Atmospheric Environment 382 (2026) 122222

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Multi-level governance for improving air quality in cities in the UNECE region: a science policy perspective

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HIGHLIGHTS

- Cities offers a unique opportunity to reduce air pollution related health impacts.
- Dominant sources differ from city to city and from pollutant to pollutant.
- Multi-level governance is needed to improve the air quality in cities.
- Measures exist and offer synergies to other environmental and policy objectives.

ARTICLE INFO

Keywords:
Air quality
Governance
City
Source apportionment
Particulate matter
Nitrogen dioxide

ABSTRACT

Air pollution is the most harmful environmental risk factor to human health. Cities with high population density and associated high levels of air pollution offer a unique opportunity to significantly improve public health. The major sources of air pollution in cities differ from city to city and from pollutant to pollutant. In most cities combustion from residential heating or transport are the most relevant local sources of primary particulate matter and nitrogen dioxide. Other significant sources lie outside cities. The diversity of sources and pollutants means that no single government body can implement measures on its own to sufficiently improve the air quality to meet the air quality guideline levels of the WHO. Cross-governmental collaboration is also needed, because measures that reduce emissions in a wider region could deliver greater health benefits, by reducing the average exposure, than local measures targeting hotspots. Local information on sources as well as air quality monitoring and modelling are essential to assess which sectors are most relevant for each city. The most effective combination of policies to improve the air quality depends on the local context, the pollutant and its sources, but in all cases collaboration across government levels is essential. We give examples of how these levels of air quality management interact, which sources are most relevant and which pollutant-specific features should be considered in multi-level governance. Synergies across different policy areas, notably between climate, transport and air quality policies, offer various benefits among other environmental issues, e.g. urban planning and noise pollution.

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https://doi.org/10.1016/j.atmosenv.2026.122222
Received 16 April 2026; Received in revised form 24 June 2026; Accepted 9 July 2026
Available online 10 July 2026

1. Introduction

Air pollution is harmful to human health and the environment. Human activities cause air pollution due to emissions of particles, gases, heavy metals, and persistent organic pollutants, such as polycyclic aromatic hydrocarbons (PAH) or per- and polyfluoroalkyl substances (PFAS). There is strong scientific evidence for the negative impacts of air pollutants such as particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and ozone (O_3) to both human health and ecosystems (EEA, 2024b, b; GBD, 2024; UBA, 2022; UNECE, 2016; WHO, 2021, 2025). In this paper the focus is on these pollutants, while acknowledging that there is growing evidence on health and environmental effects of, e.g., black carbon, ultrafine particles (UFP) or PFAS. Despite great progress in recent decades and successes in European air quality management policy, guidelines of the World Health Organization (WHO, 2021) are not met and current air pollution levels remain a major threat to public health globally (WHO, 2024a). Exposure to air pollution can lead to many health problems including respiratory and cardiovascular diseases, as well as cancer (Fig. 1, WHO (2024a)). Latest estimates suggest that three to four hundred thousand premature deaths are attributable to air pollution in the European region (EEA, 2022; WHO, 2024b). The effects of air pollution on human health and environmental quality also place a burden on the healthcare system and the economy.

Effects of air pollution are especially relevant for cities with their high population density and relatively high levels of air pollutants. Here, we use both the terms 'city' and 'urban' to describe areas of settlement with a high population density and supporting infrastructure. We recognize that how urban areas and cities function and what they look like varies between different regions in the world. Measures can therefore also differ, e.g., in costs and effectiveness.

The most common metrics for assessing health burden of air pollution are mass concentrations of $PM_{2.5}$, NO_2, and ozone (WHO, 2025). The focus here is primarily on long term exposure to ambient air pollution (e.g., annual averages) as opposed to short term exposure to peak concentrations. This is because: (i) long-term concentrations are better correlated with the observed effects on human health, and (ii) short-term policies to improve the air quality within hours or days are limited in scale and effectiveness.

The WHO (2021) has set air quality guidelines for the concentrations of harmful air pollutants. These guidelines are not legally binding, and the European Union and other countries have set their own air quality standards, most regard them as rigorous evidence-based guidelines for the longer term. For instance, the EU has significantly lowered most of its limit and target values in the revised air quality directive (EU, 2024a). In addition, an average exposure reduction obligation has been set to meet the WHO guidelines for NO_2 and $PM_{2.5}$, at least in urban backgrounds, in the long-term. Furthermore, the EU is aiming to meet the WHO guidelines in 2050 as part of its broader Zero Pollution Action Plan (EU, 2021).

In many cases, policies to reduce greenhouse gas emissions also improve air quality. Policies that lead to electrification of industrial processes, transportation and other sectors shift away from combustion and lead to a reduction of both carbon dioxide and air pollutants such as NO_2 and $PM_{2.5}$, if the power generation shifts to renewables in parallel (IEA, 2021; Jacobson et al., 2015). This is also the case with policies that encourage modal shift of transportation away from roads and towards more energy-efficient modes such as public transport, walking, cycling, etc. (see section 4). However, in some cases climate mitigation policies can be a risk to air quality, such as when biomass is used as a substitute for coal or natural gas in combustion processes. This can lead to higher emissions of PM and the climate forcer BC (Bond et al., 2013; Vicente and Alves, 2018). Also, the higher weight of electric vehicles, compared to internal combustion vehicles, could yield higher non-exhaust PM emissions, but that depends very much on the extent of regenerative braking and the effect on total emissions is probably small for passenger cars (Beddows and Harrison, 2021). The air quality implications for electric vehicles also depends on the manor and location the electricity is produced.

