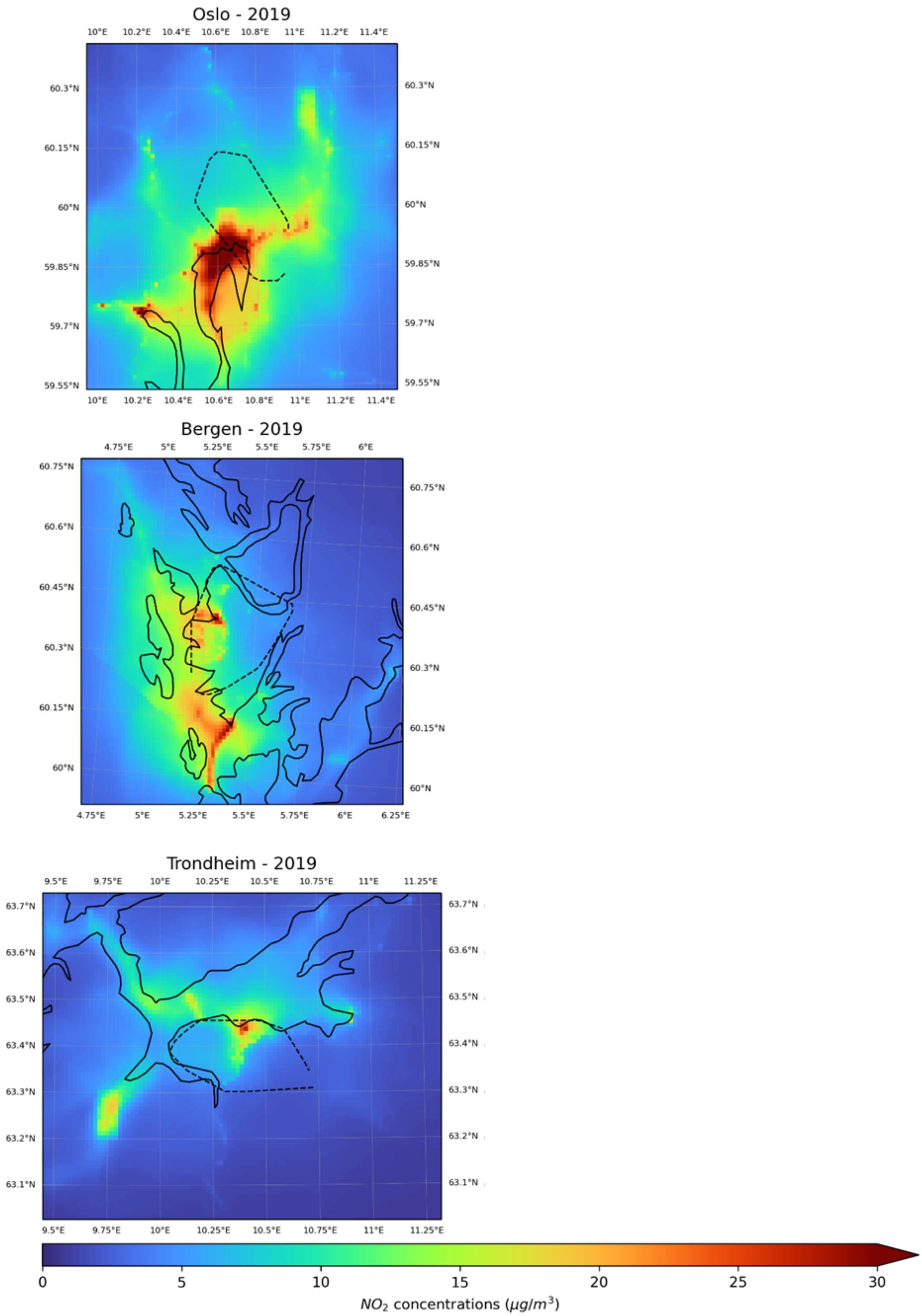


Figure 6.4. Concentration maps showing annual mean values of NO_2 for the Norwegian cities Oslo (top panel), Bergen (middle panel) and Trondheim (bottom panel) for 2019. Dashed line indicates the extension of the city mask.

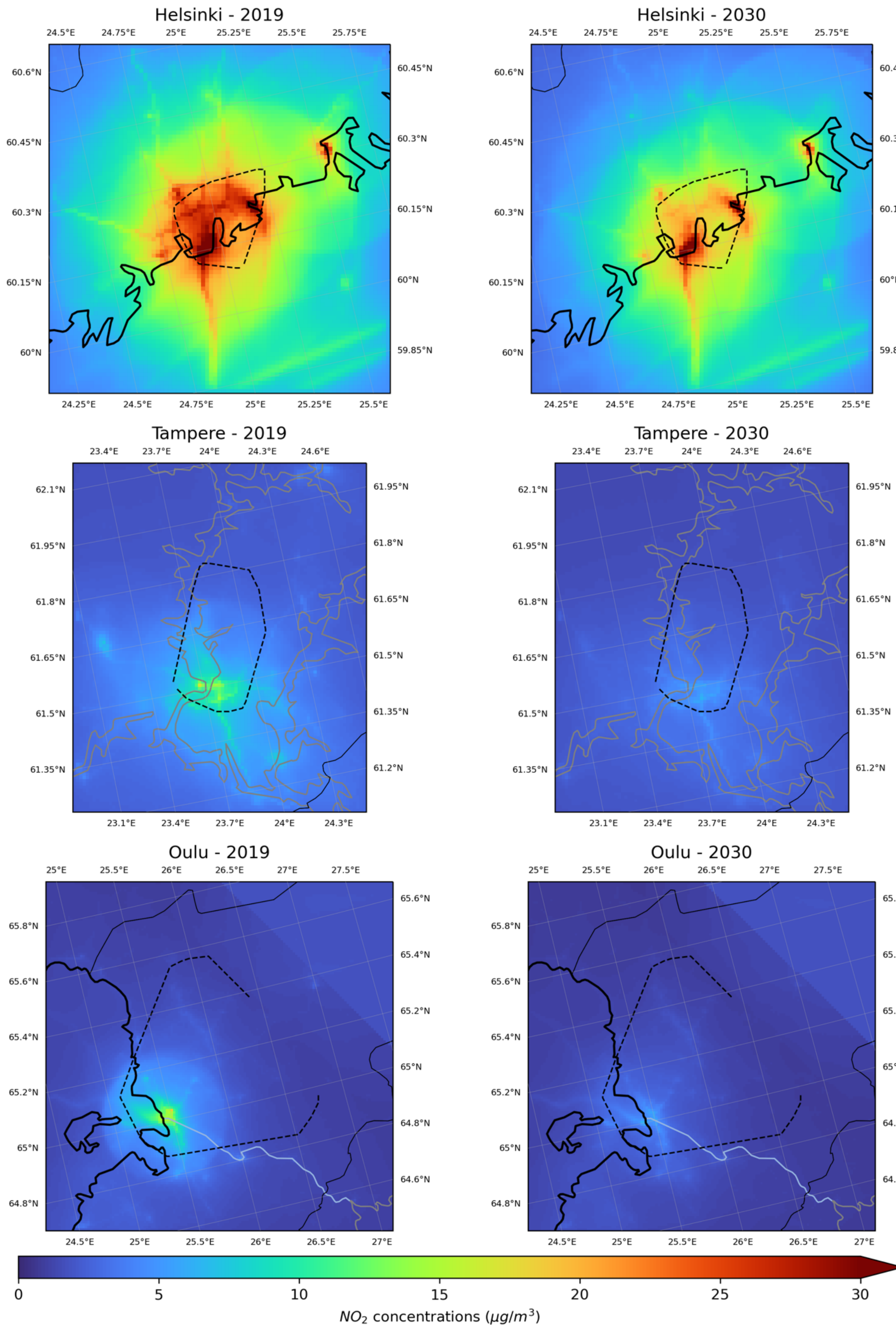


Figure 6.5. Concentration maps for annual means of NO_2 for Finnish cities for 2019 and 2030. Helsinki (top panel), Tampere (middle panel), and Oulu (bottom panel).

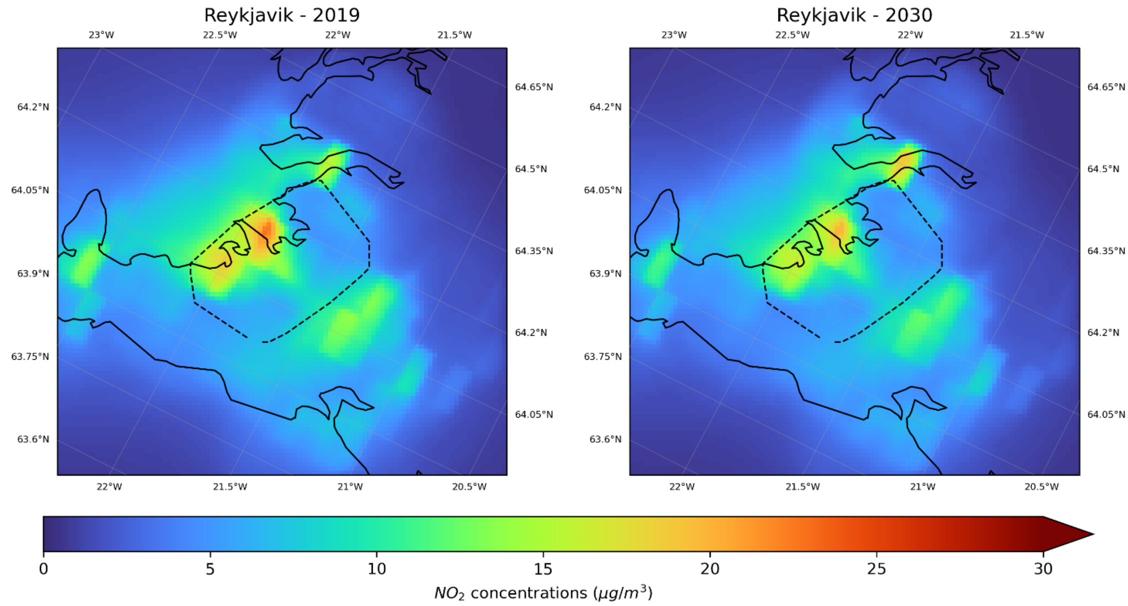


Figure 6.6. Concentration maps for annual means of NO_2 for Reykjavík for 2019 and 2030.

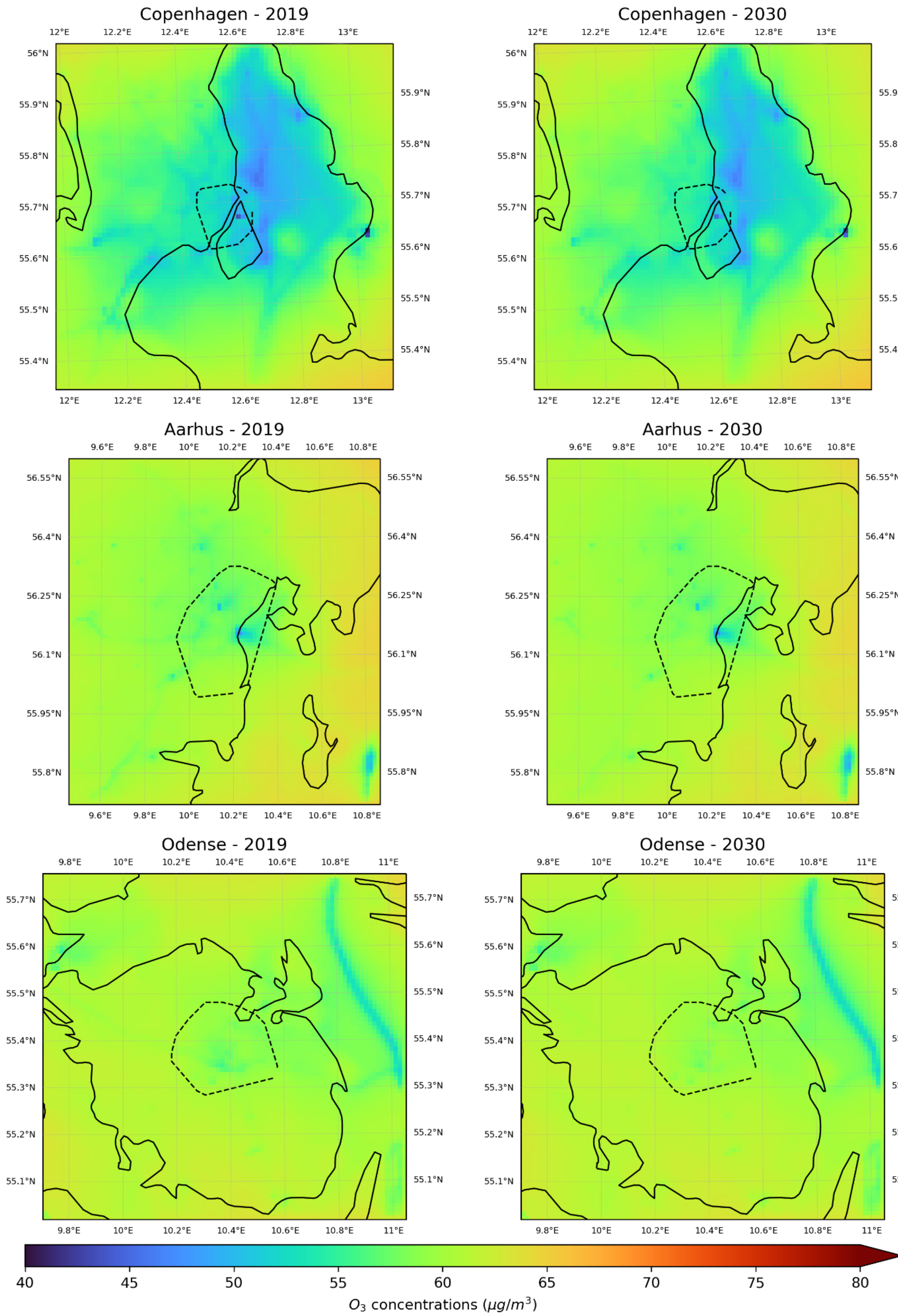


Figure 6.7. Concentration maps showing annual mean values of O_3 for the Danish cities København (top panel), Aarhus (middle panel) and Odense (bottom panel) for 2019 (left column) and 2030 (right column). The dashed line indicates the extension of the city mask.

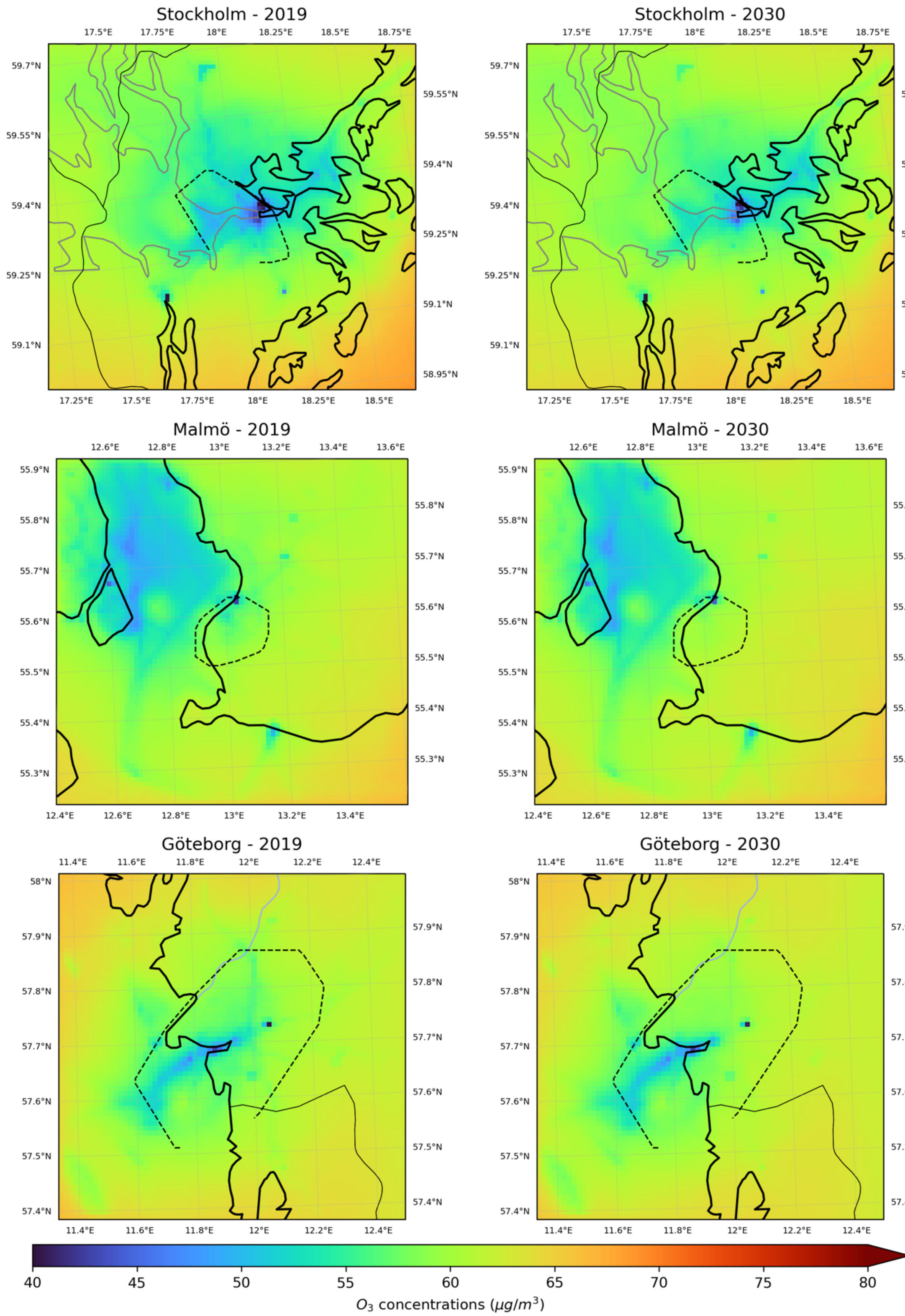


Figure 6.8. Concentration maps showing annual mean values of O_3 for the Swedish cities Stockholm (top panel), Malmö (middle panel) and Göteborg (bottom panel) for 2019 (left column) and 2030 (right column). Dashed line indicates the extension of the city mask.

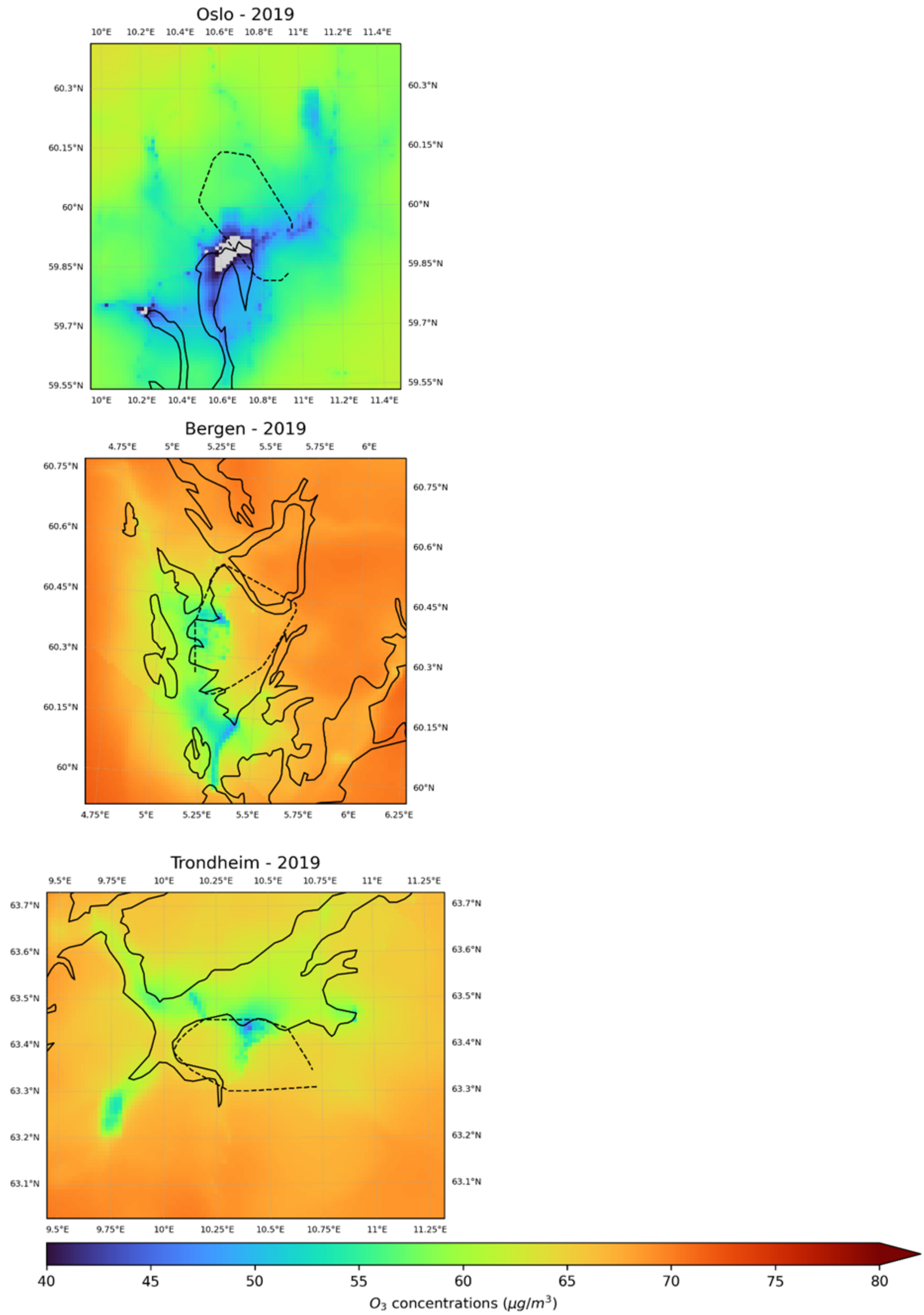


Figure 6.9. Concentration maps showing annual mean values of O_3 for the Norwegian cities Oslo (top panel), Bergen (middle panel) and Trondheim (bottom panel) for 2019. Dashed line indicates the extension of the city mask.