Air pollution does not respect borders. Therefore, efforts to address air pollution have to be multi-level and ideally internationally coordinated for most pollutants. It is evident that the rural population also benefits from multi-level air quality management, given that they are also affected by pollution from urban areas (e.g., Thunis et al. (2021)). Policies at the local or regional level can require legislation or coordination at the national or supranational level. The transboundary nature of pollution has long been recognized and led to the Convention on Long-range Transboundary Air Pollution (UNECE, 1979). Important protocols to control emissions under the Convention, such as the Gothenburg Protocol, were based on targets for reducing risks to ecosystems and human health. Even though such targets were set at the national level, whereas urban air pollution was historically often perceived as a local problem, these spheres are strongly connected both physically

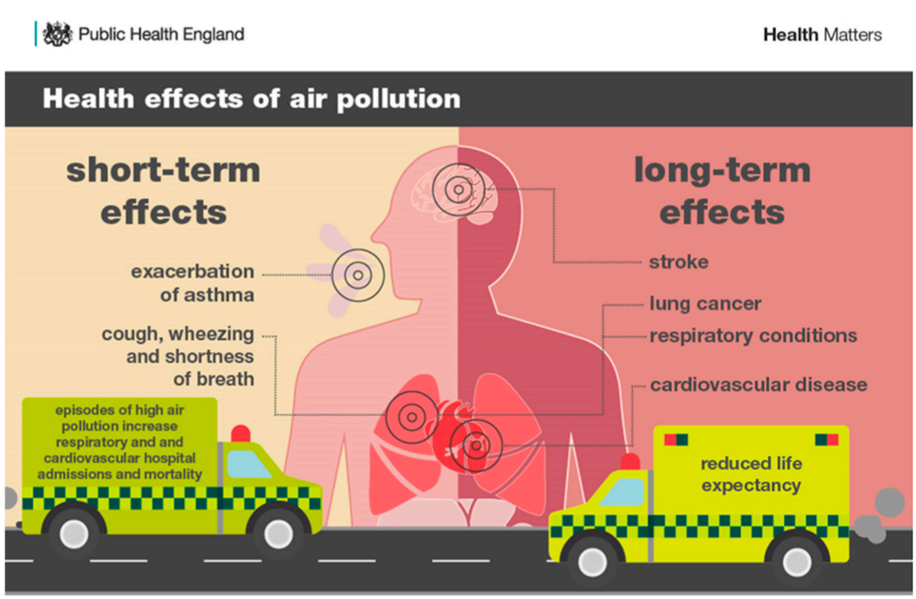

Fig. 1. Health effects of air pollution (from Public Health England, https://www.gov.uk/government/publications/health-matters-air-pollution/health-matters-air-pollution, accessed April 9 2026, UK Open Government Licence v3.0).

through the transport of pollution, as well as in a regulatory sense, as national emission control legislation directly influences urban emissions and ambient pollution levels too.

Thus far policy development in the UNECE (United Nations Economic Commission for Europe) region as focused on reduction of transboundary air pollution. Now, for the first time policymakers increase their attention to the local scale since actions at EU or national level alone are not sufficient to improve air quality. This places more focus on multi-level governance actions to improve air quality.

This paper, a science policy perspective, further addresses the need for multi-level governance, that accounts for each pollutant specificities, to tackle air pollution. In section 2, we describe why it is important to address air quality at the city level. Section 3 describes sources of air pollution impacting cities, followed by section 4 in which we look at measures that can be taken on city, national, regional, and supranational level to improve air quality in cities and how these measures are linked. This paper focusses on countries in Europe, the Caucasus and central Asia, but most of the discussion and conclusions are also applicable to countries in other parts of the world. The institutions and policy processes in, e.g., east Asia, Africa and South America differ from those in the EU, but the sources of air pollution in cities are similar, although probably different in magnitude. The air quality in cities will also there be influenced by both local, regional and long distance contributions and different government levels will have to work together to improve air quality in cities (see, e.g., (Amann et al., 2017; Majumdar et al., 2020).

2. The air quality in cities

A city can be defined as a densely populated settlement with numerous functions, such as housing, transportation, production of goods, sanitation, communication and many others. In short, a place where many people live, work, recreate and breathe. Air quality in cities is key for human health. Harmful air pollutants are emitted in cities and get dispersed through the atmosphere to and from cities.

Air quality standards are established and regularly revised in order to minimize the health burden of air pollution, see e.g., EU (2024a). Such standards are the result of political negotiations, where trade-offs are made between public health and other common objectives, such as to minimize socio-economic losses. Air quality management in cities is therefore always a compromise between reducing the average exposure of the city's population to air pollution while still facilitating the activities of people and businesses in cities.

Air quality management has already achieved significant reductions in urban air pollution in most cities in Europe (EEA, 2025a). In the EU, the number of premature deaths attributable to $PM_{2.5}$ levels above the WHO guideline of 5 μg/m^3 decreased by 45% from 2005 to 2022 (EEA, 2025c). Some examples of air quality measures are flue gas cleaning in industrial plants, particulate filters in diesel vehicles, and the expansion of renewable energy (WEF (2024). However, current air pollutant concentrations are still above the values recommended by the WHO (2021). In the year 2021, 97% of the urban population in EU member states was exposed to concentrations of $PM_{2.5}$ above the WHO (2021) air quality guidelines. For NO_2 and ozone this was 90% and 94%, respectively (EEA, 2024a). Especially regarding $PM_{2.5}$, attaining the WHO guidelines is particularly challenging in countries that still rely on burning fossil fuels for residential heating.

There are large differences between cities, with large conglomerations of closely connected cities (e.g., Paris region, Po basin in northern Italy), cities in large industrial areas (e.g., Ruhr area in Germany, Upper Silesian region in Poland, southern Bulgaria), and cities surrounded mostly by agricultural land (e.g., the Netherlands) or mountains (e.g., Balkans). However, there are a few key points that are crucial for managing air quality in cities, regardless of the specific source contribution:

- The contribution of cities to their own air pollution is dominating in the case of NO_2 (JRC, 2019; Pültz et al., 2025), is often significant in the case of PM, depending on city specifics, and is generally low for ozone (see section 4). For ten large cities in Europe the emissions from the city alone contribute more than 80% to the total NO_2 concentrations in the city. For $PM_{2.5}$ the contribution of the city ranges from 25% to 60%, and for ozone 25% or less (see Fig. 5, Pisoni et al. (2022)). For these cities emissions from all EU countries make up the remainder for $PM_{2.5}$, but only about 25% for ozone. The highest $PM_{2.5}$ concentrations in 150 cities in Europe are on average about 24% from emissions from the cities themselves, increasing up to about 50% in specific cities (JRC, 2025). See also Fig. S1 in Annex 2.
- A significant part of urban air pollution originates from sources outside the city itself, especially for the exposure to $PM_{2.5}$ due to emissions of precursors for secondary inorganic aerosols (SIA), forming particles in the atmosphere (JRC, 2019). For ozone, the sources of precursor emissions are almost completely from outside the city.
- Cities emit relevant quantities of air pollutants, in particular of primary $PM_{2.5}$ and precursors of secondary PM like NO_x, which can then be transported over long distances away from the city to affect other cities and rural areas, where they are considered part of the background pollution.
- Local measures are essential to improve air quality when the local contribution is high, especially for NO_2. However, to achieve the WHO air quality guideline values for $PM_{2.5}$ and ozone, collaboration at the (inter)national, regional, and city levels is necessary. This is also the case for NO_2, where implementation of local measures often needs multi-level governance, too.
- Public health in general benefits more from the reduction of the average exposure of the total population than from reducing the local exceedances of limit values at hotspots. Local measures, such as restricting vehicle categories for one specific street might solve an NO_2 exceedance locally, but will not reduce the average exposure in the city significantly.
- There are many measures that offer win-win solutions to objectives in other policy areas, such as the energy transition towards renewables, low-meat diets, or transitions in the transport system in combination with urban planning to reduce overall 'fossil' mileage.

For improving health, reducing the average exposure to air pollution in cities is key and multi-level approaches to improve air quality inside and outside the cities are needed. As the concentration-response function is linear, every microgram reduction of individual exposure will have the same health benefit, disregarding whether the concentration in an area is below or above a recommended limit value. As considerably less people are exposed to high concentrations along busy roads, than people exposed to city background levels, a s.1 μg reduction of the average exposure will entail more total health benefits than reducing 1 μg at so-called hotspots. Health impact assessments and cost-benefit analyses also focus on average population exposure and not (only) on the impact for the relatively few people living at a hotspot. However, measures targeting hotspots remain important for protecting vulnerable populations, e.g., at school, homes for elderly, and hospitals, located near busy roads.

Examples of important combinations of measures at the EU level and local level are the EU emissions standards for vehicles (EU, 2007), in combination with local low emission zones to accelerate the introduction of vehicles compliant with the new emission standards into the local fleet, which reduced primary PM exhaust emissions significantly in the EU (EEA, 2025b). Since EU type approval had to be based on emission measurements under real driving conditions on the road, NO_x emissions of diesel vehicles also dropped. Another example of the importance of combinations of policies is the EU Ecodesign framework (EU, 2024b) in combination with national regulations, which stipulate an end date for the operation of old installations, reduced PM concentrations or at least stopped emissions from further increasing due to growing numbers and use of solid fuel boilers. Further, the multi-level Clean Air Agreement in the Netherlands (I&W, 2020), that contains measures at different levels of government on different topics, not only strengthens the effectiveness of measures, but also encourages exchange of knowledge and experience between participants. However, sometimes the benefits of measures are partially or fully compensated by an increase in activity or substitution by another activity, such as an increase in total vehicle mileage, electricity consumption or energy demand for heating and cooling. To meet WHO guidelines, decarbonisation/fossilization will be one of the key issues, and sectors need to come together to leave silo-thinking behind and find comprehensive packages of measures. See section 4 and Annex 1 for a list of measures and which governance levels are involved for a successful implementation.

3. Sources of air pollution impacting cities

The success of an urban air quality plan depends on the political process and the availability of relevant knowledge (see Annex 2). The latter can be obtained from independent scientists in an assessment of the problem: air quality monitoring, inventory of the emissions, dispersion modelling, and health impact assessment. Key is knowledge on the main sources of air pollution in the city, at present and in the future, assuming implementation of local and (inter)national legislation. Source apportionment based on dispersion models can be used to obtain this kind of information.

3.1. Source apportionment

The contribution of different sectors and regions to the urban air pollutant concentrations varies between cities. Source apportionment is the first step in designing a cost-effective multi-scale air quality strategy for a city. Two examples of Europe-wide estimates derived from model calculations are the urban $PM_{2.5}$ atlas of JRC (2023) and runs by the GAINS model (Amann et al., 2011), in support of the ongoing revision process of the Gothenburg Protocol. The GAINS model uses source-receptor relations from the EMEP model (EMEP, 2023; Simpson et al., 2012), while the JRC urban atlas uses the SHERPA model (Clappier et al., 2015). These models provide contributions of emission sources in the urban environment and show the relative importance of local, regional, and transboundary sources to urban $PM_{2.5}$ levels. The dominant source sectors identified by these two assessments are shown in Fig. 2 (JRC urban atlas) and Fig. 3 (GAINS calculations). Both assessments agree on the dominance of residential combustion in many Central and Eastern European countries. The GAINS model, however, sees transport as the dominant source in Western Europe, while the JRC atlas ranks agricultural contributions first in Belgium, Netherlands, Luxembourg and western Germany, with residential sources ranking first in other parts of western Europe. Differences are likely due to a combination of factors like the model setup, the choice of emission data, its spatial resolution and reference year, the definition of urban boundaries and the meteorological year(s) for which the atmospheric calculations were performed. Since the maps show only the most important sector, it is not straightforward to tell how different these results really are. A breakdown of the EMEP/GAINS results to country averages of cities (Fig. 4) shows for the countries not only the most