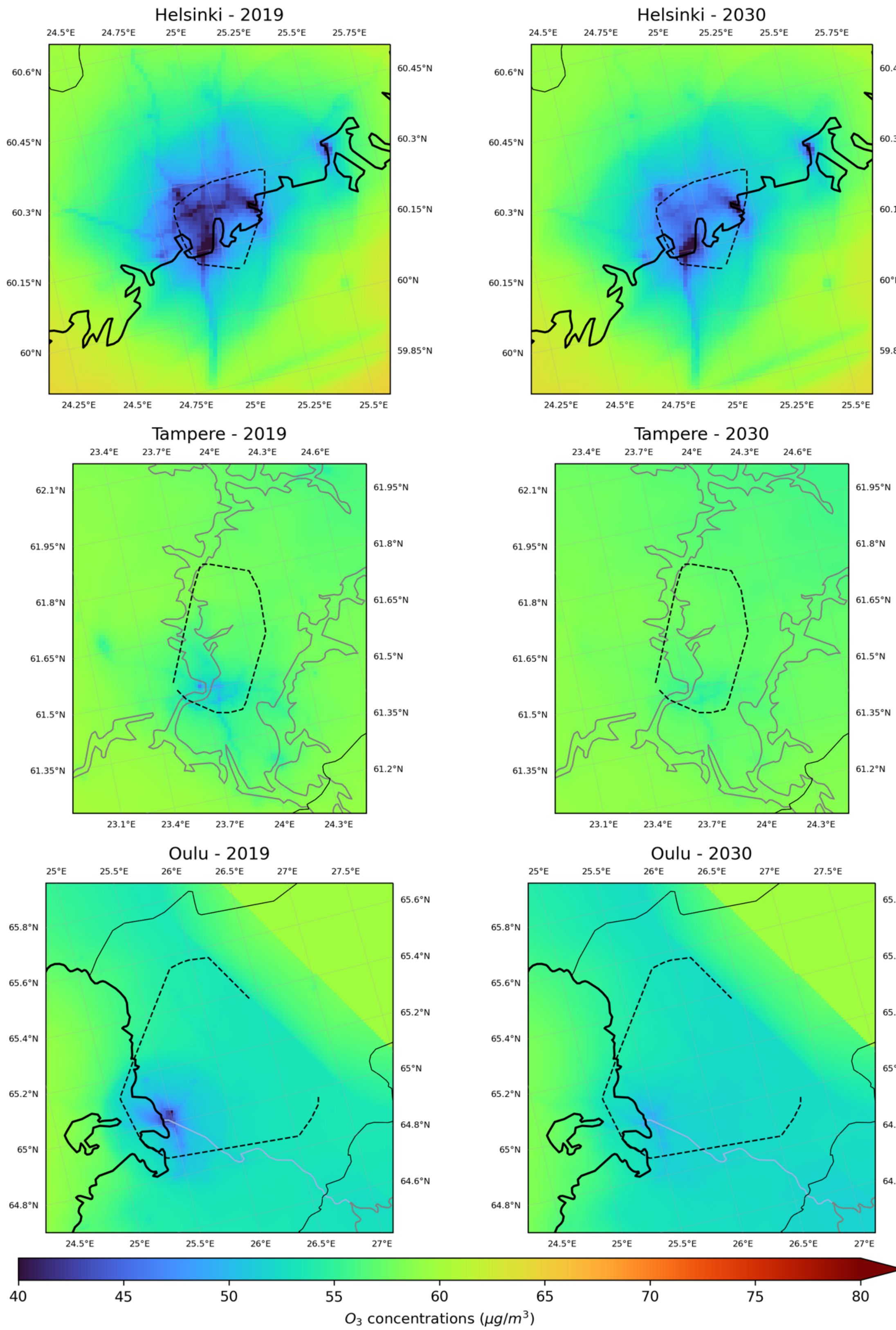


Figure 6.10. Concentration maps showing annual mean values of O_3 for the Finnish cities Helsinki (top panel), Tampere (middle panel) and Oulu (bottom panel) for 2019 (left column) and 2030 (right column). Dashed line indicates the extension of the city mask.

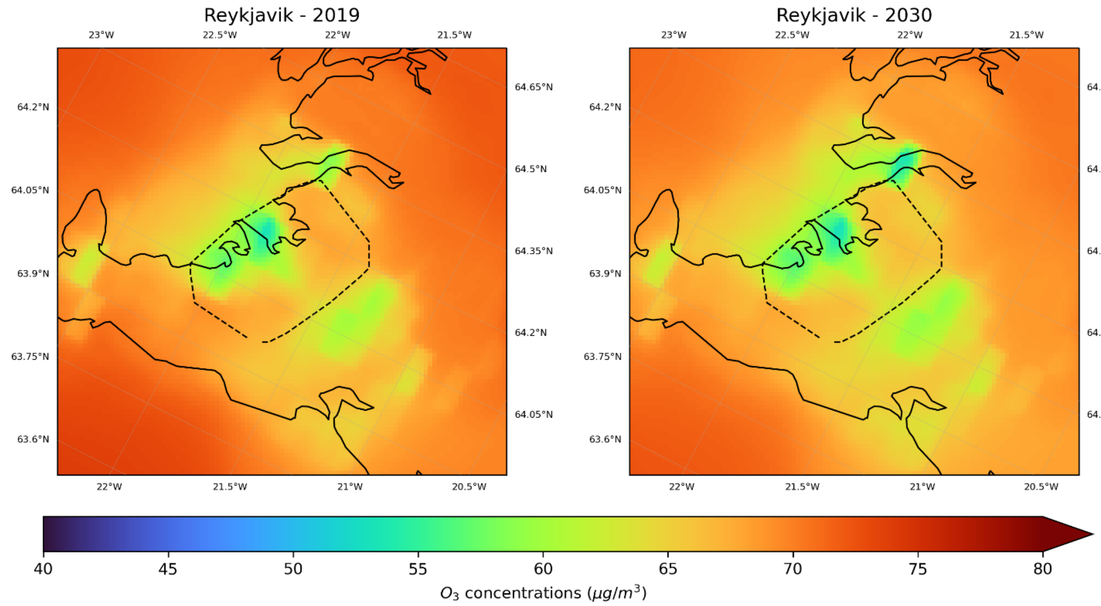


Figure 6.11. Concentration maps for annual means of O_3 for Reykjavík for 2019 and 2030.

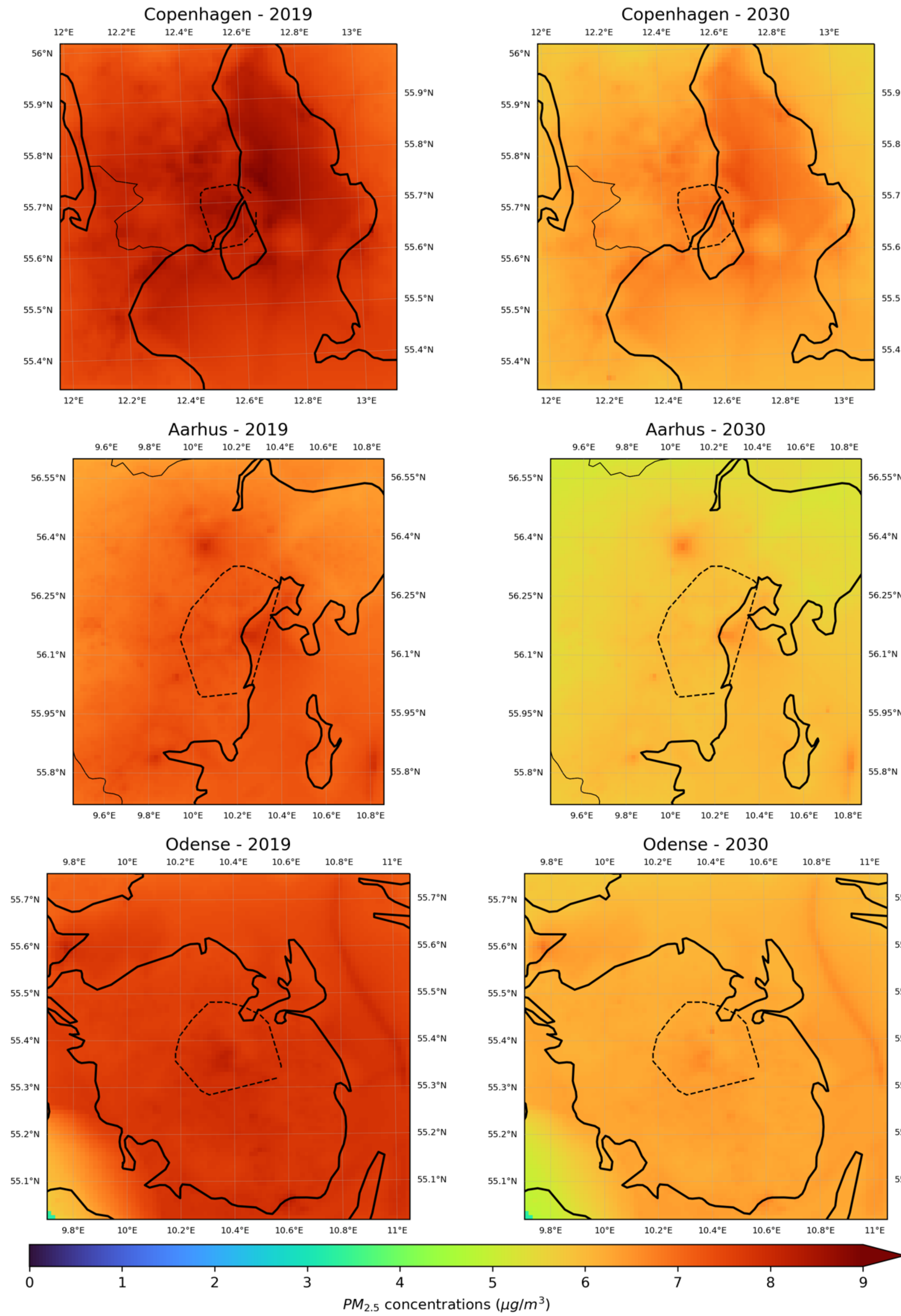


Figure 6.12. Concentration maps showing annual mean values of $PM_{2.5}$ for the Danish cities København (top panel), Aarhus (middle panel) and Odense (bottom panel) for 2019 (left column) and 2030 (right column). The dashed line indicates the extension of the city mask.

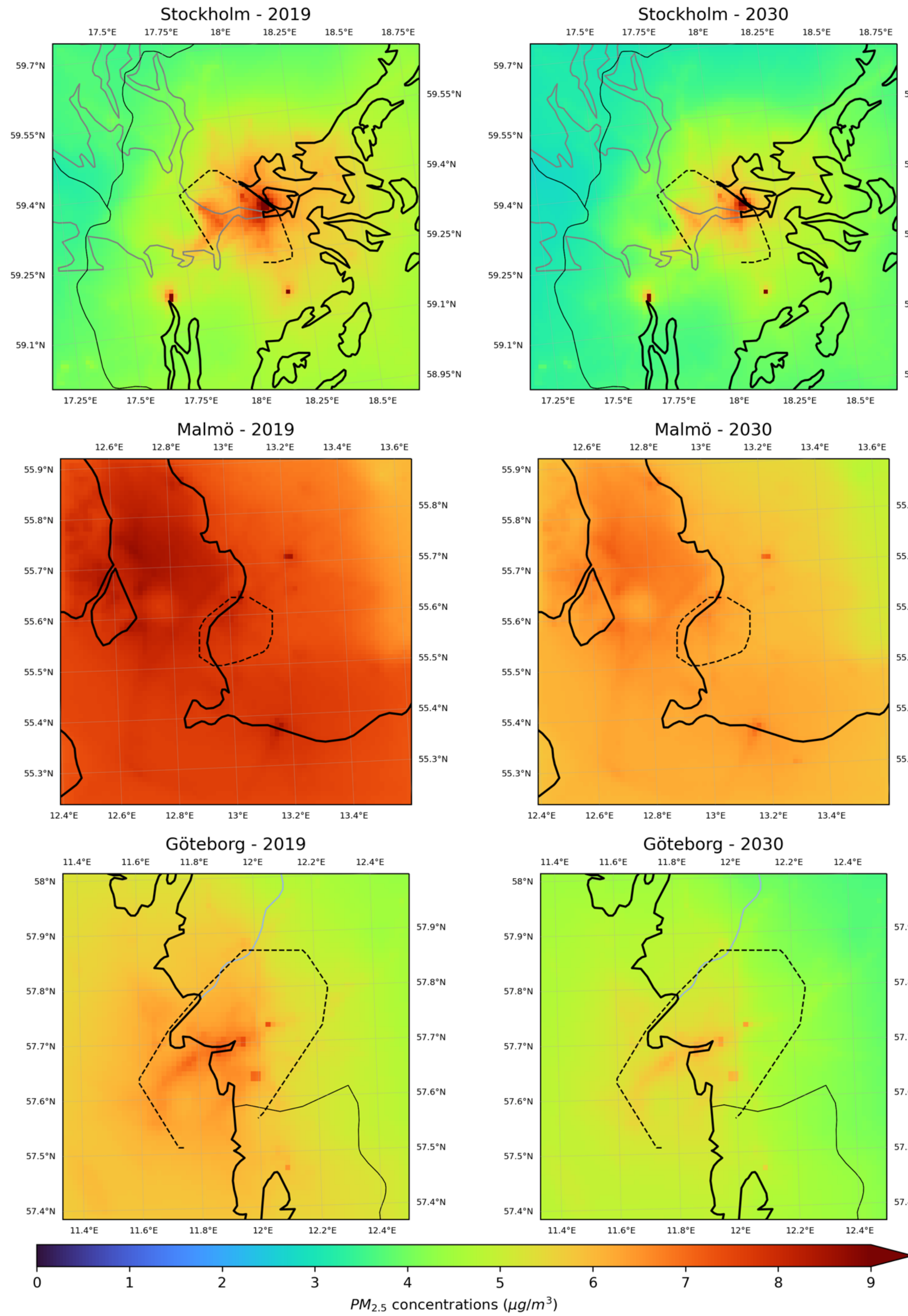


Figure 6.13. Concentration maps showing annual mean values of $PM_{2.5}$ for the Swedish cities Stockholm (top panel), Malmö (middle panel), and Göteborg (bottom panel) for 2019 (left column) and 2030 (right column). Dashed line indicates the extension of the city mask.

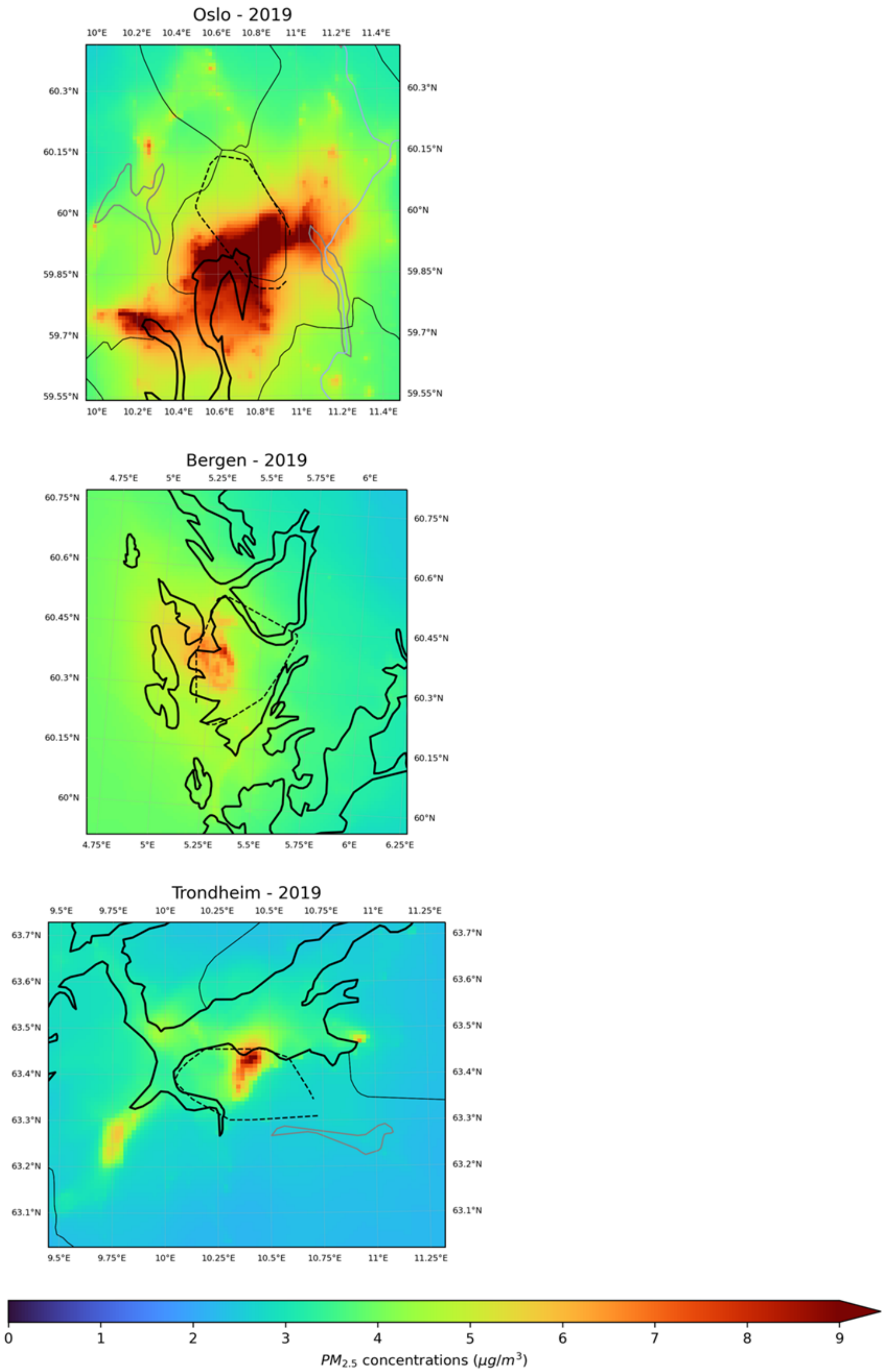


Figure 6.14. Concentration maps showing annual mean values of $PM_{2.5}$ for the Norwegian cities Oslo (top panel), Bergen (middle panel) and Trondheim (bottom panel) for 2019. Dashed line indicates the extension of the city mask.

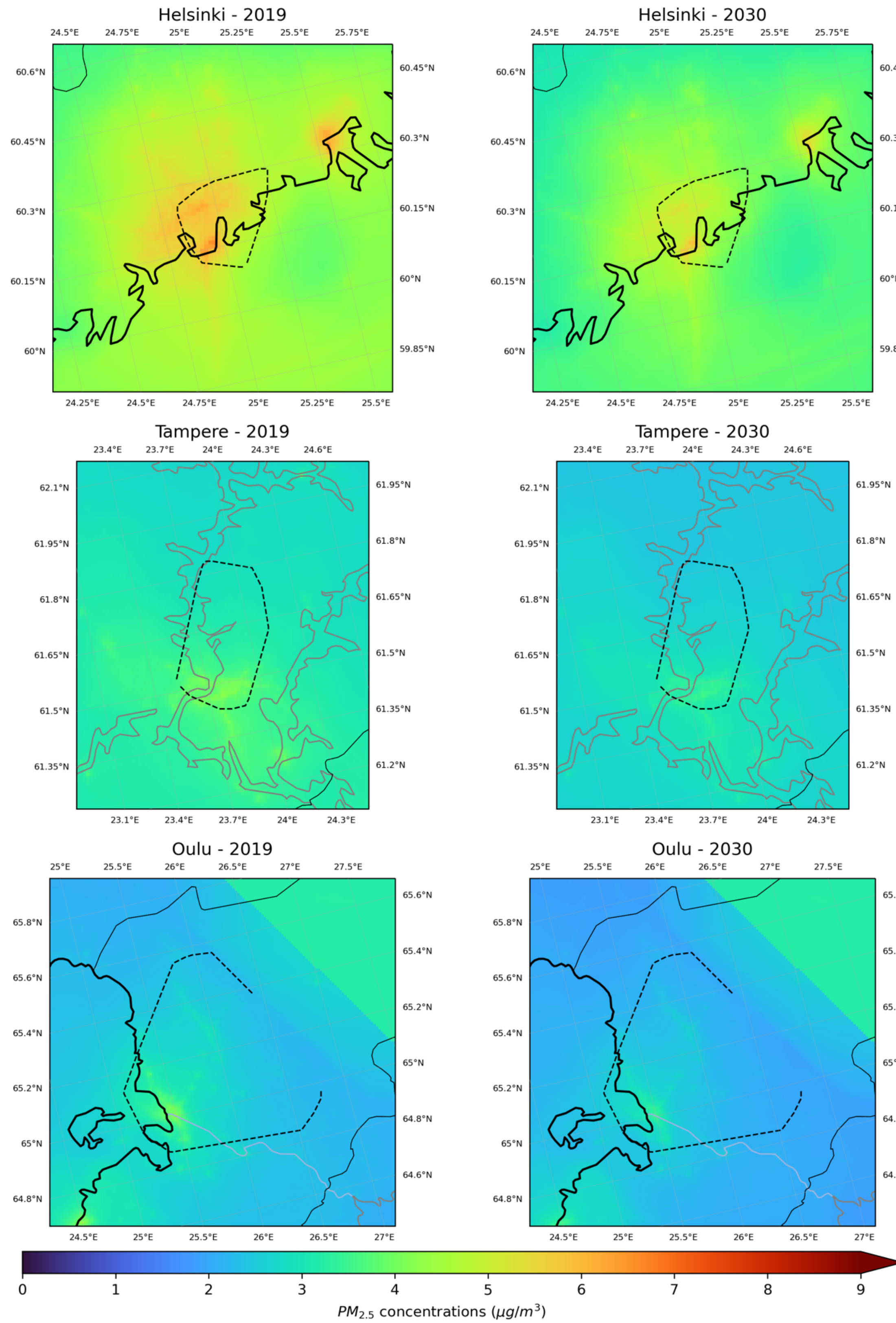


Figure 6.15. Concentration maps showing annual mean values of $PM_{2.5}$ for the Finnish cities Helsinki (top panel), Tampere (middle panel) and Oulu (bottom panel) for 2019 (left column) and 2030 (right column, only Helsinki). Dashed line indicates the extension of the city mask.

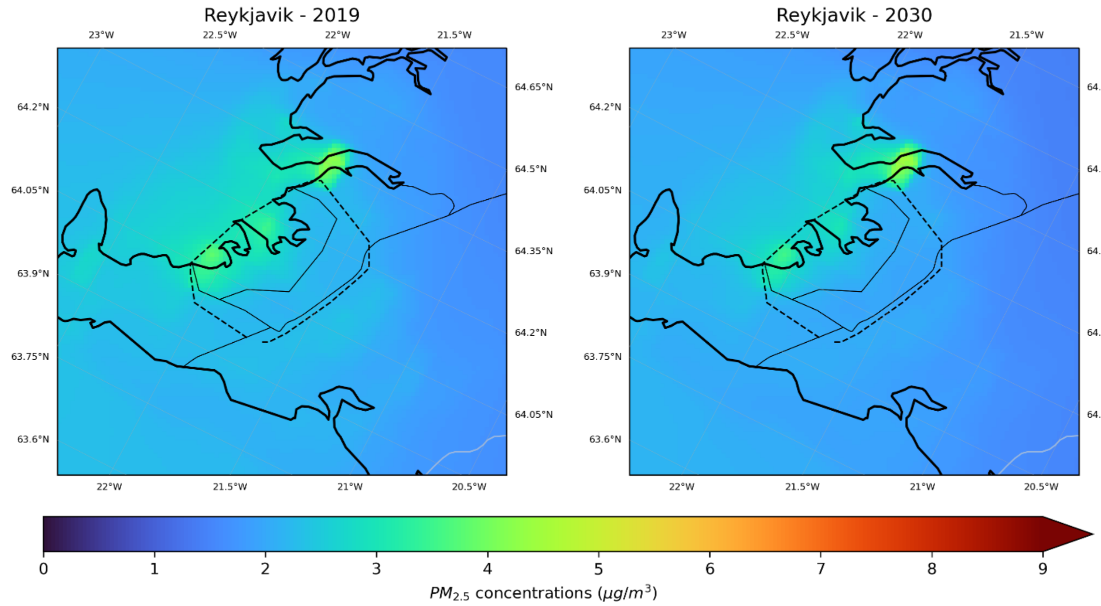


Figure 6.16. Concentration maps for annual means of $PM_{2.5}$ for Reykjavík for 2019 and 2030.

7. Emission sector contributions to air quality in 2030

In the following sections we will provide information for the Nordic capital cities København, Helsinki, Stockholm and Reykjavík on the contribution to air quality in the city from different emission sectors. The results are divided into the contribution from the city, the contribution from the country of the city (disregarding emissions from the city) and the contribution from sources abroad. Abroad includes both anthropogenic emissions at land and sea as well as natural sources e.g. sea salt, and the concentration contribution to the city is not broken down by emission sectors but given as a total concentration contribution. The reason why the contribution from abroad has not been broken down on emission sectors is that as it is computationally expensive and it would also be too time consuming to analyse and report on results.

The results for each city are presented as the average concentration contribution to the urban background concentration over the city defined as the area given by the administrative boundaries, see Appendix 1. Estimates are based on calculations with DEHM and UBM. The analysis focuses on 2030 to illustrate the potential benefits of regulation of the different emission sectors in the future. Furthermore, the focus is on $PM_{2.5}$ and NO_2 as they are the largest contributors to health effects.

A former modelling study based on DEHM has also looked into the sectoral contributions of anthropogenic emissions in the four Nordic countries (Denmark, Finland, Norway and Sweden) on air pollution levels and the associated health impacts and costs over the Nordic and the Arctic regions for the year 2015 (Im et al., 2019).

7.1 København

The contributions to urban background concentrations in København from different emission sectors in København, from emission sectors in the rest of Denmark and from emission sources abroad are shown in Table 7.1 for $PM_{2.5}$ and for NO_2 in Table 7.2.

The contribution of $PM_{2.5}$ to the urban background concentration in København from the city is approx. 8% (0.6 µg/m^3), from the rest of Denmark approx. 16% (5.1 µg/m^3), and from abroad approx. 76% (6.8 µg/m^3). The contribution from emissions abroad is very high due to the location of København, which is affected by a large contribution from both primary but especially secondary particles formed in the atmosphere due to emissions in Central Europe and atmospheric transport (Jensen et al., 2021).

Table 7.1. Emission sector contributions to the urban background $PM_{2.5}$ concentrations in København in 2030.

København	Contribution to the urban background concentration in 2030							
	From city	From DK	Abroad	Total	From city	From DK	Abroad	Total
	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$
SNAP emission sectors	(µg/m^3)	(µg/m^3)	(µg/m^3)	(µg/m^3)	(%)	(%)	(%)	(%)
1 (Energy) 3 (Industrial comb.) 4 (Industrial proc.)	0.1	0.1			1%	1%		
2 (Residential comb.)	0.2	0.4			3%	6%		
5 (Extraction etc.) 6 (Solvents) 9 (Waste)	0.03	0.1			0%	1%		
7 (Road transport)	0.2	0.2			3%	3%		
8 (Off-road, without shipping)	0.01	0.1			0%	1%		
10 (Agriculture)	<0.01	0.2			0%	3%		
Total	0.6	1.1	5.1	6.8	8%	16%	76%	100%

For NO_2 the picture is somewhat different as local sources play a larger role where local combustion sources are important contributors compared with $PM_{2.5}$. The NO_2 contribution to the urban background concentration in København from the city is approx. 18% (3.0 µg/m^3), from the rest of Denmark approx. 28% (4.8 µg/m^3), and from abroad approx. 54% (9.3 µg/m^3).

Table 7.2. Emission sector contributions to the urban background NO_2 concentrations in København in 2030.

København	**Contribution to the urban background concentration in 2030**							
	From city	**From DK**	**Abroad**	**Total**	**From city**	**From DK**	**Abroad**	**Total**
	NO_2	**NO_2**	**NO_2**	**NO_2**	**NO_2**	**NO_2**	**NO_2**	**NO_2**
SNAP emission sectors	(µg/m^3)	(µg/m^3)	(µg/m^3)	(µg/m^3)	(%)	(%)	(%)	(%)
1 (Energy) 3 (Industrial comb.) 4 (Industrial proc.)	0.8	1.0			5%	6%		
2 (Residential comb.)	0.2	0.5			1%	3%		
5 (Extraction etc.) 6 (Solvents) 9 (Waste)	0.01	0.1			1%	1%		
7 (Road transport)	1.0	1.0			6%	6%		
8 (Off-road, without shipping)	0.9	2.0			5%	12%		
10 (Agriculture)	<0.01	0.2			0%	1%		
Total	3.0	4.8	9.3	17.81	18%	28%	54%	100%

The two single largest contributions to the urban background concentrations in 2030 from *city emissions* of $PM_{2.5}$, are from the sectors road transport (SNAP7) and residential wood combustion (SNAP2). For NO_2 the single largest contribution is from road transport (SNAP7), but all other emission sectors including combustion sources also contribute.

The single largest contribution to the urban background concentrations in 2030 from *country emissions* of $PM_{2.5}$ is from the sector residential wood combustion (SNAP2), but all other sectors also contribute. For NO_2 the three largest contributions are from the sectors off-road (SNAP8), road transport (SNAP7) and the combined sector of energy, industrial combustion and industrial processes (SNAP134).

7.2 Stockholm

The contributions to the urban background concentrations in Stockholm from different emission sectors in Stockholm, emission sectors in the rest of Sweden and emission sources abroad are shown in Table 7.3 for $PM_{2.5}$ and for NO_2 in Table 7.4.

The contribution of $PM_{2.5}$ to the urban background concentration in Stockholm from the city is approx. 26% (1.5 µg/m^3), from the rest of Sweden approx. 23% (1.3 µg/m^3), and from abroad approx. 51% (2.9 µg/m^3). The contribution from abroad is largely due to a large contribution from secondary long-range transported particles.

Table 7.3. Emission sector contributions to the urban background $PM_{2.5}$ concentrations in Stockholm in 2030.

Stockholm	Contribution to the urban background concentration in 2030							
	From city	From SE	Abroad	Total	From city	From SE	Abroad	Total
	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$
SNAP emission sectors	(µg/m^3)	(µg/m^3)	(µg/m^3)	(µg/m^3)	(%)	(%)	(%)	(%)
1 (Energy) 3 (Industrial comb.) 4 (Industrial proc.)	0.5	0.2			9%	4%		
2 (Residential comb.)	0.2	0.3			4%	5%		
5 (Extraction etc.) 6 (Solvents) 9 (Waste)	0.1	0.1			2%	2%		
7 (Road transport)	0.6	0.5			11%	9%		
8 (Off-road, without shipping)	0.1	0.1			2%	2%		
10 (Agriculture)	<0.01	0.1			0%	2%		
Total	1.5	1.3	2.9	5.7	26%	23%	51%	100%

For NO_2 there is only a slightly larger contribution from the city and country compared with $PM_{2.5}$. However, the difference is much less profound compared with København. The contribution of NO_2 to the urban background concentration in Stockholm from the city is approx. 27% (3.7 µg/m^3), from rest of Sweden approx. 18% (2.5 µg/m^3), and from abroad approx. 55% (7.7 µg/m^3).

Table 7.4. Emission sector contributions to the urban background NO_2 concentrations in Stockholm in 2030.

Stockholm	Contribution to the urban background concentration in 2030							
	From city	From SE	Abroad	Total	From city	From SE	Abroad	Total
	NO_2	NO_2	NO_2	NO_2	NO_2	NO_2	NO_2	NO_2
SNAP emission sectors	(µg/m^3)	(µg/m^3)	(µg/m^3)	(µg/m^3)	(%)	(%)	(%)	(%)
1 (Energy) 3 (Industrial comb.) 4 (Industrial proc.)	2.0	0.6			14%	4%		
2 (Residential comb.)	0.2	0.4			1%	3%		
5 (Extraction etc.) 6 (Solvents) 9 (Waste)	<0.01	0.01			0%	0%		
7 (Road transport)	1.0	0.9			7%	6%		
8 (Off-road, without shipping)	0.5	0.5			4%	4%		
10 (Agriculture)	<0.01	0.1			0%	1%		
Total	3.7	2.5	7.7	13.9	27%	18%	55%	100%

The two largest contributions to the urban background concentrations in 2030 from *city emissions* of $PM_{2.5}$ are from the sectors road transport (SNAP7) and the combined sector of energy, industrial combustion and industrial processes (SNAP134). The contribution from residential wood combustion (SNAP2) is the third largest with the same contribution as in København (0.2 $\mu g/m^3$). For NO_2 the two sectors with the largest contributions are the combined sector of energy, industrial combustion and industrial processes (SNAP134) and transport (SNAP7).

For *country emissions* of $PM_{2.5,}$ the single largest contribution to urban background concentrations in 2030 is from the sector road transport (SNAP7), followed by residential wood combustion (SNAP2) and the combined sector of energy, industrial combustion and industrial processes (SNAP134). For NO_2 the three largest contributions are from the same sectors but in slightly different order: road transport (SNAP7), the combined sector of energy, industrial combustion and industrial processes (SNAP134) and residential wood combustion (SNAP2).

7.3 Helsinki

The contribution to the urban background concentrations in Helsinki from different emission sectors in Helsinki, emission sectors in the rest of Finland and emission sources abroad are shown in Table 7.7 for $PM_{2.5}$ and for NO_2 in Table 7.8.

The contribution of $PM_{2.5}$ to the urban background concentration in Helsinki from the city is approx. 15% (0.7 $\mu g/m^3$), from the rest of Finland approx. 22% (1.0 $\mu g/m^3$), and from abroad approx. 62% (2.9 $\mu g/m^3$). The contribution from abroad is largely due to a large contribution from secondary long-range transported particles.

Table 7.5. Emission sector contributions to the urban background $PM_{2.5}$ concentrations in Helsinki in 2030.

Helsinki	Contribution to the urban background concentration in 2030							
	From city	From FI	Abroad	Total	From city	From FI	Abroad	Total
	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$
SNAP emission sectors	(µg/m^3)	(µg/m^3)	(µg/m^3)	(µg/m^3)	(%)	(%)	(%)	(%)
1 (Energy) 3 (Industrial comb.) 4 (Industrial proc.)	0.1	0.2			2%	4%		
2 (Residential comb.)	0.1	0.3			2%	6%		
5 (Extraction etc.) 6 (Solvents) 9 (Waste)	0.1	0.0			2%	1%		
7 (Road transport)	0.3	0.3			6%	6%		
8 (Off-road, without shipping)	0.1	0.1			2%	2%		
10 (Agriculture)	<0.01	0.1			0%	2%		
Total	0.7	1.0	2.9	4.7	15%	22%	62%	100%

For NO_2 there is a larger contribution from the city compared with $PM_{2.5}$ as local sources play a larger role where combustion sources are important contributors. The NO_2 contribution to the urban background concentration in Helsinki from the city is approx. 25% (4.7 µg/m^3), from the rest of Finland approx. 22% (4.1 µg/m^3), and from abroad approx. 54% (10.3 µg/m^3).

Table 7.6. Emission sector contributions to the urban background NO_2 concentrations in Helsinki in 2030.

Helsinki	Contribution to the urban background concentration in 2030							
	From city	From FI	Abroad	Total	From city	From FI	Abroad	Total
	NO_2	NO_2	NO_2	NO_2	NO_2	NO_2	NO_2	NO_2
SNAP emission sectors	(µg/m^3)	(µg/m^3)	(µg/m^3)	(µg/m^3)	(%)	(%)	(%)	(%)
1 (Energy) 3 (Industrial comb.) 4 (Industrial proc.)	3.0	2.0			16%	10%		
2 (Residential comb.)	0.1	0.4			1%	2%		
5 (Extraction etc.) 6 (Solvents) 9 (Waste)	<0.01	<0.01			0%	0%		
7 (Road transport)	0.9	1.0			5%	5%		
8 (Off-road, without shipping)	0.7	0.6			4%	3%		
10 (Agriculture)	0.01	0.1			0%	1%		
Total	4.7	4.1	10.3	19.1	25%	22%	54%	100%

The emission sector contributing the most to the urban background concentrations of $PM_{2.5}$ in 2030 from *city emissions* is road transport (SNAP7), but all other sectors also contribute, except agriculture (SNAP10).

The three largest contributions to urban background concentrations of $PM_{2.5}$ in 2030 from *country emissions* are from the sectors residential wood combustion (SNAP2), road transport (SNAP7) and the combined sector of energy, industrial combustion and industrial processes (SNAP134). For NO_2 the three largest contributions are from the combined sector of energy, industrial combustion and industrial processes (SNAP134), road transport (SNAP7) and off-road (SNAP8).

7.4 Reykjavík

The contribution to the urban background concentrations in Reykjavík from different emission sectors in Reykjavík, emission sectors in the rest of Iceland and emission sources abroad are shown in Table 7.9 for $PM_{2.5}$ and for NO_2 in Table 7.10.

The contribution of $PM_{2.5}$ to the urban background concentration in Reykjavík from the city is approx. 10% (0.2 µg/m^3), from rest of Iceland approx. 23% (0.5 µg/m^3), and from abroad approx. 67% (1.5 µg/m^3). Due to the remote location, the concentration levels of $PM_{2.5}$ are low compared with other capital cities, however, the contribution from abroad is relatively large although the absolute levels are low. The contribution from abroad are from ship emissions, long-range transport and sea salt.

Table 7.9. Emission sector contributions to the urban background $PM_{2.5}$ concentrations in Reykjavík in 2030.

Reykjavík	Contribution to the urban background concentration in 2030							
	From city	From IS	Abroad	Total	From city	From IS	Abroad	Total
	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$
SNAP emission sectors	(µg/m^3)	(µg/m^3)	(µg/m^3)	(µg/m^3)	(%)	(%)	(%)	(%)
1 (Energy) 3 (Industrial comb.) 4 (Industrial proc.)	0.05	0.2			2%	10%		
2 (Residential comb.)	<0.01	<0.01			0%	0%		
5 (Extraction etc.) 6 (Solvents) 9 (Waste)	0.03	<0.01			1%	0%		
7 (Road transport)	0.1	0.0			3%	2%		
8 (Off-road, without shipping)	0.1	0.2			3%	7%		
10 (Agriculture)	0.01	0.1			0%	4%		
Total	0.2	0.5	1.5	2.3	10%	23%	67%	100%

For NO_2 there is a larger contribution from the city compared with $PM_{2.5}$ as local sources play a larger role where combustion sources are important contributors. The NO_2 contribution to the urban background concentration in Reykjavík from the city is approx. 35% (3.6 µg/m^3), from the rest of Iceland approx. 42% (4.3 µg/m^3), and from abroad approx. 23% (2.4 µg/m^3).

Table 7.10. Emission sector contributions to the urban background NO_2 concentrations in Reykjavik in 2030.

Reykjavik	Contribution to the urban background concentration in 2030							
	From city	From IS	Abroad	Total	From city	From IS	Abroad	Total
	NO_2	NO_2	NO_2	NO_2	NO_2	NO_2	NO_2	NO_2
SNAP emission sectors	(μg/m^3)	(μg/m^3)	(μg/m^3)	(μg/m^3)	(%)	(%)	(%)	(%)
1 (Energy) 3 (Industrial comb.) 4 (Industrial proc.)	0.1	0.6			1%	6%		
2 (Residential comb.)	0.01	<0.01			0%	0%		
5 (Extraction etc.) 6 (Solvents) 9 (Waste)	<0.01	<0.01			0%	0%		
7 (Road transport)	0.1	0.01			1%	0%		
8 (Off-road, without shipping)	2.9	3.5			28%	34%		
10 (Agriculture)	0.4	0.2			4%	1%		
Total	3.6	4.3	2.4	10.3	35%	42%	23%	100%

The two largest contributions to the urban background concentrations of $PM_{2.5}$ in 2030 from *city emissions* are from the sectors road transport (SNAP7) and off-road (SNAP8). The latter includes emissions from the fishing fleet where there is uncertainty of the geographic distribution of emissions that leads to overestimation of the contribution to concentrations in Greater Reykjavík. As the only Nordic capital city, the contribution from residential wood combustion (SNAP2) is insignificant. For NO_2 the largest contribution is from off-road (SNAP8) but this is also overestimated due to the incorrect geographic distribution of emissions from fisheries.

The three largest contributions to the urban background concentrations of $PM_{2.5}$ in 2030 from *country emissions* are from the combined sector of 5 (Extraction etc.) 6 (Solvents) and 9 (Waste) (SNAP569), the combined sector of energy, industrial combustion and industrial processes (SNAP134) where an important source is ferroalloys production, and off-road (SNAP8) related to the fishing fleet. For NO_2 the three largest contributions are from the sectors off-road (SNAP8), the combined sector of energy, industrial combustion and industrial processes (SNAP134) and agriculture (SNAP10).

7.5 Summary of contributions to air quality in 2030

Table 7.11 summarises the contributions to air quality in 2030 for the Nordic capital cities.

Table 7.11. The contribution to the urban background concentrations of $PM_{2.5}$ (top rows) and NO_2 (bottom rows) from city emissions, from country emissions and from emissions abroad in 2030 for the Nordic capital cities.

	From city	From country	From abroad	Total
	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$
København	8%	16%	76%	100%
Stockholm	26%	23%	51%	100%
Oslo	n.a.	n.a.	n.a.	n.a.
Helsinki	15%	22%	62%	100%
Reykavík	10%	23%	67%	100%
	NO_2	NO_2	NO_2	NO_2
København	18%	28%	54%	100%
Stockholm	27%	18%	55%	100%
Oslo	n.a.	n.a.	n.a.	n.a.
Helsinki	25%	22%	54%	100%
Reykavík	35%	42%	23%	100%

The contribution to urban background concentrations of $PM_{2.5}$ in 2030 for the Nordic capital cities ranges from 8% to 26% from city emissions, 16% to 23% for country emissions and 51% to 76% from abroad emissions. The corresponding numbers for NO_2 are 18% to 35%, 18% to 42% and 23% to 55%, respectively.

København stands out with the highest contribution from emissions abroad and low contributions from city and country emissions to urban background concentrations of $PM_{2.5}$ also due to its location close to Central Europe.

Reykjavík has a relatively large contribution from abroad despite its location in the North Atlantic Ocean. However, the absolute levels are the lowest among the capital cities. Possible explanations could be the influence of ship emissions, long-range transport and sea salt. Moreover, Reykjavík and Iceland have a relatively small population further adding to the relative importance of emissions from abroad.

The results for Stockholm and Helsinki are more similar to each other and the contributions from emissions from city, country and abroad differ from that found for Reykjavík and København.

The three largest contributions to the urban background concentrations of $PM_{2.5}$ in 2030 from *city emissions* are from road transport (SNAP7), residential wood combustion (SNAP2) and the combined sector of energy, industrial combustion and industrial processes (SNAP134), except for Reykjavík where the contribution from residential wood combustion is insignificant and off-road (SNAP8) plays a larger role due to the fishing fleet although overestimated. For NO_2 the largest contribution is from the sector road transport (SNAP8), but all other sectors with emissions from combustion sources also contribute.

For *country emissions*, the largest contributions to the urban background concentrations of $PM_{2.5}$ in 2030 are from residential wood combustion (SNAP2) (except for Iceland), road transport (SNAP7), the combined sector of energy, industrial combustion and industrial processes (SNAP134) and off-road (SNAP8), but also agriculture (SNAP10) contributes. For NO_2 the largest contributions are from the sectors off-road (SNAP8), road transport (SNAP7), and the combined sector of energy, industrial combustion and industrial processes (SNAP134).

The contribution from abroad has not been broken down in emission sectors.

8. Emission sector contributions to health effects and external costs in 2030

Based on the urban background concentrations modelled with UBM for the Nordic capital cities, the EVA-system has been used to model the share of health effects and related external costs from individual emission sectors in each selected Nordic capital city in 2030 sub-divided by transboundary, country, and city boundaries.

8.1 Assumptions

Population data in 2019 and 2030

The population data applied in the current version of the EVA system are based on information from Eurostat.

The most recent gridded population dataset from Eurostat is valid for 2018 on a 1 km x 1 km grid (https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/geostat). In this project, this distribution has been scaled so the annual totals sum up to the available reported and projected national totals in the specific years of 2019 and 2030. A baseline projection of the development in national totals and the age distribution for 2030 has also been obtained from Eurostat (https://ec.europa.eu/eurostat/databrowser/view/proj_19np/default/table?lang=en).

The national reported and projected totals for 2019 and 2030 and the fraction of the population aged 30 years and above are given in Table 8.1.

Table 8.1. Inhabitants in the five Nordic countries in 2019 and 2030 (mio.) and the share of individuals aged 30+. Lowest panel displays the change in total population density from 2019 to 2030.

	DK	FI	IS	NO	SE
Year	2019	2019	2019	2019	2019
Total	5.8	5.5	0.4	5.3	10.2
Above 30	3.7	3.7	0.2	3.4	6.5
Above 30 in %	64%	66%	59%	63%	64%
Year	2030	2030	2030	2030	2030
Total	6.0	5.5	0.4	5.8	11.1
Above 30	4.0	3.8	0.3	3.8	7.2
Above 30 in %	67%	70%	64%	66%	65%
Year	2019 to 2030	2019 to 2030	2019 to 2030	2019 to 2030	2019 to 2030
Difference in %	3%	0%	17%	8%	8%

Like in many other European countries, the inhabitants in the Nordic countries have increased their expected lifetime and the fraction of people older than 30 years are increasing slightly in all the Nordic countries towards 2030. The total population is also projected to increase between less than 1% (Finland) to about 17% (Iceland).

The spatial distribution of the gridded population data from 2018 is shown in Figure 8.1.