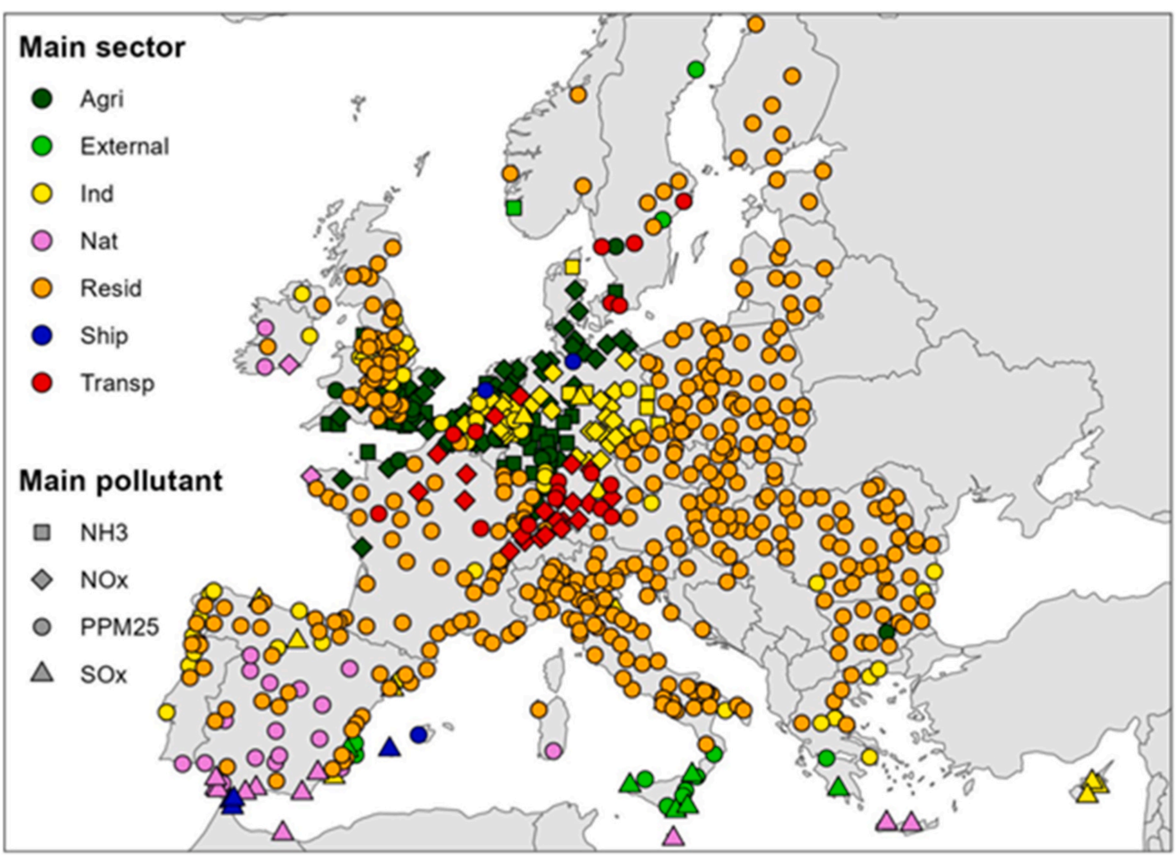

Fig. 2. Main emission sector and precursor in each city in 2019 based on the urban $PM_{2.5}$ atlas of JRC (2023). Sectors are expressed by colour, and precursors by shape, showing how they are contributing to $PM_{2.5}$ concentrations in each city (PPM25 means primary $PM_{2.5}$). Note that the main sector and main precursor are estimated independently from each other. Figure from Zauli-Sajani et al. (2024), under license CC-BY 4.0. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

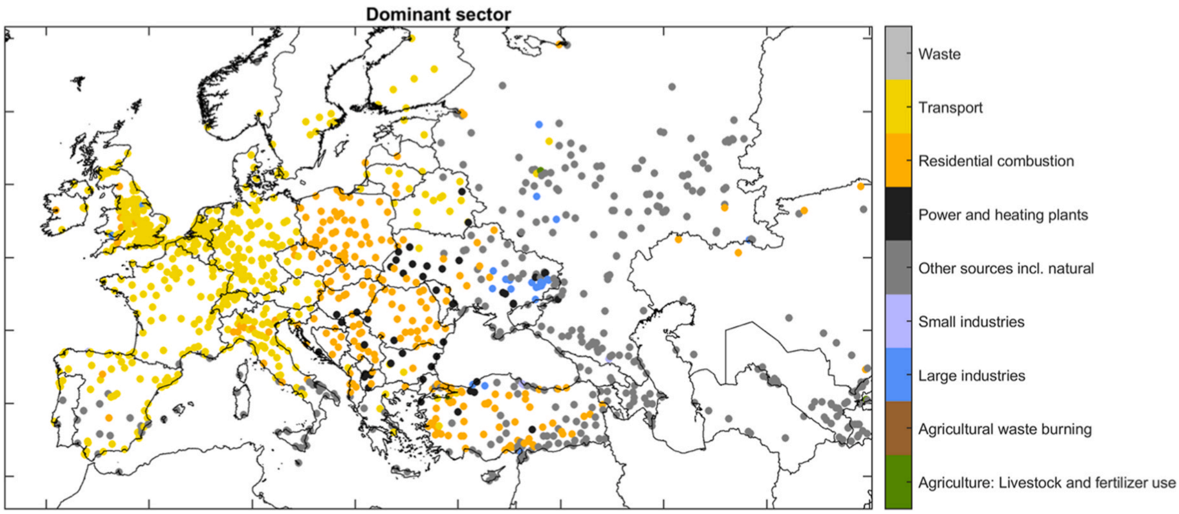

Fig. 3. Main emission sector contributing to ambient $PM_{2.5}$ in cities in the UNECE area, as estimated with the GAINS model.