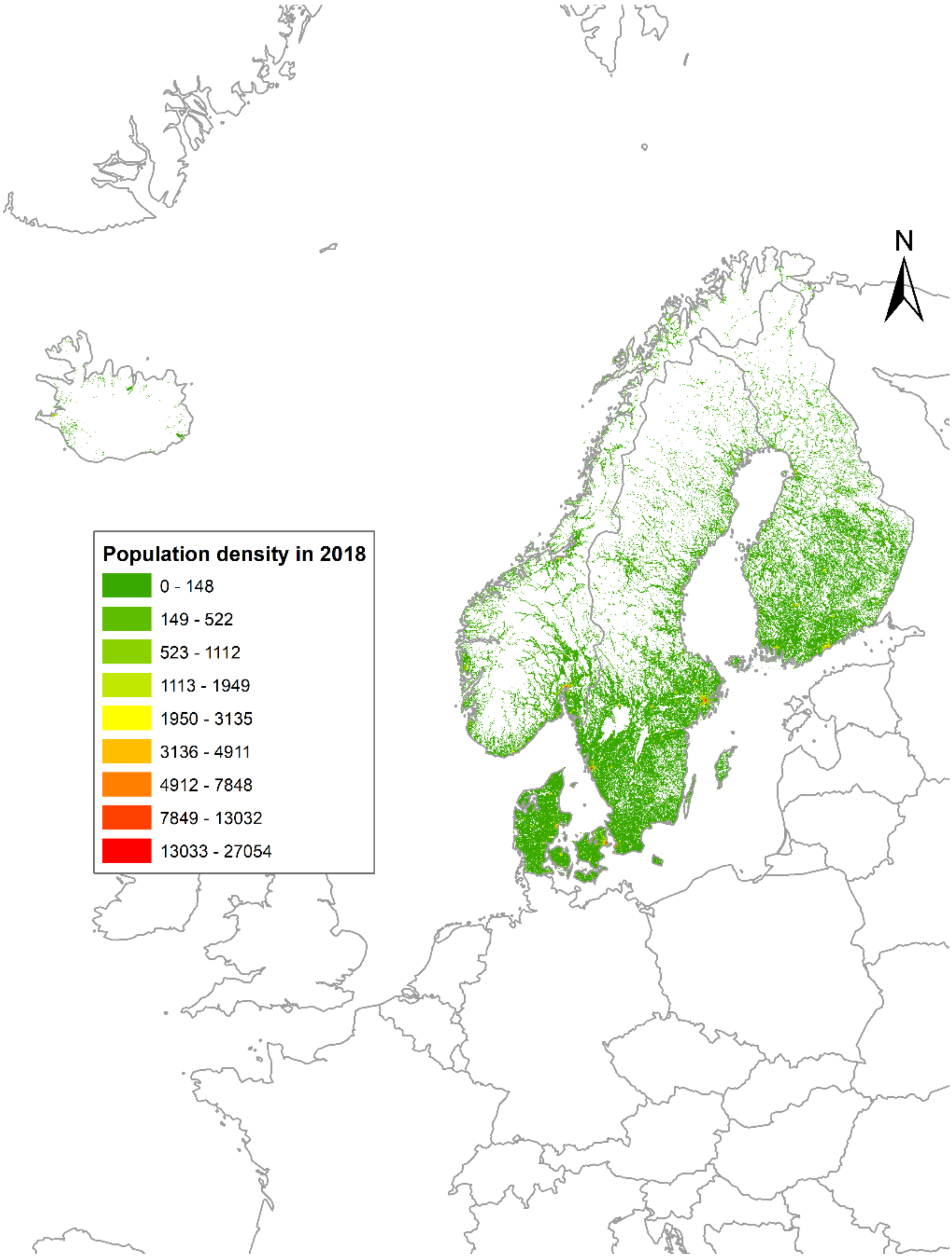


Figure 8.1. Population density in the Nordic countries from Eurostat on 1 km x 1 km in 2018 (inhabitants/km^2).

Standard costs for mortality and morbidity

The EVA model system applies a set of standard costs for acute and chronic mortality as well as for morbidity, derived for Denmark. To apply the EVA system for other countries, this set of standard costs can either be replaced by a set of locally developed standard costs that applies for the specific country, or be transformed to represent another country using the OECD benefit transfer methodology formula (OECD 2012: 138):

$$VSLVN = VSLDK\left(\frac{YVN}{YDK}\right)^{\beta}$$

Here VSL is the value of a statistical life, and Y is the Gross Domestic Product (GDP) per capita (adjusted for purchasing power parity - PPP) and ß is the income elasticity based on the OECD central estimate.

The official VSL values for Denmark, Norway and Sweden were used to derive by benefit transfer VSL values for Finland and Iceland, which to our knowledge, that do not have official recommendations on VSL-values for socio-economic analysis. Subsequently we calculated a population weighted Nordic average for VSL.

The Nordic value of a life year (VOLY) were derived from the Nordic-VSL using the standard OECD methodology, whereby VSL is the net present value of the sum of discounted VOLY's over the average remaining lifetime for a traffic fatality (see also DØRS, 2016). A declining discount rate of 3% for the first 35 years and 2% for the remaining time was used, derived with the Ramsey formula (cf. European Commission, 2014). The value of a chronic VOLY was calculated by assuming an average air pollution victim latency period of five years, cf. US-EPA methodology. A premature death is equivalent to a loss of 11.4 life years in Denmark, 10.4 years in Finland, 12.6 years in Iceland, 10.7 years in Norway and 9.5 years in Sweden.

Data for GDP has been obtained from Eurostat and results are provided as 2020-prices.

For morbidity, while the exposure-response functions reflect the background incidence in each of the Nordic countries, the unit costs (e.g. for hospitalizations) are derived from Danish circumstances.

Exposure-response relationships in EVA-system for current project

The assumptions related to exposure-response functions in this project are the same as in the version of the EVA-system used in the Danish national air quality monitoring program for 2020 (Ellermann et al., 2022). Exposure-response relationships in the applied version of the EVA-system are based on WHO (2013).

Assumptions about exposure-response relationships for the different pollutants are important especially for $PM_{2.5}$ that is responsible for most of the health impacts.

For $PM_{2.5}$ we use a relative risk of 1.062 based on WHO (2013), that is, a 6.2% increase in mortality per 10 μg/m^3 increase in annual mean $PM_{2.5}$. Furthermore, no lower threshold of health effects for $PM_{2.5}$ is assumed based on the precautionary principle. Available studies only include concentration levels down to 2.4 μg/m^3 but the exposure-response relationships are stronger for lower levels compared with higher levels and health effects will most likely continue below 2.4 μg/m^3 (WHO, 2021; Raaschou-Nielsen et al., 2020; Sommar et al., 2021). For NO_2 a threshold of 20 μg/m^3 (WHO, 2013) is assumed below which no effects occur. Health effects from ozone primarily originate from exposure to high concentrations, so a parameter (SOMO35) is used, where only ozone concentrations above 35 ppb (=70 μg/m^3) are taken into account (WHO, 2013).

The assumptions about thresholds, relative risks (RR), age groups affected and the valuation of health endpoints are given in Table 8.2.

Table 8.2. The health endpoints and relative risks (RR) used in the EVA system for the present analysis. It is mainly based on a set of RR recommended by HRAPIE/WHO for use in health and cost assessments (Héroux et al., 2015). The RR for SO_2 is taken from the ExternE project. The valuation (the standard costs) are based on work done in the NordicWelfAir project and represents the weighted average cost across the five Nordic countries (given in 2020 prices in Euros).

Health endpoint	Pollutant	Range	Ages	RR per 10 µg/m^3	Valuation
Mortality:					
Acute mortality	O_3	>35* ppb	all	1.0029	4526000 €/case
	NO_2 (1h max)	no thresh.	all	1.0027	4526000 €/case
	$PM_{2.5}$	no thresh.	all	1.0123	4526000 €/case
	SO_2	no thresh.	all	1.00072	4526000 €/case
Acute mortality infants	$PPM_{2.5}$ (from PPM_{10})	no thresh.	Infants, postneonatal	1.0400	6789000 €/case
Chronic mortality	$PM_{2.5}$	no thresh.	>30	1.062	141000 €/YOLL
	NO_2	>20 ug/m^3	>30	1.0550	141000 €/YOLL
Hospital admissions (HA):					
Cardiovascular HA/incl. stroke	$PM_{2.5}$	no thresh.	all	1.0091	16494 €/case
Cardiovascular HA/excl. stroke	O_3	>35* ppb	>65	1.0089	16368 €/case
Respiratory HA	$PM_{2.5}$	no thresh.	all	1.0190	10247 €/case

Respiratory HA	O_3	>35* ppb	>65	1.0044	10247 €/case
Respiratory HA	NO_2	no thresh.	all	1.0180	10247 €/case
Bronchitis (KOL)/ children	$PM_{2.5}$ from PM_{10}	no thresh.	<16	1.0480	167 €/case
Bronchitis (KOL)/ adults	$PM_{2.5}$ from PM_{10}	no thresh.	>16	1.1170	40664 €/case
Asthma symptoms/ children	$PM_{2.5}$ from PM_{10}	no thresh.	<16	1.0280	1366 €/case
Days with restricted activity (sick days) (RAD)	$PM_{2.5}$	no thresh.	all	1.0470	160 €/day
Working days lost (WLD)	$PM_{2.5}$	no thresh.	>30	1.0460	301 €/day
Days with minor restricted activity (MRAD)	O_3	>35* ppb	all	1.0154	81 €/day
Lung cancer morbidity	$PM_{2.5}$	no thresh.	>30	1.14	74943 €/case

*Actually as SOMO35 calculated from the sum of the highest ozone concentrations, and indicates the sum of 8-hour daily maximum values over 35 ppb during the year.

Revisions and sensitivity analysis for Danish conditions

The exposure-response relationships in the EVA-system has been under revision during the course of the current project in light of the new WHO AQG from 2021 and the studies behind.

WHO's new guidelines (WHO, 2021) encompass a thorough review of the international research on the association between exposure to a number of air pollutants and effects on human health. The review documents that the health impacts are larger than previously known and that the impacts on human health are observed at lower concentration levels than previously documented, which is of particular relevance for the Nordic countries with generally lower concentrations. For example, the relative risk for chronic mortality associated with $PM_{2.5}$ has in the new guidelines increased from 1.062 to 1.08. Other things being equal, this will lead to higher estimates of health effects of air pollution.

The new guidelines from WHO have been implemented in the model calculations of the health impacts for Denmark in the most recent air quality assessment for 2021 (Ellermann et al., 2023). This has resulted in a change in the number of premature deaths originating from the different air pollutants. However, the overall number of premature deaths is approximately the same as previous years despite these changes. This is due to a parallel update of the average life expectancy and to the recommendation in the new WHO guidelines to use of a new lower threshold as well as changes in RRs for the health impact of NO_2. The result is a lower number of premature deaths in general as well as from NO_2 exposure, which balances out the higher number of premature deaths due to the change in RR for $PM_{2.5}$.

A sensitivity analysis was also carried out in relation to the air quality assessment for 2021 for Denmark. The baseline assumes a relative risk for $PM_{2.5}$ of 1.08 with no threshold value for this pollutant resulting in 3,900 premature deaths in Denmark. Scenarios with a relative risk for $PM_{2.5}$ of 1.08 and a threshold of 2.4 µg/m^3 gave 2,600 premature deaths, a relative risk for $PM_{2.5}$ of 1.12 (as has been seen in Danish cohort studies, see Ellermann et al., 2023) and no threshold gave 5,800 premature deaths and a relative risk for $PM_{2.5}$ of 1.12 and a threshold of 2.4 µg/m^3 gave 3,800 premature deaths. This illustrates that prediction of the number of premature deaths is highly sensitive to the assumptions applied.

Emission sector contributions in selected Nordic countries

In the following sections we will provide information for each of the Nordic capital cities on mortality and morbidity effects of air pollution and related external costs in 2019 and 2030, and the contribution from different emission sectors as well as the contribution from the city, the country of the city and abroad sources. Estimates are based on calculations with DEHM, UBM and the EVA-system.

8.2 Health effects and sector contributions in København

Mortality and morbidity effects of air pollution in 2019 and 2030

A summary of mortality and morbidity effects of air pollution in 2019 and 2030 is shown in Table 8.3. Note that figures are rounded for case except for percentage figures.

Total premature deaths are predicted to be approx. 400 in 2019 and 300 in 2030 showing a decrease of approx. 20%. The decrease is a combined effect of an increase in population including more elderly persons and a decrease in air pollution levels. It is also seen that approx. 2/3 of the premature deaths are related to chronic premature deaths due to long-term exposure and approx. 1/3 to acute premature deaths due to short-term exposure with elevated air pollution levels.

The number of morbidity cases is also predicted to decrease from 2019 to 2030.

Aarhus University carried out a health impact assessment in 2019 for the Municipality of København that estimated 440 premature deaths, that is, in the same range as the above estimate as expected although also with some differences in the assumptions about the geographic extent of København, emissions, population data and life expectancy (Jensen et al. 2021).

Table 8.3. Mortality and morbidity effects of air pollution in København in 2019 and 2030 (figures rounded).

Health effects	2019	2030	Difference
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	140	110	-20%
Chronic mortality ($PM_{2.5}$, NO_2)	270	200	-23%
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	410	310	-22%
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	490	410	-17%
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	130	120	-8%
Episodes with asthma among children ($PM_{2.5}$)	30	25	-18%
Episodes with bronchitis among adults ($PM_{2.5}$)	290	240	-17%
Episodes with bronchitis among children ($PM_{2.5}$)	1300	1200	-11%
Working days lost ($PM_{2.5}$)	18000	15000	-14%
Days with restricted activity (sick days) ($PM_{2.5}$)	220000	190000	-17%
Days with minor restricted activity (O_3)	35000	34000	-1%
Lung cancer morbidity ($PM_{2.5}$)	50	45	-14%
Total inhabitants	594679	610810	3%
Inhabitants over age of 30 years	381011	406416	7%
Inhabitants over age of 30 years (%)	64%	67%	4%

Contribution of different emission sectors in 2030

The analysis of the contribution of the different emission sectors focuses on 2030 to illustrate the potential benefits of regulation of the different emission sectors in the future.

City to city

Table 8.4 shows the contribution to København of the emission sectors within København.

Approx. 50 premature deaths can be attributed to emission sources within the city equivalent to about 15% of the total number of premature deaths (310).

It is seen that the two single largest contributions to mortality and morbidity in 2030 are the emission sectors road transport (SNAP7) and residential wood combustion (SNAP2). Obviously, agriculture (SNAP10) does not contribute to premature deaths as there is very limited agriculture in København.

Negative values for days with minor restricted activity due to ozone is a result of chemistry in the atmosphere, where NO_x emissions ($NO+NO_2$) emitted in the city lead to lower ozone concentrations in the city as NO consumes ozone in formation of NO_2.

Table 8.4. Contributions to mortality and morbidity in København from the emission sectors within København in 2030 (figures rounded).

	City contribution to city						City to city
Health effects of air pollution in 2030	SNAP2	SNAP7	SNAP8	SNAP10	SNAP134	SNAP569	All
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	2	7	5	0	5	1	20
Chronic mortality ($PM_{2.5}$, NO_2)	7	7	2	0	7	1	24
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	10	15	7	0	12	3	47
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	7	24	14	0	16	2	64
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	3	1	-1	0	0	0	3
Episodes with asthma among children ($PM_{2.5}$)	1	1	0	0	0	0	3
Episodes with bronchitis among adults ($PM_{2.5}$)	8	7	1	0	2	2	20
Episodes with bronchitis among children ($PM_{2.5}$)	28	23	2	0	6	5	63

Working days lost ($PM_{2.5}$)	540	440	33	1	120	97	1200
Days with restricted activity (sick days) ($PM_{2.5}$)	6500	5400	400	11	1400	1200	15000
Days with minor restricted activity (O_3)	-220	-1300	-890	-1	-750	-110	-3200
Lung cancer morbidity ($PM_{2.5}$)	2	1	0	0	0	0	4

Country to city

Table 8.5 shows the contribution to København from the emission sectors within Denmark disregarding emissions from København.

Residential wood combustion (SNAP2) is the emission sector with the largest contribution, followed by road transport. Off-road is also a relatively large contributor (SNAP8) as well as agriculture (SNAP10). The contribution from agriculture is related to ammonia emissions that are transformed to ammonium in the atmosphere and thereby becomes part of secondary particles contributing to $PM_{2.5}$ as ammonium nitrate and ammonium sulphate.

The contribution from Danish emissions to premature deaths in København is approx. 70 which is about 23% of the total premature deaths in København.

Table 8.5. Contribution to mortality and morbidity in København from emission sectors in Denmark (excluding København) in 2030 (Figures rounded).

	Contribution of Denmark to city						Denmark to city
Health effects of air pollution in 2030	SNAP2	SNAP7	SNAP8	SNAP10	SNAP134	SNAP569	All
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	5	7	8	2	7	1	30
Chronic mortality ($PM_{2.5}$, NO_2)	13	8	4	6	5	2	38
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	19	16	13	8	12	3	71
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	15	23	22	7	19	3	89
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	5	2	0	3	1	1	11
Episodes with asthma among children ($PM_{2.5}$)	2	1	0	1	1	0	5
Episodes with bronchitis among adults ($PM_{2.5}$)	15	8	3	7	4	2	39
Episodes with bronchitis among children ($PM_{2.5}$)	49	25	9	17	13	7	120
Working days lost ($PM_{2.5}$)	970	490	190	420	270	140	250

Days with restricted activity (sick days) ($PM_{2.5}$)	12000	5900	2300	5100	3200	1700	30000
Days with minor restricted activity (O_3)	-320	-930	-1100	310	-420	89	-2400
Lung cancer morbidity ($PM_{2.5}$)	3	2	1	1	1	1	8

Abroad to city

Table 8.6 shows a summary of the contribution from emissions abroad to the city together with city to city contribution and contribution from Denmark (with København excluded).

The contribution from abroad is only given as the total health effects and is not broken down on emission sectors.

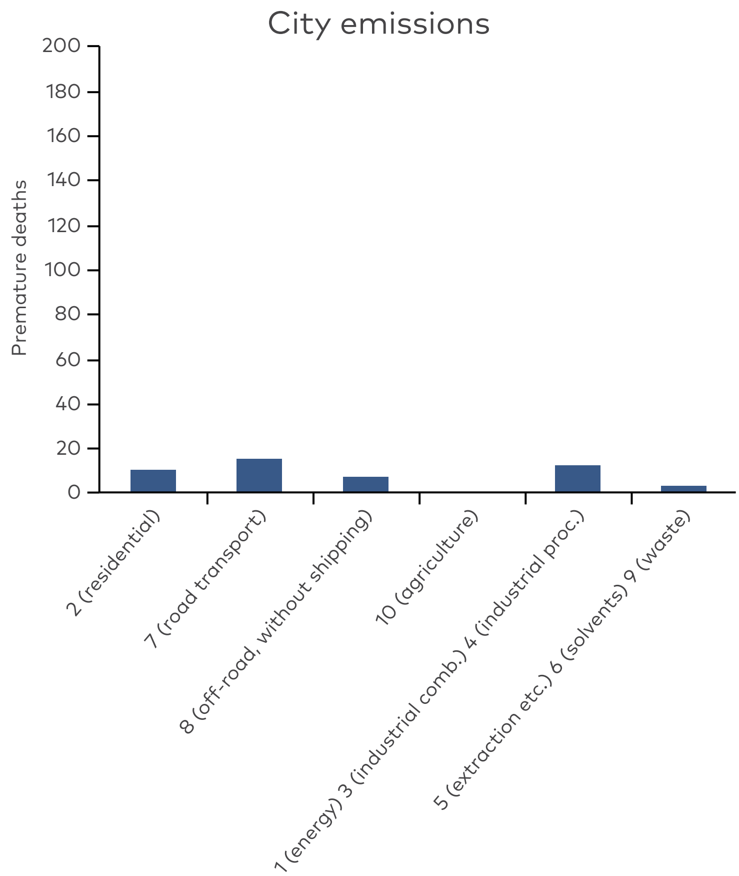
The contribution from emissions abroad to premature deaths in København is approx. 140, which is about 63% of the total premature deaths in København.

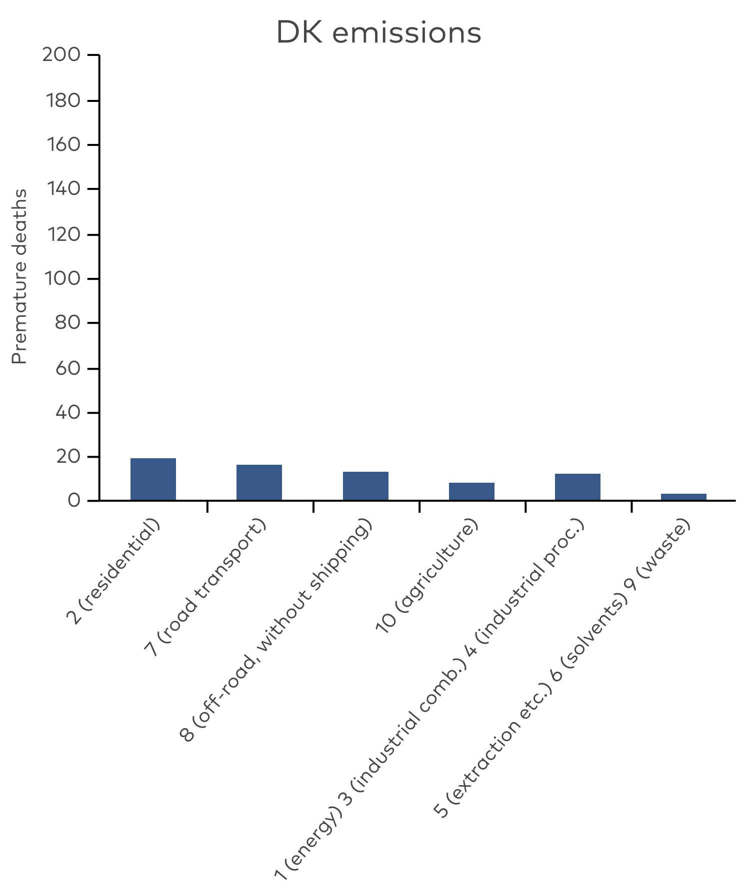
Table 8.6. Summary of contributions from city to city, Denmark to city and contribution from abroad to health effects in København in 2030 (number of cases).

	City to city	Denmark to city	Contribution from abroad	Total
Health effects of air pollution in 2030	**All**	**All**	**All**	**All**
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	20	30	60	110
Chronic mortality ($PM_{2.5}$, NO_2)	24	38	140	200
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	50	70	200	310

Total premature deaths (percentage)	15%	23%	63%	100%
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	64	89	250	410
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	3	11	110	120
Episodes with asthma among children ($PM_{2.5}$)	3	5	17	25
Episodes with bronchitis among adults ($PM_{2.5}$)	20	39	180	240
Episodes with bronchitis among children ($PM_{2.5}$)	63	120	970	1200
Working days lost ($PM_{2.5}$)	1200	2500	12000	15000
Days with restricted activity (sick days) ($PM_{2.5}$)	15000	30000	140000	190000
Days with minor restricted activity (O_3)	-3200	-2400	40000	34000
Lung cancer morbidity ($PM_{2.5}$)	4	8	32	45

The contributions are also visualised as a histogram in Figure 8.2


City emissions
Premature deaths
200
180
160
140
120
100
80
60
40
20
0
2 (residential)
7 (road transport)
8 (off-road, without shipping)
10 (agriculture)
1 (energy) 3 (industrial comb.) 4 (industrial proc.)
5 (extraction etc.) 6 (solvents) 9 (waste)


DK emissions
Premature deaths
200
180
160
140
120
100
80
60
40
20
0
2 (residential)
7 (road transport)
8 (off-road, without shipping)
10 (agriculture)
1 (energy) 3 (industrial comb.) 4 (industrial proc.)
5 (extraction etc.) 6 (solvents) 9 (waste)

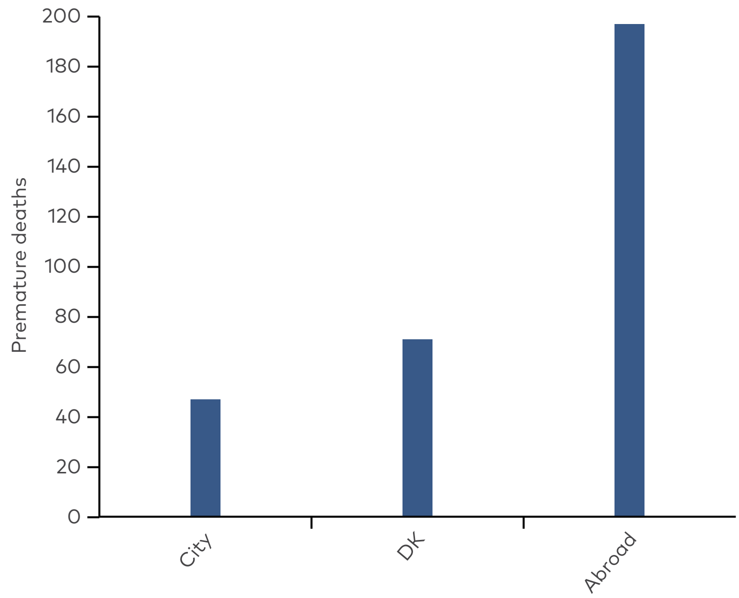


Figure 8.2. Visualisation of emission sector contributions to the premature deaths in København in 2030.

8.3 External costs and sector contributions in København

This section summarises the external costs of health effects in København in 2030 and the emission sector contributions to the costs.

The external costs will be similarly distributed as the health effects described in the previous section and hence a more concise description will be given in this section. The external costs are dominated by the costs associated with premature death.

External costs of health effects of air pollution in 2019 and 2030

The total costs of air pollution in København in 2019 is estimated to 1.1 billion EUR and 0.89 billion EUR in 2030. The decrease in costs is 21% from 2019 to 2030 similar to the predicted reduction in premature deaths of 22%.

External costs of mortality and morbidity of air pollution in 2030

The distribution of external costs on mortality and morbidity in 2030 is shown in Table 8.7.

Approx. 94% of the external costs in København in 2030 is associated with mortality and 6% with morbidity.

Table 8.7. External costs of health effects in København in 2030 (mio. EUR).

Health effects in 2030	Mio. EUR	%
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	500	
Chronic mortality ($PM_{2.5}$, NO_2)	330	
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	830	94%
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	4	
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	2	
Episodes with asthma among children ($PM_{2.5}$)	0	
Episodes with bronchitis among children and adults ($PM_{2.5}$)	10	
Working days lost ($PM_{2.5}$)	5	
Days with restricted activity (sick days) ($PM_{2.5}$)	30	
Days with minor restricted activity (O_3)	3	
Lung cancer morbidity ($PM_{2.5}$)	3	
Total morbidity	56	6%
Total premature death and morbidity	890	100%

Contribution of different emission sectors in 2030

The contribution to the external costs of different emission sectors as well as the contribution from the city, the country of the city and from sources abroad are for København shown in Table 8.8.

As expected the distribution of external costs closely follows the distribution of premature deaths shown in the previous section.

Table 8.8. Emission sector contributions to external costs of air pollution in København in 2030 (mio. EUR).

2030	City contribution to city						Contribution of Denmark to city						City to city	Denma to city	Contri-bution from abroad	Total
	SNAP 2	SNAP 7	SNAP 8	SNAP 10	SNAP 134	SNAP 569	SNAP 2	SNAP 7	SNAP 8	SNAP 10	SNAP 134	SNAP 569	All	All	All	All
Cost of health effects	25	48	25	0	35	7	48	48	46	20	41	9	140	210	530	890
Costs in %	3%	5%	3%	0%	4%	1%	5%	5%	5%	2%	5%	1%	16%	24%	60%	100%

8.4 Health effects and sector contributions in Stockholm

Mortality and morbidity effects of air pollution in 2019 and 2030

A summary of mortality and morbidity effects of air pollution in 2019 and 2030 is shown in Table 8.9.

The total number of premature deaths is predicted to approx. 600 in 2019 and approx. 500 in 2030 showing a decrease of approx. 19%. The decrease is a combined effect of an increase in population including more elderly persons and a decrease in air pollution levels. It is also seen that approx. 2/3 of premature deaths are related to chronic premature deaths due long-term exposure and approx. 1/3 to acute premature deaths due to short-term exposure to elevated air pollution levels.

The number of morbidity cases is predicted to decrease from 2019 to 2030.

Table 8.9. Mortality and morbidity effects of air pollution in Stockholm in 2019 and 2030.

Health effects	2019	2030	Difference
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	200	160	-24%
Chronic mortality ($PM_{2.5}$, NO_2)	420	350	-17%
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	620	510	-19%
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	590	470	-20%
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	180	180	-1%
Episodes with asthma among children ($PM_{2.5}$)	42	37	-11%
Episodes with bronchitis among adults ($PM_{2.5}$)	400	380	-5%
Episodes with bronchitis among children ($PM_{2.5}$)	1700	1600	-5%
Working days lost ($PM_{2.5}$)	81000	78000	-4%
Days with restricted activity (sick days) ($PM_{2.5}$)	440000	410000	-6%
Days with minor restricted activity (O_3)	52000	55000	4%
Lung cancer morbidity ($PM_{2.5}$)	36	35	-4%
Total inhabitants	1064033	1154401	8%
Inhabitants over age of 30 years	677363	750685	11%
Inhabitants over age of 30 years (%)	64%	65%	2%

Contribution of different emission sectors in 2030

The analysis of the contribution of the different emission sectors focuses on 2030 to illustrate the potential benefits of regulation of the different emission sectors in the future.

City to city

Table 8.10 shows the contribution to Stockholm of the emission sectors within Stockholm.

Approx. 200 premature deaths can be attributed to emission sources within the city, which is equivalent to about 35% of total premature deaths (500). The percentage attributed to emission sources within the city is higher for Stockholm compared with København (15%). Possible explanations could be that the geographic extent of Stockholm is larger and the population is also larger and background concentrations of (long-range transported) $PM_{2.5}$ are lower.

It is seen that the single largest contribution to mortality and morbidity in 2030 is from the emission sector transport (SNAP7) and the combined sectors of energy, industrial combustion and industrial processes (SNAP134) are responsible for the second largest contribution whereas residential wood combustion (SNAP2) seems to be of less importance compared with København. Agriculture (SNAP10) does not contribute to premature deaths as there is very limited agriculture in Stockholm.

Negative values for days with minor restricted activity due to ozone is a result of chemistry in the atmosphere, where NO_x emissions lead to lower ozone concentrations.

Table 8.10. Contribution to mortality and morbidity in Stockholm from emission sectors in Stockholm in 2030 (figures rounded).

	City contribution to city						City to city
Health effects of air pollution in 2030	SNAP2	SNAP7	SNAP8	SNAP10	SNAP134	SNAP 569	All
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	5	21	7	0	25	1	60
Chronic mortality ($PM_{2.5}$, NO_2)	14	50	8	0	36	7	110
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	19	71	15	0	61	8	180
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	13	53	21	0	47	2	140
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	4	14	1	0	8	3	29
Episodes with asthma among children ($PM_{2.5}$)	2	5	1	0	3	1	11
Episodes with bronchitis among adults ($PM_{2.5}$)	15	50	5	0	28	8	110
Episodes with bronchitis among children ($PM_{2.5}$)	48	160	15	0	89	26	340
Working days lost ($PM_{2.5}$)	3100	10000	950	1	5700	1700	22000
Days with restricted activity (sick days) ($PM_{2.5}$)	16000	55000	5000	8	30000	8700	110000
Days with minor restricted activity (O_3)	-500	-2100	-940	-5	-1300	-6	-4900
Lung cancer morbidity ($PM_{2.5}$)	1	5	0	0	3	1	10

Country to city

Table 8.11 shows the contribution to Stockholm from the emission sectors within Sweden disregarding emissions from Stockholm.

The contribution from Swedish emissions to premature deaths in Stockholm is approx. 90 which is about 18% of total premature deaths in Stockholm.

The three largest contributions to health effects are from the emission sectors road transport (SNAP7), residential wood combustion (SNAP2) and the combined sectors of energy, industrial combustion and industrial processes (SNAP134). Off-road emissions also contribute (SNAP8) as well as agriculture (SNAP10). The contribution from agriculture is related to ammonia emissions that are transformed to ammonium nitrate and ammonium sulphate in the atmosphere and thereby becomes part of secondary particles of $PM_{2.5}$.

Table 8.11. Contribution to mortality and morbidity in Stockholm from emission sectors in Sweden in 2030 (figures rounded).

Health effects of air pollution in 2030	Contribution of Sweden to city						Sweden to city
	SNAP2	SNAP7	SNAP8	SNAP10	SNAP134	SNAP569	All
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	5	10	4	1	7	1	28
Chronic mortality ($PM_{2.5}$, NO_2)	14	25	4	5	10	4	63
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	19	35	8	6	17	5	90
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	11	25	10	4	14	2	66
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	5	8	1	2	4	2	23
Episodes with asthma among children ($PM_{2.5}$)	2	3	0	1	1	1	7
Episodes with bronchitis among adults ($PM_{2.5}$)	16	27	4	5	11	5	67
Episodes with bronchitis among children ($PM_{2.5}$)	50	84	12	14	32	15	200
Working days lost ($PM_{2.5}$)	3200	5500	820	1100	2200	1000	14000

Days with restricted activity (sick days) ($PM_{2.5}$)	17000	29000	4300	5700	11000	5400	73000
Days with minor restricted activity (O_3)	-1	-300	-15	440	350	140	610
Lung cancer morbidity ($PM_{2.5}$)	1	2	0	0	1	0	6

Abroad to city

Table 8.12 shows a summary of the contribution from emissions abroad to the city together with city-to-city contribution and contribution from Sweden (excluding the city).

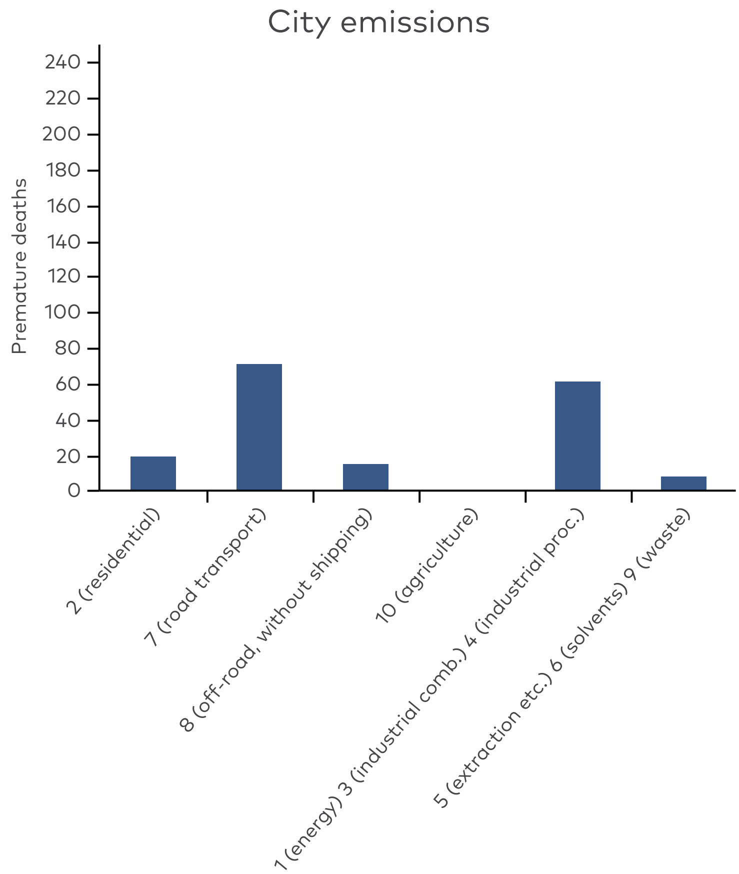
The contribution from abroad is only given as the total health effects and is not broken down on emission sectors.

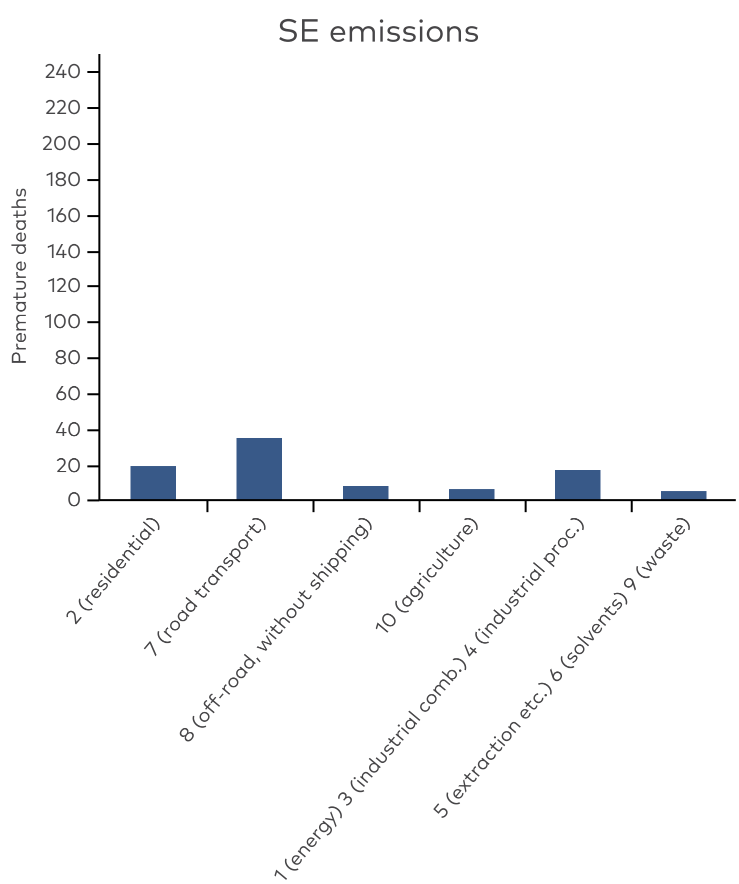
The contribution from emissions abroad to premature deaths in Stockholm is approx. 240, which is about 47% of the total premature deaths in Stockholm. The percentage is lower than for København (63%) due to lower background concentration of $PM_{2.5}$ in Stockholm compared with København, but also because the contribution from Stockholm itself plays a larger role as explained above.

Table 8.12. Summary of contributions from city to city, country to city and contribution from abroad to health effects in Stockholm in 2030 (number of cases). (Figures rounded).

	City to city	Country to city	Contribution from abroad	Total
Health effects of air pollution in 2030	**All**	**All**	**All**	**All**
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	60	28	68	160
Chronic mortality ($PM_{2.5}$, NO_2)	120	63	170	350
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	180	90	240	500
Total premature deaths (percentage)	35%	18%	47%	100%
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	140	66	270	470
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	29	23	130	180
Episodes with asthma among children ($PM_{2.5}$)	11	7	19	37
Episodes with bronchitis among adults ($PM_{2.5}$)	110	67	210	380
Episodes with bronchitis among children ($PM_{2.5}$)	340	210	1100	1600
Working days lost ($PM_{2.5}$)	22000	14000	43000	78000
Days with restricted activity (sick days) ($PM_{2.5}$)	115000	73000	230000	410000
Days with minor restricted activity (O_3)	-4900	610	59000	55000
Lung cancer morbidity ($PM_{2.5}$)	10	6	20	35

The contributions are also visualised as a histogram in Figure 8.3.





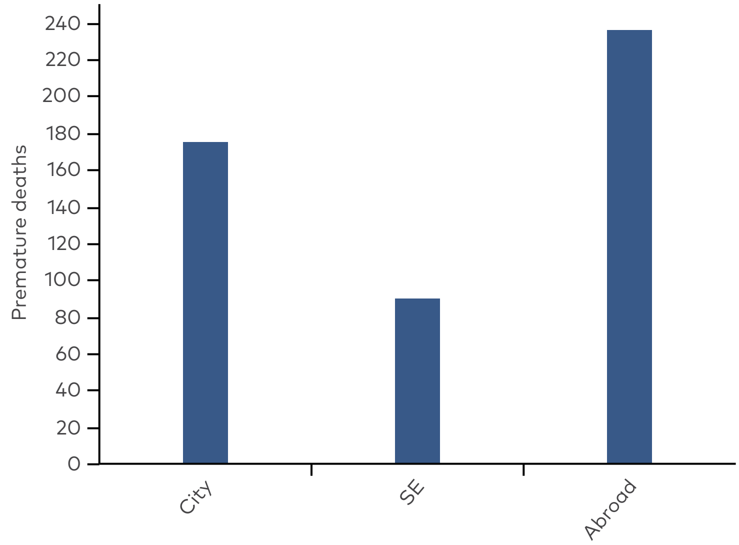


Figure 8.3. Visualisation of emission sector contributions to premature deaths in Stockholm in 2030.

8.5 External costs and sector contributions in Stockholm

This section summarises the external costs of health effects in Stockholm in 2030 and emission sector contributions.

The external costs will be similarly distributed as the health effects and hence a more concise description for external costs is given in the following. The external costs are dominated by the costs associated with premature mortality. The number of premature deaths is dominated by chronic deaths whereas costs are dominated by acute deaths due to the higher costs for acute deaths compared with chronic deaths.

External costs of health effects of air pollution in 2019 and 2030

The total costs of air pollution in Stockholm in 2019 is estimated to 1.6 billion EUR and to 1.3 billion EUR in 2030. The decrease in costs is 20% from 2019 to 2030, similar to the predicted reduction in premature deaths of 19%.

External costs of mortality and morbidity of air pollution in 2030

The distribution of external costs on mortality and morbidity in 2030 is shown in Table 8.13.

Approx. 91% of the external costs in Stockholm in 2030 is associated with mortality and 9% with morbidity, similar to results from København (94%/6%).

Table 8.13. External costs of health effects in Stockholm in 2030 (million EUR) (rounded figures).

Health effects in 2030	Mio. EUR	%
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	710	
Chronic mortality ($PM_{2.5}$, NO_2)	460	
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	1200	91%
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	5	
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	3	
Episodes with asthma among children ($PM_{2.5}$)	0	
Episodes with bronchitis among children and adults ($PM_{2.5}$)	16	
Working days lost ($PM_{2.5}$)	24	
Days with restricted activity (sick days) ($PM_{2.5}$)	66	
Days with minor restricted activity (O_3)	4	
Lung cancer morbidity ($PM_{2.5}$)	3	
Total morbidity	120	9%
Total premature death and morbidity	1300	100%

Contribution of different emission sectors in 2030

The contribution to external costs of different emission sectors as well as the contribution from the city, the country of the city and from sources abroad are for Stockholm shown in Table 8.14.

As expected the distribution of external costs closely follows the distribution of premature deaths shown in the previous section.

Table 8.14. Sector contributions to external costs of air pollution in Stockholm in 2030 (mio. EUR). (Rounded figures).

2030	City contribution to city					Contribution of Sweden to city							City	Sweden	Abroad	Total
	SNAP 2	SNAP 7	SNAP 8	SNAP 10	SNAP 134	SNAP 569	SNAP 2	SNAP 7	SNAP 8	SNAP 10	SNAP 134	SNAP 569	All	All	All	All
Cost of health effects	47	180	46	0	170	18	45	88	23	15	47	11	460	230	600	1290
Costs in %	4%	14%	4%	0%	13%	1%	3%	7%	2%	1%	4%	1%	36%	18%	47%	100%

8.6 Health effects and sector contributions in Helsinki

Mortality and morbidity effects of air pollution in 2019 and 2030

A summary of mortality and morbidity effects of air pollution in 2019 and 2030 is shown in Table 8.15.

Total premature deaths are predicted to approx. 390 in 2019 and 330 in 2030 showing a decrease of approx. 15%. The decrease is a combined effect of an increase in population including more elderly persons and a decrease in air pollution levels. It is also seen that approx. 60% of premature deaths are related to chronic premature deaths due long-term exposure and approx. 40% to acute premature deaths due to short-term exposure with elevated air pollution levels.

The number of morbidity cases is also predicted to decrease from 2019 to 2030.

Table 8.15. Mortality and morbidity effects of air pollution in Helsinki in 2019 and 2030. (Rounded figures).

Health effects	2019	2030	Difference
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	170	140	-18%
Chronic mortality ($PM_{2.5}$, NO_2)	220	190	-13%
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	390	330	-15%
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	460	370	-19%
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	120	110	-7%
Episodes with asthma among children ($PM_{2.5}$)	40	29	-29%
Episodes with bronchitis among adults ($PM_{2.5}$)	230	200	-11%
Episodes with bronchitis among children ($PM_{2.5}$)	930	750	-19%
Working days lost ($PM_{2.5}$)	17000	16000	-9%
Days with restricted activity (sick days) ($PM_{2.5}$)	180000	160000	-13%
Days with minor restricted activity (O_3)	16000	16000	-1%
Lung cancer morbidity ($PM_{2.5}$)	26	23	-9%
Total inhabitants	687693	687865	0%
Inhabitants over age of 30 years	456697	478652	5%
Inhabitants over age of 30 years (%)	66%	70%	5%

Contribution of different emission sectors in 2030

The analysis of the contribution of the different emission sectors focuses on 2030 to illustrate the potential benefits of regulation of the different emission sectors in the future.

City to city

Table 8.16 shows the contribution to Helsinki of the emission sectors within Helsinki.

Approx. 80 premature deaths can be attributed to emission sources within the city, equivalent to about 25% of total premature deaths (330). The percentage attributed to emission sources within the city is higher than for København (15%), but lower than for Stockholm (35%). Possible explanations could be that the size of the population in Helsinki is similar to København, but background concentrations of $PM_{2.5}$ are lower.

The largest contribution comes from the combined sectors of energy, industrial combustion and industrial processes (SNAP134), but the largest single contribution is from the emission sector road transport (SNAP7). Residential wood combustion (SNAP2) has the fourth largest contribution. Agriculture (SNAP10) does not contribute to premature deaths as there is very limited agriculture in Helsinki.