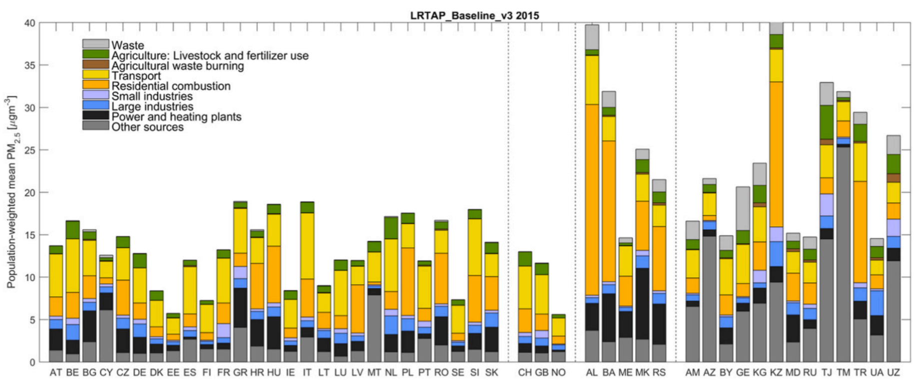

Fig. 4. Sector source contributions to cities in UNECE countries (population-weighted average of all cities >50,000 inhabitants within each country). Source: CIAM/IIASA, GAINS model calculations for the Gothenburg Protocol Revision, described in TFIAM Policy Brief (UNECE, 2023).

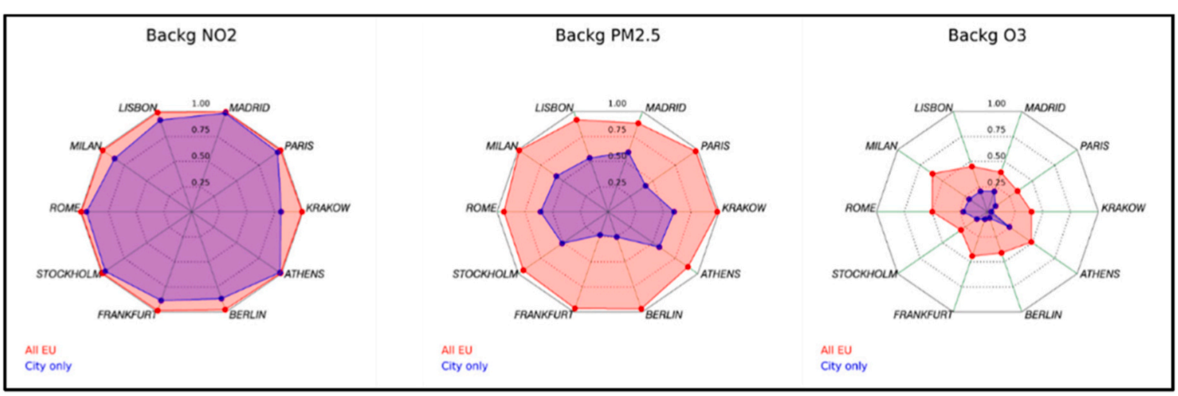

Fig. 5. Comparison of EMEP model responses (relative potential) to local (blue) and EU reductions (red) for annually averaged $PM_{2.5}$, annually averaged NO_2 and summertime daily 8-h maximum of ozone. Emission reduction impacts are assessed at the city location where the maximum base case concentration is modelled. The responses of local measures on those concentrations were simulated with the EMEP model (EMEP, 2023; Simpson et al., 2012) by switching off the emissions from the city, plus the surrounding economic and functional urban area based on daily movements of people. Responses were expressed as percentages of a base case that included all emissions everywhere in the model domain. By switching off all emissions in Europe the response to EU-policy was determined. Figure from Pisoni et al. (2022), under license CC-BY 4.0. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

important sector, but also the contributions of other sectors.

The importance of a sectoral or spatial source contribution depends on how the indicator is calculated at the receptor location. While the focus is often to conduct source apportionment for a specific hotspot, it can also be performed in population weighted terms over an entire city area. Recent analysis shows that, in general, there is a good correlation between results obtained with both types of indicators. The correlation is higher for sectors that are spatially well-distributed at city scale, such as residential and traffic, and lower for sectors characterized by important local emissions, such as waste and shipping. In most cases, results based on average indicators underestimate those based on hotspot location. While the choice of indicator has a strong impact on the estimation of the local contribution to air pollution in the city, the relative share of the sectors is generally preserved across indicators. In other words, the priority sector remains similar, but the resulting scale of action can differ in some cities (Thunis et al., 2025).

Here the source apportionment from two models are discussed as examples of the kind of information models can provide for decision makers. Apart from these two, other models are being used for source attribution at the national level, e.g., the large-scale concentrations maps for the Netherlands (Mijnen-Visser et al., 2024), or the European level, e.g., the LOTOS-EUROS model (Manders et al., 2017) and CHIMERE (Menut et al., 2024). Models all have their strengths and weaknesses, may be tailored to specific regions or pollutants, and all use somewhat different emissions and modelling assumptions. Output from one air quality model should therefore be interpreted with some caution taking into account the input data, parameterization and assumptions as well as sensitivities. While regional models like EMEP/GAINS and JRC/SHERPA can provide internally consistent analysis for a large number of cities, they rely on gridded proxies for emission distribution and are typically not calibrated to city specific inventories. A sensitivity test done with GAINS revealed that shifting the spatial emission distribution to the data set used in the JRC atlas can eliminate some of the differences.

Preferably, results of more than one model, and wherever possible locally calibrated models, are to be used as input for reliable decision making. Also, models are a simplification of reality and their output are only one source of information for policymakers. They will also have to consider other policies areas, the cultural and political background in the country, legislative procedures, implementation costs, potential institutional barriers, etc., which all very much depend on the local situation.

Below the sources of particulate matter, nitrogen dioxide and ozone are discussed and in section 4 and Annex 1 measured to reduce their concentrations.

3.2. Particulate matter (PM)

3.2.1. Local sources

Sources that emit near the ground contribute significantly to peaks in local $PM_{2.5}$ concentrations, while emissions from high-stack industrial sources within cities are dispersed more widely outside of the city. In locations with stable inversion layers in winter and/or mountainous terrain limiting air exchange, the importance of local sources is strongly increased compared to windy flatter areas. The following sources are important at the local scale:

- Residential combustion with solid fuels leads to large quantities of primary $PM_{2.5}$ along with condensables, (i.e., gases that condense to form particles) and to some extent NO_x, especially in central and eastern European countries, the West Balkans and some EECCA (Organisation for Economic Co-operation and Development, Eastern Europe, Caucasus and Central Asia) countries (see Figs. 2 and 3). In cities without a district heating network, this can be a dominant source for local $PM_{2.5}$ concentrations.
- Road transport is an important source of emissions from combustion (e.g., NO_x and $PM_{2.5}$ from diesel engines) and of non-exhaust emissions (PM from brake and tyre wear and road abrasion (Harrison et al., 2021), especially in many of the larger cities like Paris, London, Stockholm, Madrid, etc. (Thunis et al., 2018).
- Construction activities can contribute significantly to the urban population's exposure to PM. Despite their local and time-limited impact, which is often not represented by the measured annual means, construction emissions are an ubiquitous urban source. Combustion emissions from construction machines appear in the ultra-fine and $PM_{2.5}$ fraction in terms of toxic, ultra-fine diesel particle emissions since the majority of such machinery still lacks a diesel particle filter (Desouza et al., 2020). On the other hand, rather coarse particles are generated during the demolition of buildings and through re-suspension of deposited construction waste, mostly contributing to PM_{10}.
- Municipal waste burning can be an important source locally in cities where the collection system is not functioning well or where landfills are not well managed (Krecl et al., 2021). In the UNECE region, this is relevant in some non-EU countries.
- In some cities with large industrial facilities, e.g., in the Netherlands, Portugal, Germany or Belgium, industry can also make a significant contribution to urban background levels.
- The same holds for emissions from ports (shipping and port activities) in cities like Rotterdam, Malaga, Valletta, Genova or Hamburg (see e.g., Pozzoli et al. (2024)).

3.2.2. National and regional sources

Potentially important national and regional sources of primary PM and NO_x are large industrial plants, highways, airports, and national shipping. Agriculture emissions of ammonia also have a significant impact on urban background PM concentrations with impacts reaching up to 25% of the observed urban levels in north-western Europe (Germany, United Kingdom, Belgium, northern France) (Fig. 4). Although these sources of emissions are at distance from the city environment, they significantly impact ambient air quality in cities and contribute to the urban background concentrations. National and regional authorities therefore have an important role in achieving clean air in cities. Combustion of solid fuels for heating often takes place outside cities, with exceptions in countries in e.g., Eastern Europe and western Balkan, but can still significantly impact urban air quality. Note that the impact of agricultural emissions slightly decreases over the years as a result of the uneven reductions in NO_x and NH_3 emissions. While NO_x emissions continue to decrease in many places, this is not the case for the NH_3 emissions leading to less marked NH_3 limited regimes resulting in larger sensitivity to NO_x emission reductions. Therefore, larger reductions in NH_3 emissions would be necessary, compared to reductions in NO_x emissions, to get the same reduction in $PM_{2.5}$ concentrations (Jonson et al., 2022).

An important part of the national/regional contribution of PM are secondary inorganic aerosols: mainly aerosol formation in the atmosphere from ammonia and nitrogen or sulfur oxides. However, primary PM emission sources also contribute: wood burning (e.g., in the northern part of Italy), agricultural waste burning, forest fires and emissions from large industrial combustion plants, which can sometimes also still be a major source of sulfur dioxide.

3.2.3. Transboundary sources

The contribution of transboundary sources to $PM_{2.5}$ concentrations largely depends on the location of the city with respect to the country borders and on the size of the country itself. Transboundary means here that air pollution travels across borders. For $PM_{2.5}$ concentrations the contribution of transboundary sources can be significant, especially in cities close to borders. Similarly to national and regional sources, the transboundary contribution is mostly secondary aerosol, but primary PM emission sources also contribute, such as wood burning, agricultural waste burning, forest fires, and large industrial combustion plants.

3.3. Nitrogen dioxide (NO_2)

Emissions from NO_2 originate from combustion of fossil fuels from road transport (passenger cars, busses and heavy duty vehicles), from power plants, industry, shipping, and households. NO_2 is mostly emitted as nitrogen oxide (NO) and converted to NO_2 in the ambient atmosphere. Due to is relatively short lifetime of a few hours the highest concentrations are found close to its sources. Therefore, most of the NO_2 concentration originates from local sources of which transport remains the main sector in most urban environments (JRC, 2019). In some cities emissions from industry and shipping are significant sources, too. In Germany road transport was found to contribute up to 59% of the NO_2 concentration in the urban background in major cities (Pültz et al., 2025). National and transboundary sources contribute to the background concentration, but the background is less important for the exceedance of NO_2 air quality limit values in most cities. Diesel vehicles are a major source of the traffic related NO_2 emissions. Local policies, such as promoting electric vehicles or shifts in modal transport (use of public transport, walking, cycling), can effectively reduce NO_2 concentration in cities. Low emission zones in cities can also help, provided the polluting vehicles are not merely taking other routes in the city (JRC, 2019).

3.4. Ozone (O_3)

Ozone is a typical transboundary or even transcontinental pollutant. It is formed in the atmosphere from anthropogenic and biogenic emissions of non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), and methane, under the influence of sunlight. Precursor emission sources can be thousands of kilometers from the places where high ozone concentrations are experienced. The continental ozone background concentration depends on the methane background concentration, which is increasing for many decades. NMVOCs comprise of many chemicals from both natural and anthropogenic origin from (chemical) industry, transport, building materials (ethane, benzene, etc.) and forest (terpenes, etc.). Important for ozone formation is the ratio of NMVOC over NO_x in the plumes where ozone is formed. Cities influence ozone concentrations directly when destruction of ozone by reaction with nitrogen monoxide (NO) is locally important. Reduction of NO_x emissions in urbanized areas can therefore lead to higher ozone concentrations in cities (Sillman et al., 1990), especially because of the relatively high share of NO in NO_x close to emission sources. This should however not be seen as a reason not to reduce the emissions of NO_x. Effectively tackling ozone precursor emissions requires internationally coordinated actions, with increased attention to methane mitigation (JRC, 2024). However, to reduce ozone peak season concentrations, local to regional reduction of NO_x and VOC emissions is still necessary (Lupaşcu and Butler, 2019).