Negative values for days with minor restricted activity due to ozone is a result of chemistry in the atmosphere, where NO_x emissions lead to lower ozone concentrations.

Table 8.16. Contribution to mortality and morbidity in Helsinki from emission sectors in Helsinki in 2030. (Figures rounded).

Health effects of air pollution in 2030	City contribution to city						City to city
	SNAP2	SNAP7	SNAP8	SNAP10	SNAP134	SNAP569	All
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	1	7	5	0	35	1	48
Chronic mortality ($PM_{2.5}$, NO_2)	5	14	4	0	8	3	35
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	6	21	9	0	43	3	83
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	4	22	16	0	54	1	96
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	2	4	0	0	-2	1	5
Episodes with asthma among children ($PM_{2.5}$)	1	2	1	0	1	0	4
Episodes with bronchitis among adults ($PM_{2.5}$)	5	15	4	0	5	3	32

Episodes with bronchitis among children ($PM_{2.5}$)	14	38	9	1	13	8	83
Working days lost ($PM_{2.5}$)	420	1100	270	17	390	230	2400
Days with restricted activity (sick days) ($PM_{2.5}$)	4300	12000	2800	170	4000	2400	25000
Days with minor restricted activity (O_3)	-82	-780	-810	-2	-2100	-4	-3800
Lung cancer morbidity ($PM_{2.5}$)	1	2	0	0	0	0	3

Contribution from Finland to city

Table 8.17 shows the contribution to Helsinki from the emission sectors within Finland disregarding emissions from Helsinki.

The contribution from emissions in Finland to premature deaths in Helsinki is approx. 70 which is about 21% of total premature deaths in Helsinki.

The three emission sectors with the largest contribution to health effects are the combined sectors of energy, industrial combustion and industrial processes (SNAP134), road transport (SNAP7) and residential wood combustion (SNAP2). Off-road emissions are also contributing (SNAP8) as well as agriculture (SNAP10). The contribution from agriculture is related to ammonia emissions that are transformed to ammonium nitrate and ammonium sulphate in the atmosphere and thereby become part of secondary particles of $PM_{2.5}$.

Table 8.17. Contribution to mortality and morbidity in Helsinki from emission sectors in Finland in 2030.

Health effects of air pollution in 2030	Contribution of Finland to city						Finland to city
	SNAP2	SNAP7	SNAP8	SNAP10	SNAP134	SNAP569	All
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	3	6	3	1	14	0	27
Chronic mortality ($PM_{2.5}$, NO_2)	12	13	5	2	8	2	43
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	16	19	8	3	22	2	70
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	9	19	10	3	35	1	77
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	5	5	2	1	1	1	15
Episodes with asthma among children ($PM_{2.5}$)	2	2	1	0	1	0	6
Episodes with bronchitis among adults ($PM_{2.5}$)	13	14	5	2	7	2	42

Episodes with bronchitis among children ($PM_{2.5}$)	34	35	12	5	16	4	110
Working days lost ($PM_{2.5}$)	1000	1100	390	190	520	130	3300
Days with restricted activity (sick days) ($PM_{2.5}$)	10000	11000	4000	1900	5300	1300	34000
Days with minor restricted activity (O_3)	-120	-390	-210	140	-650	33	-1200
Lung cancer morbidity ($PM_{2.5}$)	1	1	0	0	1	0	4

Abroad to city

Table 8.18 shows a summary of the contribution from abroad to the city together with city to city contribution and contribution from Finland.

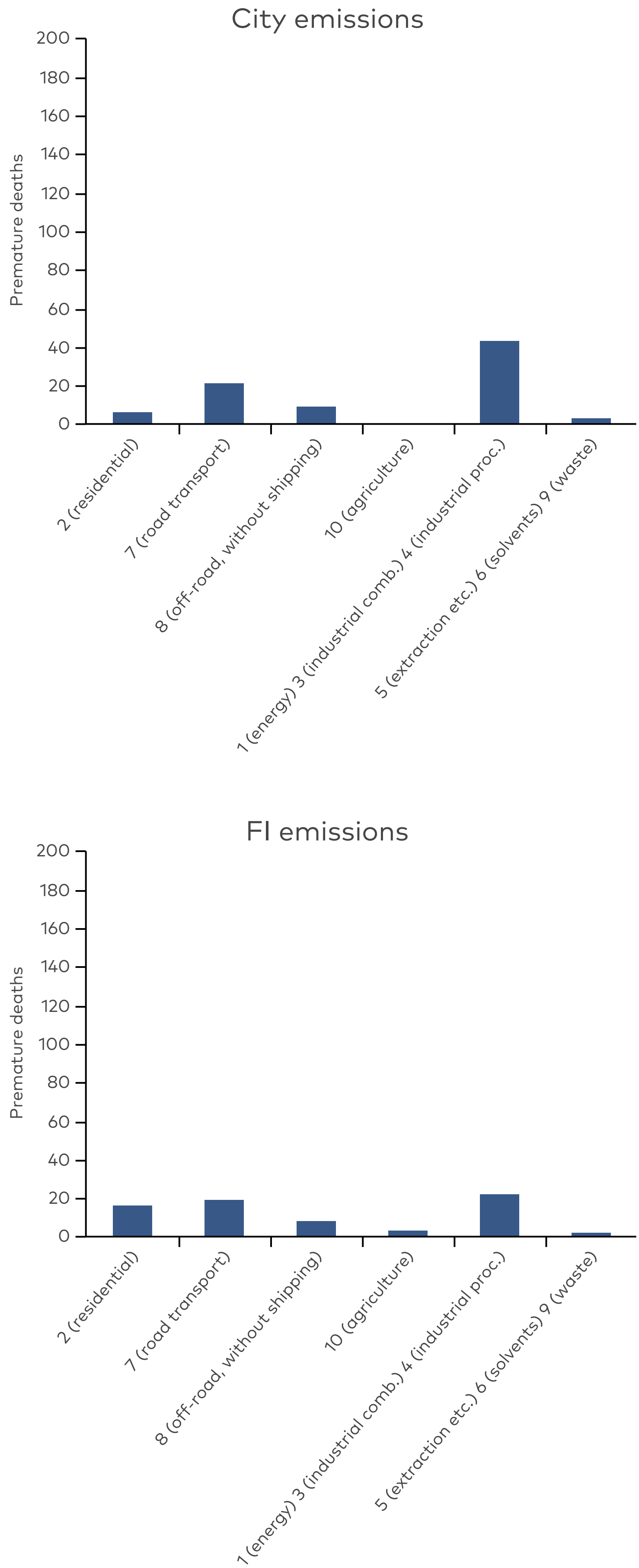
The contribution from abroad is only given as the total health effects and is not broken down on emission sectors.

The contribution from emissions abroad to premature deaths in Helsinki is approx. 180 which is about 53% of total premature deaths in Helsinki. The percentage is comparable to Stockholm (47%) for the same reasons as given for Stockholm when compared with København.

Table 8.18. Summary of contributions from city to city, country to city and contribution from abroad to health effects in Helsinki in 2030 (number of cases).

Health effects of air pollution in 2030	City to city All	Country to city All	Contribution from abroad All	Total All
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	48	27	66	140
Chronic mortality ($PM_{2.5}$, NO_2)	35	43	110	190
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	83	70	180	330
Total premature deaths (percentage)	25%	21%	53%	100%
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	96	77	200	370
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	5	15	87	110
Episodes with asthma among children ($PM_{2.5}$)	4	6	18	29
Episodes with bronchitis among adults ($PM_{2.5}$)	32	42	130	200
Episodes with bronchitis among children ($PM_{2.5}$)	83	110	560	750
Working days lost ($PM_{2.5}$)	2400	3300	9800	16000
Days with restricted activity (sick days) ($PM_{2.5}$)	25000	34000	100000	160000
Days with minor restricted activity (O_3)	-3800	-1200	21000	16000
Lung cancer morbidity ($PM_{2.5}$)	3	4	16	23

The contributions are also visualised as a histogram in Figure 8.4.



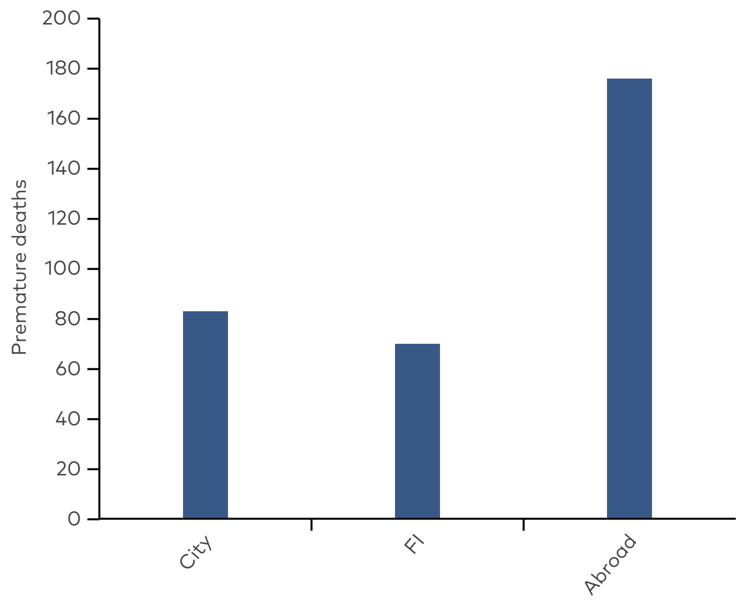


Figure 8.4. Visualisation of emission sector contributions to premature deaths in Helsinki in 2030.

8.7 External costs and sector contributions in Helsinki

This section summarises the external costs of health effects in Helsinki in 2030 and the emission sector contributions.

The external costs are dominated by the costs associated with premature mortality. The number of premature deaths are dominated by the chronic deaths whereas costs are dominated by acute deaths due to the higher costs for acute deaths compared with chronic deaths.

External costs of health effects of air pollution in 2019 and 2030

The total costs of air pollution in Helsinki in 2019 is estimated to 1.2 billion EUR and 0.9 billion EUR in 2030. The decrease in costs is 16% from 2019 to 2030 similar to the predicted reduction in premature deaths of 15%.

External costs of mortality and morbidity of air pollution in 2030

The distribution of external costs on mortality and morbidity in 2030 is shown in Table 8.19.

Approx. 95% of the external costs in Helsinki in 2030 is associated with mortality and 5% with morbidity similar to results from København (94%/6%) and Stockholm (91%/9%).

Table 8.19. External costs of health effects in Helsinki in 2030 (mio. EUR). (Figures rounded).

Health effects in 2030	Mio. EUR	%
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	640	
Chronic mortality ($PM_{2.5}$, NO_2)	280	
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	920	95%
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	4	
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	2	
Episodes with asthma among children ($PM_{2.5}$)	0	
Episodes with bronchitis among children and adults ($PM_{2.5}$)	8	
Working days lost ($PM_{2.5}$)	5	
Days with restricted activity (sick days) ($PM_{2.5}$)	25	
Days with minor restricted activity (O_3)	1	
Lung cancer morbidity ($PM_{2.5}$)	2	
Total morbidity	50	5%
Total premature death and morbidity	960	100%

Contribution of different emission sectors in 2030

The contribution to external costs of different emission sectors as well as the contribution from the city, the country of the city and sources from abroad are for Helsinki shown in Table 8.20.

As expected the distribution of external costs closely follows the distribution of premature deaths shown in the previous section.

Table 8.20. Sector contributions to external costs of air pollution in Helsinki in 2030 (million EUR). (Figures rounded).

2030	City contribution to city						Contribution of Finland to city						City	Finland	Abroad	Total
	SNAP 2	SNAP 7	SNAP 8	SNAP 10	SNAP 134	SNAP 569	SNAP 2	SNAP 7	SNAP 8	SNAP 10	SNAP 134	SNAP 569	All	All	All	All
Cost of health effects	15	55	29	1	170	8	37	48	22	8	77	4	280	200	490	960
Costs in %	2%	6%	3%	0%	18%	1%	4%	5%	2%	1%	8%	0%	29%	20%	51%	100%

8.9 Health effects and sector contributions in Reykjavík

Mortality and morbidity effects of air pollution in 2019 and 2030

A summary of mortality and morbidity effects of air pollution in 2019 and 2030 is shown in Table 8.21.

Total premature deaths are predicted to approx. 39 in 2019 and also 39 in 2030. The reason why the number of premature deaths is not changing is a combined effect of a large increase in population including more elderly persons and a decrease in air pollution levels.

Table 8.21. Mortality and morbidity effects of air pollution in Reykjavík in 2019 and 2030. (Figures rounded).

Health effects	2019	2030	Difference
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	22	21	-5%
Chronic mortality ($PM_{2.5}$, NO_2)	16	18	9%
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	39	39	1%
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	57	58	2%
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	13	14	9%
Episodes with asthma among children ($PM_{2.5}$)	6	6	-8%
Episodes with bronchitis among adults ($PM_{2.5}$)	36	37	4%
Episodes with bronchitis among children ($PM_{2.5}$)	200	300	9%
Working days lost ($PM_{2.5}$)	3900	4300	9%
Days with restricted activity (sick days) ($PM_{2.5}$)	31400	32000	2%
Days with minor restricted activity (O_3)	11900	11500	-3%
Lung cancer morbidity ($PM_{2.5}$)	3	4	9%
Total inhabitants	226661	264756	17%
Inhabitants over age of 30 years	134433	168473	25%
Inhabitants over age of 30 years (%)	59%	64%	7%

Contribution of different emission sectors in 2030

The analysis of the contribution of the different emission sectors focuses on 2030 to illustrate the potential benefits of regulation of the different emission sectors in the future.

City to city

Table 8.22 shows the contribution to Reykjavík of the emission sectors within Reykjavík.

Approx. 17 premature deaths can be attributed to emission sources within the city equivalent to about 43% of total premature deaths (39). The percentage attributed to emission sources within the city is higher than for København (15%), Helsinki (25%) and Stockholm (35%). The reason is mainly related to the location of Iceland in the North Atlantic Ocean with relative low contributions from emission sources abroad.

The contribution from different emission sources in Reykjavík shows a very different pattern than for the other Nordic capital cities. The largest contribution comes from the off-road sector (SNAP8) related to the fishing fleet. However, in the emission inventory these emissions are allocated to harbour areas and therefore the concentration contributions from this sector is overestimated as emissions correctly should be allocated to sea areas. Residential wood combustion (SNAP2) is insignificant.

Negative values for days with minor restricted activity due to ozone is a result of chemistry in the atmosphere, where NO_x emissions lead to lower ozone concentrations.

Table 8.22. Contribution to mortality and morbidity in Reykjavík from emission sectors in Reykjavík in 2030.

Health effects of air pollution in 2030	City contribution to city						City to city
	SNAP2	SNAP7	SNAP8	SNAP10	SNAP134	SNAP569	All
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	0	1	11	2	1	0	15
Chronic mortality ($PM_{2.5}$, NO_2)	0	1	1	0	0	1	4
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	0	2	12	2	1	0	17
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2 ,O_3)	0	1	22	4	1	0	28
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	0	0	-1	0	0	0	0
Episodes with asthma among children ($PM_{2.5}$)	0	0	0	0	0	0	1
Episodes with bronchitis among adults ($PM_{2.5}$)	0	2	2	0	1	1	7

Episodes with bronchitis among children ($PM_{2.5}$)	0	8	8	0	2	3	21
Working days lost ($PM_{2.5}$)	2	256	258	8	74	95	694
Days with restricted activity (sick days) ($PM_{2.5}$)	14	1912	1926	62	552	708	5175
Days with minor restricted activity (O_3)	-9	-103	-2522	-425	-46	-3	-3108
Lung cancer morbidity ($PM_{2.5}$)	0	0	0	0	0	0	1

Contribution from Iceland to city

Table 8.23 shows the contribution to Reykjavík from the emission sectors within Iceland disregarding emissions from Reykjavík.

The contribution from emissions in Iceland to premature deaths in Reykjavík is approx. 11 which is about 27% of total premature deaths in Reykjavík.

The two largest contributions to health effects come from emissions from the off-road sector (SNAP8) and the combined sector of energy, industrial combustion and industrial processes (SNAP134).

Table 8.23. Contribution to mortality and morbidity in Reykjavík from emission sectors in Iceland in 2030. (Rounded figures).

Health effects of air pollution in 2030	Contribution of Iceland to city						Iceland to city
	SNAP2	SNAP7	SNAP8	SNAP10	SNAP134	SNAP569	All
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	0	0	5	1	2	0	8
Chronic mortality ($PM_{2.5}$, NO_2)	0	0	1	1	1	0	4
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	0	0	6	1	3	0	11
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	0	0	13	1	2	0	16
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$,O_3)	0	0	0	0	1	0	1
Episodes with asthma among children ($PM_{2.5}$)	0	0	0	0	0	0	1
Episodes with bronchitis among adults ($PM_{2.5}$)	0	1	3	2	3	1	9
Episodes with bronchitis among children ($PM_{2.5}$)	0	2	9	2	8	1	23

Working days lost ($PM_{2.5}$)	1	85	308	213	282	44	933
Days with restricted activity (sick days) ($PM_{2.5}$)	8	632	2299	1589	2102	326	6957
Days with minor restricted activity (O_3)	21	12	-1095	14	-15	-4	-1067
Lung cancer morbidity ($PM_{2.5}$)	0	0	0	0	0	0	1

Contribution to city from emissions from abroad

Table 8.24 shows a summary of the contribution from abroad to the city together with city to city contribution and contribution from Iceland.

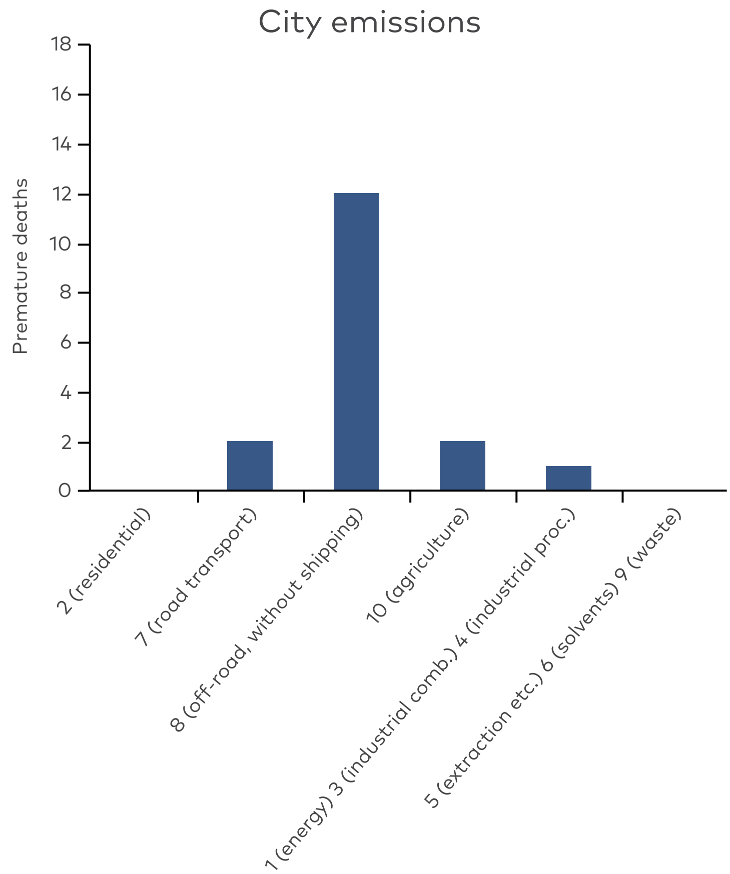
The contribution from abroad is only given as the total health effects and is not broken down on emission sectors.

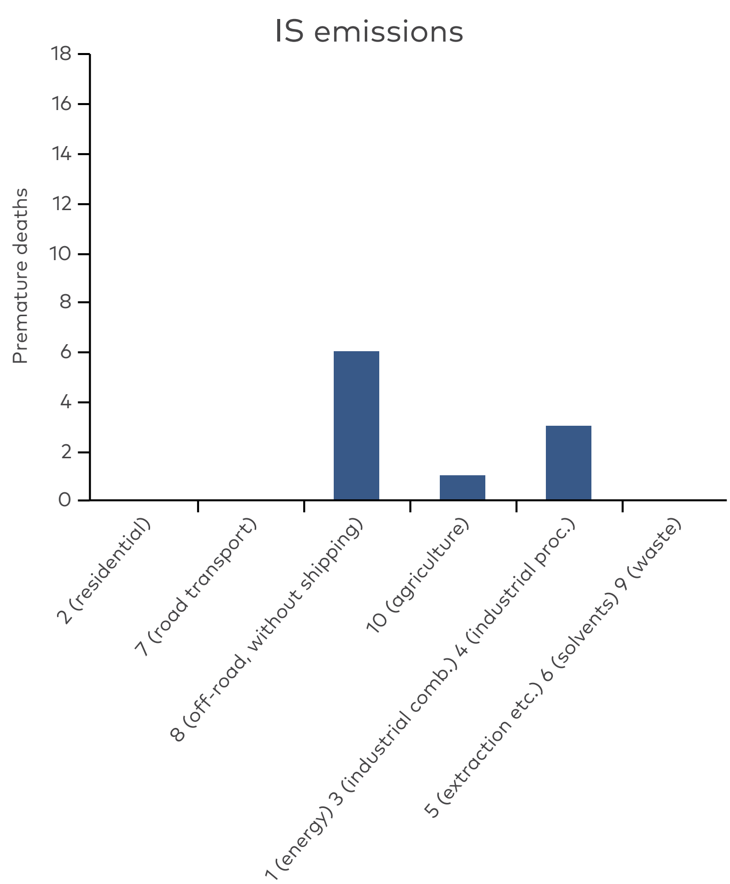
The contribution from emissions from abroad to premature deaths in Reykjavík is approx. 11 which is only approx. 30% of the total premature deaths in Reykjavík. The percentage is the lowest compared with the other Nordic capital cities. The reason is the relatively low $PM_{2.5}$ concentrations causing less chronic mortality compared with other capital cities.

Table 8.24. Summary of contributions from city to city, country to city and contribution from abroad to health effects in Reykjavík in 2030 (number of cases).

Health effects of air pollution in 2030	City to city	Country to city	Contribution from abroad	Total
	All	All	All	All
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	15	8	-2	21
Chronic mortality ($PM_{2.5}$, NO_2)	4	4	9	18
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	17	11	11	39
Total premature deaths (percentage)	43%	27%	30%	100%
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	28	16	14	58
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	0	1	13	14
Episodes with asthma among children ($PM_{2.5}$)	1	1	4	6
Episodes with bronchitis among adults ($PM_{2.5}$)	7	9	21	37
Episodes with bronchitis among children ($PM_{2.5}$)	21	23	258	302
Working days lost ($PM_{2.5}$)	694	933	2656	4282
Days with restricted activity (sick days) ($PM_{2.5}$)	5175	6957	19802	31934
Days with minor restricted activity (O_3)	-3108	-1067	15651	11475
Lung cancer morbidity ($PM_{2.5}$)	1	1	1	4

The contributions are also visualised as a histogram in Figure 8.5.