4. Measures to improve air quality

A great variety of measures have been taken by cities to reduce the exposure to air pollutants and to meet air quality standards, see for example (Khreis et al., 2017, 2023) and Annex 1 (see supplementary material). The question is, however, to what extent local measures will be applicable and sufficient to meet the WHO (2021) air quality guidelines.

4.1. Impact versus spatial scale of implementation

The effect of measures on air quality can vary quite a lot, depending on the pollutants to be tackled and depending on the spatial scale on which they are implemented. Fig. 5 shows the relative response of measures taken on a large-scale (EU) and on a city scale to reduce NO_2, $PM_{2.5}$, and ozone for several large cities. For $PM_{2.5}$ both large-scale (European and national) and local measures are almost equally important, but their relevance varies from city to city. In cities at the outer regions of the EU (e.g., Athens, Madrid, Lisbon) there is even some need for action from non-EU countries. The Urban $PM_{2.5}$ Atlas (JRC, 2023) provides information for 150 cities in the EU about where to act most effectively, on which spatial scale and in which sector. From that, it can be concluded that measures to effectively tackle $PM_{2.5}$ need to be taken on all spatial scales, given the long- and medium-range transport of $PM_{2.5}$ and its precursors of secondary PM.

For ozone, there should be an even stronger focus on large-scale measures even outside of Europe, while local measures in city domains are barely relevant. There are exceptions in a few urban areas in the Mediterranean, where orography and rather stable land-sea breeze wind patterns hamper the transport of precursors and ozone over larger distances.

For a locally dominated pollutant like NO_2, local measures prove to be very effective. The bulk of the NO_2 exposure reduction can be achieved almost entirely by local air quality management. Here, and equally important with respect to $PM_{2.5}$ abatement, the question arises, however, to what extent urban measures would require regulatory and financial support from national governments (or the EU) to be practically feasible? For instance, while local traffic is a major local source of NO_2, much of the regulation around vehicle traffic is done at a national or international level. Cities are sometimes limited in what they can do if the national or international governments do not cooperate or have no similar goals for air quality.

Multi-level and cross-sectoral governance are not easy to implement. The public acceptability and efficiency of measures as well as institutional barriers differ across UNECE-countries. Gollata and Newig (2017) studied the implementation of the EU air quality directive in Germany and concluded that multi-level governance approach was of limited success. They state that "On the one hand, local authorities are given more executive implementation power; on the other hand, they lack substantial enforcement capabilities (e.g., legal and financial backing) and are unable to obligate higher levels". However, there are examples of successful cooperation between policy departments (e.g. for air quality, energy or transport) and between government layers. See, e.g., EEA (2019) and the Clean Air Agreement in the Netherlands (I&W, 2020) (Section 2). Successes are not easy transferable to other countries. Two-way communication, agreement on common goals, joint fact-finding, and acknowledging the needs of partners are key. However, a quantitative blueprint for an optimal co-operation between stakeholders does not exist. Within the UNECE-region, some countries prefer voluntary agreements between equal partners and organize some form of public involvement (e.g. in the Netherlands). Others are more used to hierarchical and legislative solutions or the use of financial incentives. The quantitative effectiveness of the various approaches seems to depend on the cultural and political background of a country. International exchange of policy experiences and learning from each other is for the moment the best way forward.

4.2. Local versus national/international level of implementation

Annex 1 (see supplementary material) gives a list of measures relevant for local or regional authorities to improve the air quality and public health in urban areas. The Annex is largely derived from a review of interventions from Public Health England (PHE, 2019) on mobile and stationary sources and urban planning and behavioural interventions. A few measures on residential heating, industry and non-road mobile sources were added, based on other research activities and expert judgement.

Table 1 gives a qualitative indication of the effectiveness of selected local measures for reducing the average population exposure to NO_2 and of measures taken outside cities reducing $PM_{2.5}$ and NO_2 exposure. Also shown are which government level should take the lead and from whom support is needed. The responsibility for the local measures listed in Table 1 is often the local government, but they need support from the national government for the setting regulatory framework and defining standards. The effectiveness of local measures for the average $PM_{2.5}$ exposure in a city is often limited, because a substantial part of the air quality is influenced by sources outside the city.

Agricultural measures were not explicitly included in Table 1 and Annex 1 as they are rarely on the list of measures of urban air quality management. However, it should be emphasized that measures to control ammonia emissions from livestock, manure management, storage and nitrogen fertilizer application are essential to significantly reduce

Table 1
Qualitative indication of the effectiveness of a selection of measures to reduce the exposure to NO_2 and $PM_{2.5}$ in cities and which government levels are involved. More measures are given in Tables A, B, and C of Annex 1.

Policy measure	Target pollutant	Indicative effect	Action by	Support from
Local measures (effective mostly for NO_2 exposure)				
Less car traffic – more walking, cycling & public transport	NO_2, $PM_{2.5}$	+++	Local government: investments in safer/attractive infrastructure and road traffic orders	National government: funding and providing traffic regulations favouring active mobility
Electric vehicles, electric busses & light and heavy duty vehicles	NO_2, ($PM_{2.5}$)	++	Local government: development of charging infrastructure	National government and EU: providing funding and defining the harmonized technical requirements
Low emission zones	NO_2, $PM_{2.5}$	+	Local government: access restrictions for polluting vehicles	National government: providing the requisite regulatory framework
Speed limits	NO_2, $PM_{2.5}$	+	Local government, National government (for motorways)	National government: providing the requisite road traffic regulation
Traffic circulation plans, planting trees	NO_2, $PM_{2.5}$	+/−	Local government	
(Inter)national measures				
Reduction of $PM_{2.5}$ precursor emissions (NH_3, NO_x, SO_2) at international level	$PM_{2.5}$	+++	EU and national government: setting emission limits	National government: implementation in regulations and enforcement
Emission reduction from regional industry, shipping and transport	NO_2, $PM_{2.5}$	++	EU and national government: settings emission limits	National government: implementation in regulations and enforcement
Emission reduction from domestic heating in the region	NO_2, $PM_{2.5}$	+/++	Regional/local government: implementing regulations	Local government: enforcement

$PM_{2.5}$ exposure in cities. As outlined in section 3, ammonia reduction at regional (or transboundary) scale can be effective to decrease the regional background of $PM_{2.5}$ concentrations (Bessagnet et al., 2014). Action at a national or even international governance level is therefore of paramount importance to improve local air quality in cities.