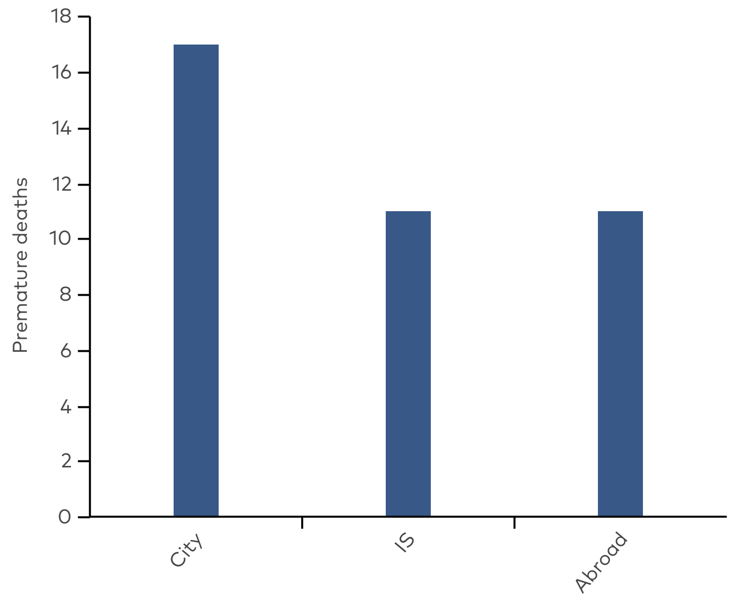


Figure 8.5. Visualisation of emission sector contributions to premature deaths in Reykjavík in 2030.

8.10 External costs and sector contributions in Reykjavík

This section summarises the external costs of health effects in Reykjavík in 2030 and sector contributions.

The external costs are dominated by the costs associated with premature mortality. In case of Reykjavík, the number of premature deaths are dominated by acute deaths, which is different from the other Nordic capital cities where chronic deaths dominate.

External costs of health effects of air pollution in 2019 and 2030

The total costs of air pollution in Reykjavík in 2019 is estimated to 0.14 billion EUR and also 0.14 billion EUR in 2030. The costs are the same in 2019 and 2030 similar to the predicted number of premature deaths.

External costs of mortality and morbidity of air pollution in 2030

The distribution of external costs on mortality and morbidity in 2030 is shown in Table 8.25.

Approx. 93% of the external costs in Reykjavík in 2030 is associated with mortality and 7% with morbidity similar to results from København (94%/6%), Stockholm (91%/9%) and Helsinki (95%/5%).

Table 8.25. External costs of health effects in Reykjavík in 2030 (million EUR).

Health effects in 2030	Mio. EUR	%
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	96	
Chronic mortality ($PM_{2.5}$, NO_2)	31	
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	127	93%
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	1	
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	0	
Episodes with asthma among children ($PM_{2.5}$)	0	
Episodes with bronchitis among children and adults ($PM_{2.5}$)	2	
Working days lost ($PM_{2.5}$)	1	
Days with restricted activity (sick days) ($PM_{2.5}$)	5	
Days with minor restricted activity (O_3)	1	
Lung cancer morbidity ($PM_{2.5}$)	0	
Total morbidity	10	7%
Total premature death and morbidity	138	100%

Contribution of different emission sectors in 2030

The contribution to external costs of different emission sectors as well as the contribution from the city, the country of the city and sources from abroad are for Reykjavík shown in Table 8.26.

As expected the distribution of external costs closely follows the distribution of premature deaths shown in the previous section.

Table 8.26. Sector contributions to external costs of air pollution in Reykjavík in 2030 (mio. EUR).

2030	City contribution to city						Contribution of Iceland to city						City	Iceland	Abro-ad	Total
	SNAP 2	SNAP 7	SNAP 8	SNAP 10	SNAP 134	SNAP 569	SNAP 2	SNAP 7	SNAP 8	SNAP 10	SNAP 134	SNAP 569	All	All	All	All
Cost of health effects	0	5	51	7	6	1	0	1	24	4	11	1	70	41	26	137
Costs in %	0%	4%	37%	5%	4%	1%	0%	1%	18%	3%	8%	1%	51%	30%	19%	100%

8.11 Health effects in Oslo

Data for 2030 is not available for Oslo due to data problems described in chapter 5, and hence health effects and related costs as well as sector contributions are not available.

Mortality and morbidity effects of air pollution in 2019

A summary of mortality and morbidity effects of air pollution for Oslo in 2019 is shown in Table 8.27.

The total number of premature deaths is calculated to approx. 450 in 2019.

Table 8.27. Mortality and morbidity effects of air pollution in Oslo in 2019.

Health effects	2019
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	130
Chronic mortality ($PM_{2.5}$, NO_2)	320
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	450
Hospital admissions due to respiratory symptoms ($PM_{2.5}$, NO_2, O_3)	490
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$, O_3)	150
Episodes with asthma among children ($PM_{2.5}$)	24
Episodes with bronchitis among adults ($PM_{2.5}$)	390
Episodes with bronchitis among children ($PM_{2.5}$)	1600
Working days lost ($PM_{2.5}$)	25000
Days with restricted activity (sick days) ($PM_{2.5}$)	300000
Days with minor restricted activity (O_3)	21000
Lung cancer morbidity ($PM_{2.5}$)	52
Total inhabitants	697526
Inhabitants over age of 30 years	439860
Inhabitants over age of 30 years (%)	63%

It is also for Oslo seen that approx. 2/3 of the premature deaths are related to chronic premature deaths due long-term exposure and approx. 1/3 to acute premature deaths due to short-term exposure with elevated air pollution levels.

8.12 External costs in Oslo

This section summarises the external costs of health effects in Oslo.

The external costs are dominated by the costs associated with premature mortality. The number of premature deaths is dominated by chronic deaths whereas costs are dominated by acute deaths due to higher costs for acute deaths compared with chronic deaths.

The total costs of air pollution in Oslo in 2019 is estimated to 1.2 billion EUR.

8.13 Summary of health effects and costs for capital cities

Premature mortality

A summary of the number of premature deaths in the Nordic capital cities due to air pollution is given in Table 8.28.

Key factors in determination of the number of premature deaths are air quality levels of $PM_{2.5}$, NO_2 and O_3 and the number of inhabitants. This is also evident from the results in Table 8.28. Although populations are expected to grow from 2019 to 2030, premature deaths are predicted to decrease as air quality improves.

Table 8.28. Number of premature deaths in the capital cities in 2019 and 2030.

	Area (km^2)	Inhabitants in 2019	Inhabitants in 2030	2019	2030	Differ-ence
København	95	594,679	610,810	410	310	-22%
Stockholm	207	1,064,033	1,154,401	620	510	-19%
Helsinki	195	687,693	687,865	390	330	-15%
Reykavik	173	226,661	264,756	39	39	1%
Oslo	262	664,000	697,526	450	n.a.	n.a.

The distribution of premature death caused by emissions from the city, from the country and from abroad for the Nordic capital cities is shown in Table 8.29.

The contribution from the city ranges from 15% to 43%, from the country from 18% to 27% and from abroad from 30% to 60%. Reykjavík has the highest contribution from the city and the lowest from abroad. The opposite picture is seen for København with the lowest contribution from the city and the highest contribution from abroad.

Table 8.29. Percentage of premature deaths in the Nordic capital cities in 2030 distributed on contributions from city to city, from country and from abroad.

	From city	From country	From abroad	Total
København	15%	23%	63%	100%
Stockholm	35%	18%	47%	100%
Helsinki	25%	21%	53%	100%
Reykavík	43%	27%	30%	100%
Oslo	n.a.	n.a.	n.a.	n.a.

External costs

The external costs related to air pollution for the capital cities are given in Table 8.30.

Table 8.30. External costs related to health effects of air pollution in capital cities in 2019 and 2030. Billion EUR.

	Area (km^2)	Inhabitants in 2019	Inhabitants in 2030	2019	2030	Differ-ence
København	95	594,679	610,810	1.1	0.9	-21%
Stockholm	207	1,064,033	1,154,401	1.6	1.3	-20%
Helsinki	195	687,693	687,865	1.2	0.9	-16%
Reykavík	173	226,661	264,756	0.14	0.14	-2%
Oslo	262	664,000	697,526	1.2	n.a.	n.a.

References

Andersen, M.S., Frohn, L.M., Brandt, J. & Jensen, S.S., 2007. External effects from power production and the treatment of wind energy (and other renewables) in the Danish energy taxation system. In: Deketelaere, K. et. al., eds.,: Critical Issues in Environmental Taxation: International and Comparative Perspectives, Volume IV. Oxford University Press, pp 319–337.

Andersen, Mikael Skou, Frohn, Lise Marie, Nielsen, Jytte Seested, Nielsen, Malene, Jensen, Joan B. Jensen, Steen Solvang, Christensen, Jesper Heile, Brandt, Jørgen, 2008. A Non-linear Eulerian Approach for Assessment of Health-cost Externalities of Air Pollution. European Association of Environmental and Resource Economists 16th Annual Conference, Gothenburg, Sverige, 25. juni 2008–28. juni 2008. pp 23, peer reviewed proceeding.

Andersen, M. S., L. M. Frohn Rasmussen og J. Brandt, 2019. Miljøøkonomiske beregningspriser for emissioner 3.0. Notat fra DCE - Nationalt Center for Miljø og Energi. Dato: 14. marts 2019. pp. 22. Institut for Miljøvidenskab, Aarhus Universitet. https://dce.au.dk/fileadmin/dce.au.dk/Udgivelser/Notater_2019/Miljoeoekonomiske_beregningspriser_for_emissioner.pdf

Anenberg, S.C., Belova, A., Brandt, J., Fann, N., Greco, S., Guttikunda, S., Heroux, M.-E., Hurley, F., Krzyzanowski, M., Medina, S., Miller, B., Pandey, K., Roos, J. and Van Dingenen, R. (2016), Survey of Ambient Air Pollution Health Risk Assessment Tools. Risk Analysis, 36: 1718–1736. https://doi.org/10.1111/risa.12540

Brandt, J., Silver, J.D., Frohn, L., Geels, C., Gross, A., Hansen, A.B., Hansen, K.M., Hedegaard, G.B, Skjøth, C. A., Villadsen, H., Zare, A., Christensen, J., H., 2012. An integrated model study for Europe and North America using the Danish Eulerian Hemispheric Model with focus on intercontinental transport. Atmospheric Environment, Volume 53, June 2012, pp, 156–176, doi:10,1016/j,atmosenv,2012,01,011.

Brandt, J., J. D. Silver, J. H. Christensen, M. S. Andersen, J. Bønløkke, T. Sigsgaard, C. Geels, A. Gross, A. B. Hansen, K. M. Hansen, G. B. Hedegaard, E. Kaas and L. M. Frohn, 2013a: "Contribution from the ten major emission sectors in Europe to the Health-Cost Externalities of Air Pollution using the EVA Model System – an integrated modelling approach". Atmospheric Chemistry and Physics, Vol. 13, pp. 7725-7746, 2013.

Brandt, J., J. D. Silver, J. H. Christensen, M. S. Andersen, J. Bønløkke, T. Sigsgaard, C. Geels, A. Gross, A. B. Hansen, K. M. Hansen, G. B. Hedegaard, E. Kaas and L. M. Frohn, 2013b: "Assessment of Past, Present and Future Health-Cost Externalities of Air Pollution in Europe and the contribution from international ship traffic using the EVA Model System". Atmospheric Chemistry and Physics. Vol. 13, pp. 7747–7764, 2013.

Christensen, J.H., 1997. The Danish Eulerian Hemispheric Model – a three-dimensional air pollution model used for the Arctic. Atmospheric Environment, 31, 4169–4191.

DØRS, 2016. Værdi af statistisk liv (Value of a statistical life), kap1 i Økonomi og Miljø 2016, Kbh: Det Miljøøkonomiske Råd (Danish Economic Councils). In Danish.

EEA, 2011. Peifer, H. About the EEA reference grid. EEA, September 2011. Note.

Ellermann, T., Nordstrøm, C., Brandt, J., Christensen, J., Ketzel, M., Massling, A., Bossi, R., Frohn, L.M., Geels, C., Jensen, S.S., Nielsen, O.-K., Winther, M., Poulsen, M.B., Monies, C., Sørensen, M.B. 2022. Luftkvalitet 2020. Status for den nationale luftkvalitetsovervågning. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, 144 s. - Videnskabelig rapport nr. 467. http://dce2.au.dk/pub/SR467.pdf. In Danish with English summary.

Ellermann, T., Nordstrøm, C., Brandt, J., Christensen, J., Ketzel, M., Massling, A., Bossi, R., Frohn, L.M., Geels, C., Jensen, S.S., Nielsen, O.-K., Winther, M., Poulsen, M.B., Monies, C., Sørensen, M.B., Andersen, M.S., Sigsgaard, T., 2023 Luftkvalitet 2021. Status for den nationale luftkvalitetsovervågning. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, 148 s. - Videnskabelig rapport nr. 533. http://dce2.au.dk/pub/SR533.pdf . In Danish with English summary.

EU 2004. Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air. Official Journal of the European Union L 23.

EU, 2008. DIRECTIVE 2008/50/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 May 2008 on ambient air quality and cleaner air for Europe.

European Commission (2014) Guide to Cost-Benefit Analysis of Investment Projects: Economic appraisal tool for Cohesion Policy 2014–2020. Luxembourg.

European Commission, 2022. Proposal for a Directive of the European Parliament and of the Council on ambient air quality and cleaner air for Europe. Brussels, 26.10.2022. COM(2022) 542 final (including the Annexes).

Friedrich, R., Bickel, P. (2001). The Impact Pathway Methodology. In: Friedrich, R., Bickel, P. (eds) Environmental External Costs of Transport. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-04329-5_2

Frohn, L. M., Christensen, J.H., Brandt, J. and Hertel, O., 2001. Development of a high resolution integrated nested model for studying air pollution in Denmark. Physics and Chemistry of the Earth (B), 26(10), 769-774. http://dx.doi.org:10.1016/S1464-1909(01)00084-3

Frohn, L.M., Geels, C., Andersen, C., Andersson, C., Bennet, C., Christensen, J.H., Im, U., Karvosenoja, N., Kindler, P.A., Kukkonen, J., Lopez-Aparicio, S., Nielsen, O.-K., Palamarchuk, Y., Paunu, V.-V., Plejdrup, M.S., Segersson, D., Sofiev, M. and Brandt, J.: "Evaluation of multi-decadal high-resolution atmospheric chemistry-transport modelling for exposure assessments in the continental Nordic countries". 2022. Atmospheric Environment, Vol. 290, 119334, https://doi.org/10.1016/j.atmosenv.2022.119334

Frohn, Lise M., Camilla Geels, Jørgen Brandt, Jesper Heile Christensen, Kaj Mantzius Hansen, Ole Hertel, Carsten Ambelas Skjøth, Gitte Brandt Hedegaard, Peter Vangsbo Madsen, Mikael Skou Andersen, Jytte Seested Nielsen og Lars Moseholm, 2008: "EVA - et model system til estimering af eksterne omkostninger relateret til luftforurening". Miljø og Sundhed. Vol. 14, No. 1, pp. 7–13, 2008.

Gao, D., Ripley, S., Weichenthal, S., Pollitt, K.J.G, 2020. Ambient particulate matter oxidative potential: Chemical determinants, associated health effects, and strategies for risk management. Free Radic Biol Med. 2020 May 1; 151:7-25. doi: 10.1016/j.freeradbiomed.2020.04.028.

Héroux et al., 2015. Quantifying the health impacts of ambient air pollutants: recommendations of a WHO/Europe project. Int J Public Health (2015) 60:619–627. DOI 10.1007/s00038-015-0690-y

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C. , Radu R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee. D., Thépaut, J. N. (2018). ERA5 hourly data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), 10.

Hvidtfeldt, U. A. Ketzel, M., Sørensen, M., Khan, J., Brandt, J., Raaschou-Nielsen, O., 2018. Evaluation of the Danish AirGIS dispersion modelling system against measured concentrations of PM2.5 and PM10. Environmental Epidemiology. June 2018 – Vol. 2 - Issue 2 - p e014.

Im, Ulas, J. H. Christensen, O.-K. Nielsen, M. Sand, R. Makkonen, C. Geels, C. Anderson, J. Kukkonen, S. L. Aparicio, and J. Brandt, 2019. Contributions of Nordic anthropogenic emissions on air pollution and premature mortality over the Nordic region and the Arctic. Atmos. Chem. Phys., 19, 12975–12992, 2019. https://doi.org/10.5194/acp-19-12975-2019.

Jensen, S. S., Brandt, J., Ketzel, M., Ellermann, T., Nielsen, O.-K. Plejdrup, M.S., Winther, M., Andersen, M.S., Sigsgaard. T. (2021): Helbredseffekter af Black Carbon i Københavns Kommune. DCE-Nationalt Center for Miljø og Energi, 74s. - Videnskabelig rapport fra DCE – Nationalt Center for Miljø og Energi nr. 430, http://dce2.au.dk/pub/SR430.pdf

Khan, J., K. Kakosimos, O. Raaschou-Nielsen, J. Brandt, S. S. Jensen, T. Ellermann, M. Ketzel, 2019. Development and Performance Evaluation of New AirGIS - A GIS Based Air Pollution and Human Exposure Modelling System. Atmospheric Environment, Vol 198, pp. 102–121.

Kumar, A. J. Brandt, M. Ketzel, R. S. Patil, A. K. Dikshit, O. Hertel, 2019. Evaluation of the Urban Background Model (UBM) and AERMOD for Mumbai city. Environmental Modelling & Assessment. Volume: 24 Issue: 1 Pages: 75–86.

Lehtomaki, H., Geels, C., Brandt, J., Rao, S., Yaramenka, K., Astrom, S., Andersen, M. S., Frohn, L. M., Im, U., and Hanninen, O.: Deaths Attributable to Air Pollution in Nordic Countries: Disparities in the Estimates, Atmosphere-Basel, 11, ARTN 467 10.3390/atmos11050467, 2020.

Ministry of Environment of Denmark, 2022. Tender specifications for advertising of a project within the auspices of the Nordic Working Group for Climate and Air (NKL) regarding Analysis of new WHO Air Quality Guidelines in the Nordic countries and Europe. 24.03.2022.

OECD, 2012. Mortality Risk Valuation in Environment, Health and Transport Policies, Paris.

OECD, 2006. Cost-benefit analysis and the environment, Paris.

Plejdrup, M.S., Nielsen, O.-K., Gyldenkærne, S. & Bruun, H.G. 2021. Spatial high-resolution distribution of emissions to air – SPREAD 3.0. Aarhus University, DCE – Danish Centre for Environment and Energy, 208 pp. Technical Report No. 215, http://dce2.au.dk/pub/TR215.pdf

Raaschou-Nielsen, O., E. Thorsteinson, S. Antonsen, G. J Holst, A. Tjønneland, M. Ketzel, T. Sigsgaard, C. Geels, J. Brandt, C. B Pedersen, U. A. Hvidtfeldt, 2020 Long-term exposure to air pollution and mortality in the Danish - a nationwide study. The Lancet EClinicalMedicine. Vol. 28, 100605, 11.2020. DOI: https://doi.org/10.1016/j.eclinm.2020.100605

Skamarock, W.C., Klemp, J., Dudhia, J., Gill, D.O., Barker, D., Wang, W. and Powers, J.G., 2008: "A Description of the Advanced Research WRF Version 3". NCAR Technical Note, NCAR/TN-475+STR. 27p.

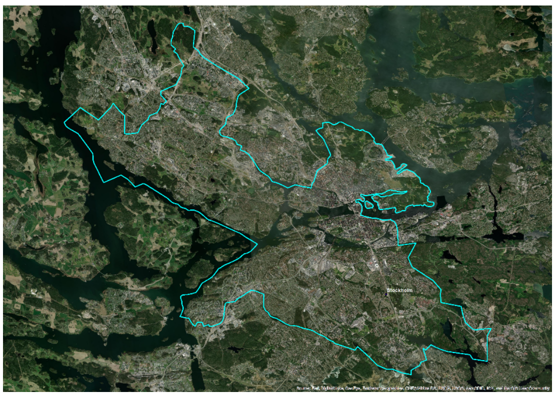
Sommar, J.N.; Hvidtfeldt, U.A.; Geels, C.; Frohn, L.M.; Brandt, J.; Christensen, J.H.; Raaschou-Nielsen, O.; Forsberg, B. Long-Term Residential Exposure to Particulate Matter and Its Components, Nitrogen Dioxide and Ozone—A Northern Sweden Cohort Study on Mortality. Int. J. Environ. Res. Public Health 2021, 18, 8476. https://doi.org/10.3390/ijerph18168476

WHO 2006. World Health Organization. Air quality guidelines: global update 2005: particulate matter, ozone, nitrogen dioxide and sulfur dioxide. World Health Organization. Regional Office for Europe. https://apps.who.int/iris/handle/10665/107823

WHO, 2013: Health risks of air pollution in Europe— HRAPIE project: recommendations for concentration-response functions for cost–benefit analysis of particulate matter, ozone and nitrogen dioxide. Copenhagen, WHO Regional Office for Europe. http://www.euro.who.int/en/health-topics/environment-and-health/airquality/publications/2013/health-risks-of-air-pollution-in-europe-hrapieprojectrecommendations-for-concentrationresponse-functions-forcostbenefit-analysis-of-particulate-matter,-ozone-and-nitrogendioxide.

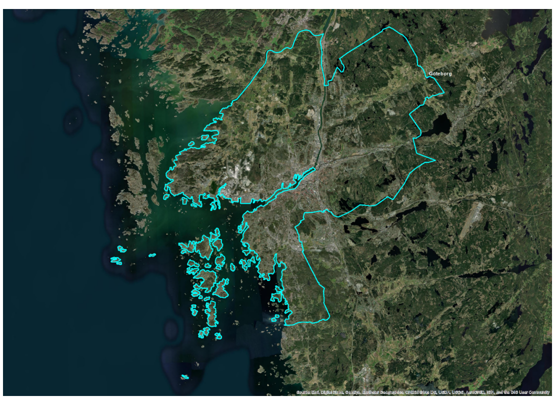
WHO 2021: WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization; 2021.
https://www.who.int/publications/i/item/9789240034228

Appendix 1 City boundaries of selected cities



Country: Sweden
City: Stockholm

Comments: Almost exclusively built-up areas.