To highlight the multi-governance aspect of air quality management, two columns were added to the tables in Annex 1: (1) indicating the main governance level responsible for the implementation and enforcement of each intervention, and, (2) highlighting the international bodies, where supportive action (regulatory and/or financial) is important for the local measure to be feasible in practice. The tables also indicate where potential measures would benefit from actions on the EU and/or international governance level.

Given the urban focus of this paper, the list of measures focuses on actions particularly relevant for urban air quality planning (see Annex 2). For most of the measures in Annex 1 local authorities are the main actor. Except for a few cases with mixed responsibility, national authorities bear the main responsibility for many other measures. It is interesting to note that around half of the local interventions cannot be implemented without some sort of national involvement: either in the form of funding a city's infrastructure enhancement, direct investments in infrastructure (rail, power grids, renewables, charging), and/or, most frequently, by providing the necessary regulatory power or technical specifications for cities to act. A prominent example are measures necessary for the implementation of Low or Zero Emission Zone schemes, which requires in many cases (e.g., the Czech Republic, France, Spain, Germany, Belgium, the Netherlands, Luxembourg, Italy, United Kingdom, Norway) an amendment of national legislation: traffic laws, vehicle labeling regulations, as well as technical specifications for vehicle retrofit and charging infrastructure. Many other traffic interventions, especially those aiming to benefit from cleaner and active transport modes, also rely on amendments of national road transport laws. Steps to influence people's behaviour to voluntarily avoid polluting activities lie almost solely in the hands of the local authorities. Unfortunately, the latter have a limited short-term impact. Hence, even for NO_2 as a locally driven pollutant, where cities have a large mitigation potential, more than half of the potentially effective measures depend on support at the national or even international level.

This is also the case for expanding the use of hydrogen in industry. The effect of hydrogen as a zero carbon alternative on air quality depends not only on the way it is produced, but also on how it is used. There are no air pollution effects when hydrogen is used in fuel cells to generate electricity, but when it is burned in engines or boilers NO_x is produced depending on the temperature of the combustion (DEFRA, 2023). National governments are responsible for standards for limiting the NO_x emissions and thereby reducing effects on air quality in and around cities.

Local measures addressing residential heating and industrial sources are also strongly bound to national or EU regulations by setting emission limit values, prescribing the scope of "best available techniques" for various types of industries, and standards for fuel quality and other products, on which local interventions strongly rely in technical and legal terms.

A recent example in Germany illustrates this dependency, not only between governance levels, but also across different policies: While national climate action strongly drives the decarbonisation of the house-heating sector and thereby incentivizes inter alia the use of biomass, the respective law (GEG, 2023) fails to require PM precipitators to be installed when opting for a new pellet boiler. Since the EU's EcoDesign regulation (EU, 2024b) does not require dust precipitators for new biomass boilers, this could result in a stagnation or even increase of PM emissions from domestic heating because burning wood without filters yields high emissions of particles (WHO, 2015). Local or regional authorities cannot counteract for legal reasons without violating EU common market regulations, despite that current PM concentrations are twice as high as the WHO (2021) air quality guidelines. As a result, climate action to meet its, sometimes sectoral, goal can create a risk for air quality policy, notwithstanding the considerable co-benefits of most decarbonisation measures for air quality. A comprehensive approach would be needed to combine climate and air quality targets.

4.3. Short-term actions versus long-term measures

Experience with short-term actions in the form of smog alerts has shown that their effectiveness in terms of a long-lasting emission reduction is fairly small, except that they help to raise awareness of the air pollution problem, see e.g. PHE (2019). Most of the adverse health effects are due to long-term exposure to air pollution. Rather than concentrating on the extremely small-scale decrease of pollutant levels in the immediate surrounding of monitoring stations as was done with air purifiers for example in Stuttgart, Germany (Bächler et al., 2021), measures should be designed to generate improvements over a wider city area, in order to gain health benefits for large parts of the urban population (Hoffmann et al., 2021).

4.4. Conclusion

A wide range of measures exist to improve the air quality in cities. The most effective combination of policies depends on the local conditions, on the targeted pollutant and associated distribution of sources. There is certainly no 'magic' bullet, but rather a combination of several measures, which leads to a widespread and tangible reduction of the exposure of urban dwellers.

While local authorities are the main actor, collaboration across all levels of government is essential to ensure that measures can effectively be implemented, independent from the pollutant and the spatial scale on which the respective action is implemented. Coordination and coherence between different policy areas is also essential to address and use synergies, notably between air quality and climate action policy, and to avoid countervailing effects. While there is often a natural symbiosis between sectoral decarbonisation and control of air pollutants, promoting biomass as a climate-friendly fuel for residential heating would result in higher particle emissions (and other toxic substances) unless filter technologies are required.

To maximize the health benefits, multi-level approaches and measures with a larger, city-wide effect on the population exposure should receive much more focus than purely hot-spot driven local interventions with a very limited spatial impact. However, measures targeting hotspots remain important for protecting vulnerable populations, e.g., at school, homes for elderly, and hospitals located near busy roads.

CRediT authorship contribution statement

Guus J.M. Velders: Conceptualization, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Andreas Eisold:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Philippe Thunis:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Gregor Kiesewetter:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Martin Lutz:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Rob Maas:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Maaike Lammerts-Huitema:** Conceptualization, Writing – original draft, Writing – review & editing. **Martine Ouwersloot:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the members of the Expert Panel on Clean Air in Cities (EPCAC), part of the UNECE's Air Convention (CLRTAP) Task Force on Integrated Assessment Modelling (TFIAM), for suggestions and comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2026.122222.

Data availability

No data was used for the research described in the article.

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