Country: Sweden
City: Göteborg

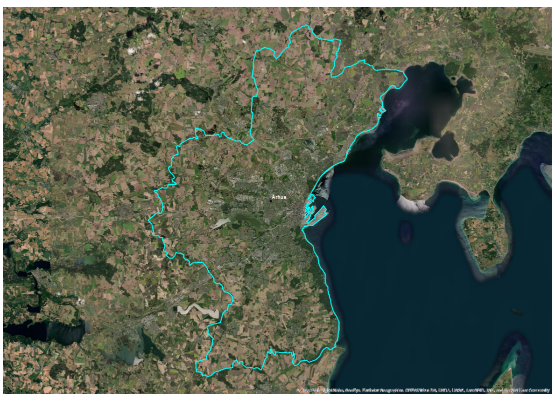
Comments: Outside the built-up city area there are forest/rural areas with minor towns.

Country: Sweden
City: Malmö

Comments: Outside the built-up city area there are rural areas with minor towns.

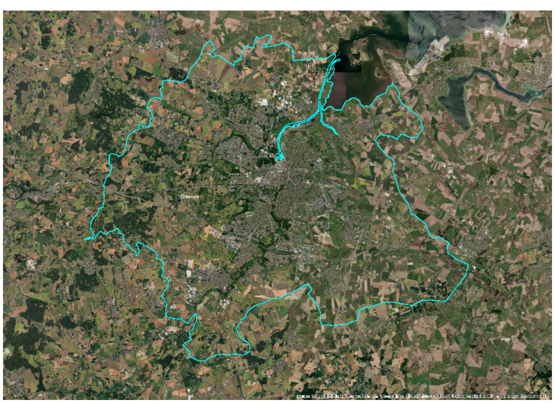
Country: Denmark
City: København

Comments: Municipality of København and Municipality of Frederiksberg. Almost exclusively built-up areas.



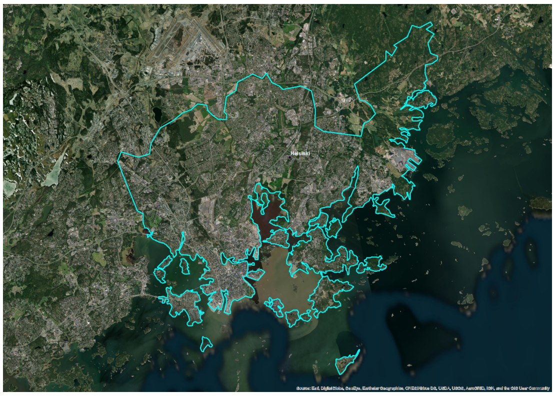
Country: Denmark
City: Aarhus

Comments: Municipality of Aarhus. The area also includes rural areas and minor towns outside the built-up city of Aarhus.



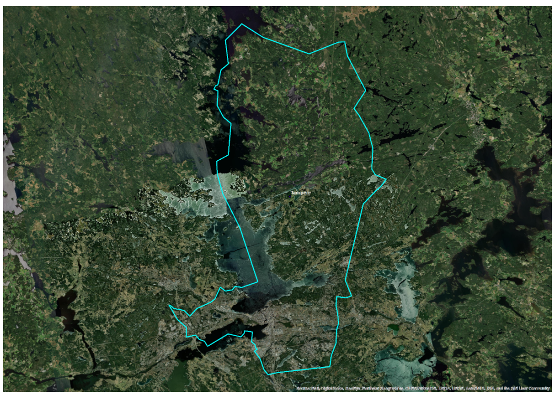
Country: Denmark
City: Odense

Comments: Municipality of Odense. The area also includes rural areas and minor towns outside the city of Odense.



Country: Finland
City: Helsinki

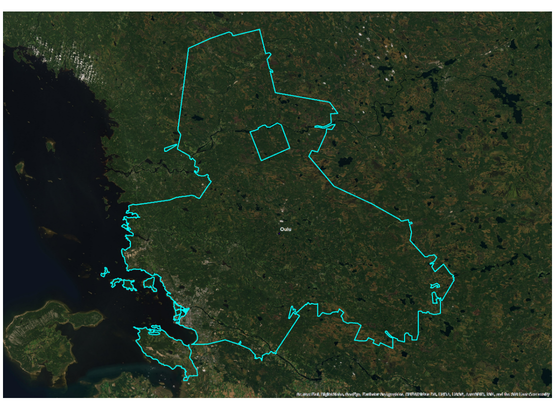
Comments: Almost exclusively built-up areas but with some larger forest areas. The cities of Espoo (2nd largest) and Vantaa (4th largest) are adjacent to Helsinki and part of Greater Helsinki.



Country: Finland
City: Tampere

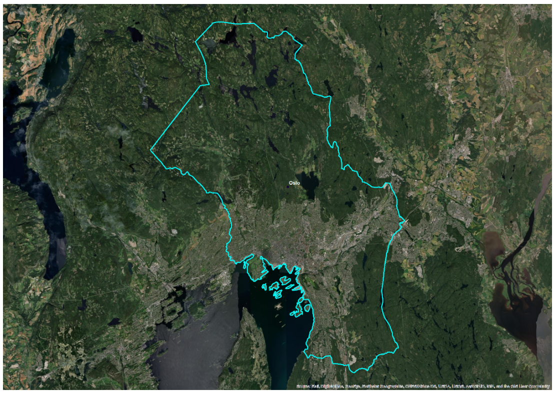
Comments: Apart from the built-up city, there are large areas of forest north of the city with very low building density.

Note that the border is in the middle of the waters. It has not been corrected as it does not have any consequence for emissions or exposure.



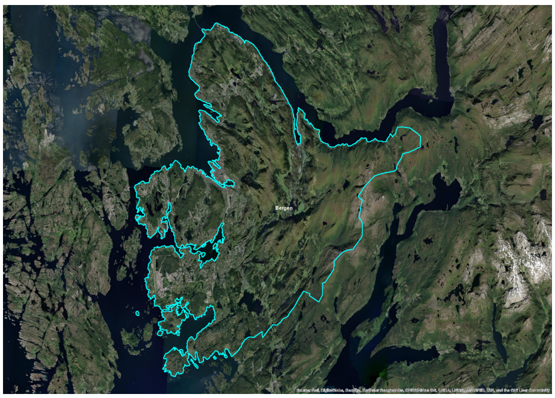
Country: Finland
City: Oulu

Comments: Apart from the built-up city, there are large areas of forest north and east of the city with very low building density.



Country: Norway
City: Oslo

Comments: Apart from the built-up city, there are large areas of forest north of the city with low building density.



Country: Norway
City: Bergen

Comments: Apart from the built-up city, there are large areas of forest north and east of the city with very low building density.

Country: Norway
City: Trondheim

Comments: Apart from the built-up city area, there are large areas of forest west and east of the city with very low building density.

Country: Iceland
City: Reykjavík

Comments: Rekjavík is Greater Reykjavík that includes six contiguous municipalities: Reykjavík, Kópavogur, Garðabær, Hafnarfjörður, Seltjarnarnes and Mosfellsbær. There are large landscape areas outside the built-up city which is uninhabited or with very low building density.

We have excluded the area to the south-west in the picture as this area is disconnected from the rest and very few people live there.

Appendix 2 Sector emissions in Nordic countries

In Table A2.1 the matching correspondence between SNAP and GNFR is given, and in Table A2.2 the emissions by sectors in 2019 and 2030 are shown for the Nordic countries and mimic the data behind Figures 4.6–4.8 in chapter 4.

Table A2.1. Matching correspondence between SNAP and GNFR.

SNAP	GNFR
1 (Energy) 3 (Industrial comb.) 4 (Industrial proc.)	A_PublicPower B_Industry
2 (Residential combustion)	C_OtherStatComb
5 (Extraction etc.) 6 (Solvents) 9 (Waste)	D_Fugitive E_Solvents J_Waste
7 (Road transport)	F_RoadTransport
8 (Off-road, without shipping)	I_Off-road H_Aviation
10 (Agriculture)	K_AgriLivestock L_AgriOther

Table A2.2 Sector emissions in 2019 and 2030 in Nordic countries (Tonnes per year).

Country	Year	Code	Pollutant	SNAP _1_3_4	SNAP _2	SNAP _5_6_9	SNAP _7	SNAP _8	SNAP _10	Total
DK	2019	DK2019	NOx	21	5	0	27	15	19	88
SE	2019	SE2019	NOx	39	4	0	47	16	13	118
NO	2019	NO2019	NOx	60	2	1	35	23	8	128
FI	2019	FI2019	NOx	49	12	0	28	15	10	113
IS	2019	IS2019	NOx	2	0	0	2	14	1	19
DK	2030	DK2030	NOx	19	8	0	12	13	18	70
SE	2030	SE2030	NOx	35	8	0	14	9	11	78
NO	2030	NO2030	NOx	49	10	2	6	20	8	94
FI	2030	FI2030	NOx	45	10	0	10	9	10	84
IS	2030	IS2030	NOx	3	0	0	0	13	1	17
DK	2019	DK2019	SOx	6	1	2	0	0	0	9
SE	2019	SE2019	SOx	14	1	1	0	0	0	16
NO	2019	NO2019	SOx	14	1	1	0	0	0	15
FI	2019	FI2019	SOx	25	4	1	0	0	0	30
IS	2019	IS2019	SOx	13	0	42	0	1	0	56
DK	2030	DK2030	SOx	6	1	1	0	1	0	10
SE	2030	SE2030	SOx	13	1	1	0	0	0	14
NO	2030	NO2030	SOx	13	1	1	0	1	0	15
FI	2030	FI2030	SOx	21	2	0	0	1	0	25
IS	2030	IS2030	SOx	14	0	27	0	0	0	41
DK	2019	DK2019	PM2.5	1	8	1	1	1	1	13
SE	2019	SE2019	PM2.5	5	6	1	4	1	1	17

NO	2019	NO2019	PM2.5	6	12	1	1	1	1	23
FI	2019	FI2019	PM2.5	3	9	1	2	1	1	16
IS	2019	IS2019	PM2.5	0	0	0	0	0	0	1
DK	2030	DK2030	PM2.5	1	6	0	1	0	1	10
SE	2030	SE2030	PM2.5	4	4	1	4	1	1	15
NO	2030	NO2030	PM2.5	5	12	1	1	1	0	20
FI	2030	FI2030	PM2.5	3	7	1	1	0	0	13
IS	2030	IS2030	PM2.5	1	0	0	0	0	0	1

Appendix 3 Description of measurement stations in selected cities

Table A3.1. Traffic stations: NO_2 annual average concentrations 2021 and the data and stations used in Figure 4.6 and 4.7 for the selected cities.

Country	City	$PM_{2.5}$ annual average µg/m3	Urban- and suburban background station name	Data coverage %
Sweden	Stockholm	26.2	E4/E20 Lilla Essingen	91.6
	Göteborg	24.5	Göteborg Gårda	99.8
	Malmö	21.1	Malmö Dalaplan	98.8
Denmark	København	26.6	København/1103	93.7
	Aarhus	20.4	Aarhus/6153	93.7
	Odense	12.1	Odense/9155	94.7
Finland	Helsinki	25.1	Töölöntulli	98.9
	Tampere*	13.9	Linja-autoasema	99.9
	Oulu	14.9	Oulun keskusta 2	95.4
Norway	Oslo	31.8	E6 Alna senter	92.8
	Bergen	27.3	Danmarks plass	99.1
	Trondheim*	24.1	E6-Tiller	90.8
Iceland	Reykjavík**	12.2	Reykjavík Bústaðavegur	99.8

** For NO_2 traffic in Tampere the station with the highest concentration is Pirkankatu (15.8 µg/m^3) but data coverage is <85% (78.6%) making the value temporally unrepresentative, why the traffic station in Tampere with the second highest NO_2 concentration > 85% has been chosen.*
*** For NO_2 traffic in Reykjavík the station with the highest concentration is Reykjavík Grensas (21.9 µg/m^3) but data coverage is <85% (72.8%) making the value temporally unrepresentative, why the measurements from the station with the second highest NO_2 concentration with data coverage > 85% has been chosen. Data provided by Þorsteinn Jóhannsson, Environment Agency of Iceland.*

Table A3.2. Urban background and suburban background stations: NO_2 annual average concentrations 2021 and information on the data and stations used in Figure 4.6 and 4.7 for the selected cities. t.u.= temporal unrepresentative data.

Country	City	$PM_{2.5}$ annual average µg/m3	Urban- and suburban background station name	Data coverage %
Sweden	Stockholm	9,7	Stockholm Torkel Knutssongatan	99.4
	Göteborg	12.7	Göteborg Femman	99.7
	Malmö	9.4	Malmö Rådhuset	98.8
Denmark	København	9.8	København/1259	93.8
	Aarhus	9.3	Aarhus/6160	93.9
	Odense	7.4	Odense/9159	93.7
Finland	Helsinki	12.4	Kallio 2	97.8
	Tampere	13.0	Kaleva	99.9
	Oulu	8.7	Pyykösjärvi	99.5
Norway	Oslo	19.2	Bryn skole	95.7
	Bergen	13.4	Klosterhaugen	93.3
	Trondheim*	**t.u. (19.2)**	**Torvet**	**49.2**
Iceland	Reykjavík**	8.2	Kópavogur Dalsmári	99.4

** Bold red: For NO_2 urban background in Trondheim 2021 there is only one measuring station (Torvet) but data coverage is only 49.2% making the NO_2 value (19.2 µg/m^3) temporal unrepresentative (t.u.), why it is not included in the graphic presentation.*
*** Kópavogur is strictly speaking not within Reykjavík administrative city unit, but Kópavogur has grown together with Reykjavík and can thus represent Reykjavík as an Urban background / suburban background station.*

Table A3.3. Rural and rural background stations: NO_2 annual average concentrations 2021 and information on the data and stations used in Figure 4.6 and 4.7 for the selected cities. n.m.= no measurements.

Country	City	$PM_{2.5}$ annual average µg/m3	Urban- and suburban background station name	Data coverage %
Sweden	Stockholm	2.1	Norr Malma	99.9
	Göteborg	3.0	Råö	100.0
	Malmö	3.3	Hallahus	98.9
Denmark	København	5.3	Risø	98.4
	Aarhus*	**3.3**	**Ulborg (120 km)**	**92.2**
	Odense*	**6.0**	**Keldsnor (80 km)**	**90.9**
Finland	Helsinki	3.9	Luukki	98.8
	Tampere	2.0	Hyytiälä	99.5
	Oulu*	**1.1**	**Oulanka (230 km)**	**99.2**
Norway	Oslo	0.4	Hurdal25	91.5
	Bergen**	- - -	**no suitable st.**	- - -
	Trondheim*	**0.1**	**Kårvatn (110 km)**	**99.7**
Iceland	Reykjavík***	2.0	Gröf	99,9

** Bold green: Rural or rural background measuring stations located more than 50 km away from the city which it is supposed to represent (the approximate distance to the city centre is given in brackets).*
*** For Bergen 2021 no suitable rural background station was found to represent the background for this oceanic influenced location (nearest rural or rural background station is located about 300 km in a rather different climate/environment).*
**** Gröf is officially defined as Industrial station, due to location of nearby industry (4 km away from the station) which primary emits SO_2 but this station can for NO_2 represent the Rural / rural background level for Reykjavík. This station is located about 20 km from Reykjavík City Centre. Comments and data provided by Þorsteinn Jóhannsson, Environment Agency of Iceland.*

Table A3.4. Traffic stations: $PM_{2.5}$ annual average concentrations 2021 and the data and stations used in Figure 4.6 and 4.7 for the selected cities. n.m.= no measurements.

Country	City	$PM_{2.5}$ annual average µg/m3	Urban- and suburban background station name	Data coverage %
Sweden	Stockholm	6.0	Stockholm St Eriksgatan	99.99
	Göteborg	7.4	Göteborg Haga	99.6
	Malmö	8.6	Malmö Dalaplan	99.1
Denmark	København	10.3	København/1103	98.1
	Aarhus	8.8	Aarhus/6153	96.4
	Odense*	**n.m.**	**n.m.**	**n.m.**
Finland	Helsinki	7.2	Mannerheimintie	99.5
	Tampere*	6.1	Epila 2	99.9
	Oulu	5.2	Oulun keskusta 2	98.2
Norway	Oslo	9.3	Bygdøy Alle	91.8
	Bergen	7.8	Danmarks plass	99.9
	Trondheim	5.9	Elgeseter	97.0
Iceland	Reykjavík**	4.4	Bústaðavegur	100

** For Odense (Denmark) there are in 2021 no traffic stations measuring $PM_{2.5}$. n.m.= no measurements.*

*** Reykjavík (Iceland). Data comes from a mobile AQ station owned by the City of Reykjavík and data from this station has not been send to EEA. This station should well reflect the situation near busy roads in Reykjavík. Comments and data provided by Þorsteinn Jóhannsson, Environment Agency of Iceland.*

Table A3.5. Urban background and suburban background stations: $PM_{2.5}$ annual average concentrations 2021 and information on the data and stations used in Figure 4.6 and 4.7 for the selected cities. n.m.= no measurements. t.u.= temporal unrepresentative data.

Country	City	$PM_{2.5}$ annual average µg/m3	Urban- and suburban background station name	Data coverage %
Sweden	Stockholm	5.1	Stockholm Torkel Knutssongatan	95.7
	Göteborg**	**t.u. (4.8)**	**Göteborg Femman**	**54.6**
	Malmö	8.3	Malmö Rådhuset	93.1
Denmark	København	8.0	København/1259	97.3
	Aarhus	7.6	Aarhus/6160	96.4
	Odense	**n.m.**	**n.m.**	**n.m.**
Finland	Helsinki	5.8	Kallio 2	99.6
	Tampere	4.5	Kaleva	95.5
	Oulu	**n.m.**	**n.m.**	**n.m.**
Norway	Oslo	9.1	Skøyen	88.4
	Bergen	6.3	Klosterhaugen	98.9
	Trondheim	6.7	Torvet	86.3
Iceland	Reykjavík***	4.9	Kópavogur Dalsmári	99.9

** For Odense (Denmark) and Oulu (Finland) there are in 2021 no urban background or suburban background stations measuring $PM_{2.5}$. n.m.= no measurements.*

*** Bold red: For $PM_{2.5}$ urban background in Göteborg there is only one measuring station, but data coverage is only 54.6% making the $PM_{2.5}$ value (4.8 µg/m^3) temporal unrepresentative (t.u.), why it is not included in the graphic presentation.*

**** Kópavogur is strictly speaking not within Reykjavík administrative city unit, but Kópavogur has grown together with Reykjavík and can thus represent Reykjavík as an Urban background / suburban background station.*

Table A3.6. Rural or rural background stations: $PM_{2.5}$ annual average concentrations 2021 and information on the data and stations used in Figure 4.6 and 4.7 for the selected cities. n.m.= no measurements.

Country	City	$PM_{2.5}$ annual average µg/m3	Rural and rural background station name	Data coverage %
Sweden	Stockholm	3.9	Norr Malma	99.95
	Göteborg*	9.1	Råö	97.8
	Malmö**	**t.u. (5.6)**	**Hallahus**	**76.8**
Denmark	København	7.4	Risø	93.5
	Aarhus***,§1	**7.4**	**Risø (130 km)**	**93.5**
	Odense***,§1	**7.4**	**Risø (110 km)**	**93.5**
Finland	Helsinki	4.5	Luukki	98.7
	Tampere***,§	**4.5**	**Luukki (140 km)**	**98.7**
	Oulu**	**2.1**	**Matorova (330 km)**	**99.5**
Norway	Oslo	2.8	Hurdal25	95.3
	Bergen*4	- - -	**no suitable st.**	- - -
	Trondheim**'	**2.1**	**Kårvatn (110 km)**	**91.2**
Iceland	Reykjavík*5	3.9	Gröf	96,3

** For Råö $PM_{2.5}$, rural background for Göteborg, there is only one measuring station available in the European Air Quality Portal (but data coverage is only 16.3% making the $PM_{2.5}$ value (5.7 µg/m^3) temporal unrepresentative, why measurements from this station have been omitted. However, from Sweden an annual average value for $PM_{2.5}$ for 2021 from Råö, but measured with another instrument, was send afterwards and it is this value (9.07 µg/m^3 with a data coverage of 357 days in 2021) that has been used.*
*** Bold red: For Hallahus $PM_{2.5}$, rural background for Malmö, there is only one measuring station but data coverage is only 76.8% making the $PM_{2.5}$ value (5.6 µg/m^3) temporal unrepresentative (t.u.), why measurements from this station are not included in the graphic presentation.*
**** Bold green: Rural or rural background measuring stations located more than 50 km away from the city which it is supposed to represent (the approximate distance to the city centre is given in brackets).*

*[*4] For Bergen no suitable rural or rural background station was found for 2021 to represent the background for this oceanic influenced location (nearest rural or rural background station is located about 300 km in a rather different climate/environment).*
*[*5] Gröf is officially defined as Industrial station, due to location of nearby industry (4 km away from the station) which primary emits SO_2 but this station can for $PM_{2.5}$ represent the Rural / rural background level for Reykjavík. This station is located about 20 km from Reykjavík City Centre. Comments and data provided by Þorsteinn Jóhannsson, Environment Agency of Iceland.*
[§1] $PM_{2.5}$ rural at Odense and Aarhus, Denmark, is both represented by the $PM_{2.5}$ value (7.4 μg/m^3) measured at the rural station, Risø, which is also representing København.
[§2] $PM_{2.5}$ rural for Tampere, Finland, is represented by the $PM_{2.5}$ value (4.5 μg/m^3) measured at the rural station, Luukki, which is also representing Helsinki.

About this publication

Air Quality, Health Effects and External Costs in Selected Cities in Nordic Countries

Analysis of new WHO Air Quality Guidelines in the Nordic countries and Europe

Steen Solvang Jensen, Jesper H. Christensen, Zhuyun Ye, Lise M. Frohn, Camilla Geels, Mikael Skou Andersen, Ole-Kenneth Nielsen, Claus Nordstrøm
Aarhus University, Department of Environmental Science, Denmark

TemaNord 2023:548

ISBN 978-92-893-7741-6 (PDF)
ISBN 978-92-893-7742-3 (ONLINE)
http://dx.doi.org/10.6027/temanord2023-548

Cover photo: Pernille Bering/Colourbox
Published: 20/12/2023

Disclaimer

This publication was funded by the Nordic Council of Ministers. However, the content does not necessarily reflect the Nordic Council of Ministers' views, opinions, attitudes or recommendations.

Rights and permissions

Nordic co-operation

Nordic co-operation is one of the world's most extensive forms of regional collaboration, involving Denmark, Finland, Iceland, Norway, Sweden, and the Faroe Islands, Greenland and Åland.

Nordic co-operation has firm traditions in politics, economics and culture and plays an important role in European and international forums. The Nordic community strives for a strong Nordic Region in a strong Europe.

Nordic co-operation promotes regional interests and values in a global world. The values shared by the Nordic countries help make the region one of the most innovative and competitive in the world.

Nordic Council of Ministers
Nordens Hus
Ved Stranden 18
DK-1061 Copenhagen
pub@norden.org

Read more Nordic publications on www.norden.org/publications