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A study on the PM 2.5 concentration over the last decade in six European cities

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Abstract

PM 2.5, particulate matter with an aerodynamic diameter of less than 2.5 micrometres, is the most harmful airborne pollutant of our time. It is the newest addition to air quality legislation and regulations worldwide and within Europe its annual concentration is limited to 25 μg m^{-3} since 2015. However, adverse health impacts are still observed at this concentration and the WHO nowadays recommends an annual mean of 5 μg m^{-3}. Especially cities, where a high population density leads to more anthropogenic emissions, struggle to keep their PM 2.5 levels within the limit. Within the cities the major sources of PM 2.5 include emissions from road traffic as well as fuel combustion in the residential sector with the purpose of heating and cooking. These are the sectors at which most reduction measures are targeted. The most problematic time for air quality in the European cities is the winter period. During cold months PM 2.5 concentrations experience a peak. This is, among other reasons, due to increased heating, more frequent use of private vehicles and the application of road sand on icy streets. Also meteorological conditions play a significant role. In this study the PM 2.5 levels in six European cities of comparable size (Vienna, Budapest, Prague as well as Helsinki, Stockholm and Oslo) are investigated. PM 2.5 monitoring networks are discussed and the most commonly used measurement techniques, gravimetric, TEOM, BAM and light scattering, are presented. The Scandinavian cities have a distinctly lower PM 2.5 concentration. On the one hand this is due to their smaller population as well as forgiving location directly at the sea, where strong winds favor the dispersion of pollutants. The middle European cities, on the other hand, experience the long-range transport of PM 2.5 from the major emitter nations, which are located within central Europe. The overall background concentration is therefore higher in the middle European cities than in the Northern cites. However, cities do also face individual challenges, which range from the political and economic landscape in Budapest to the issue of studded tires in Stockholm. Nevertheless, all cities have lowered their PM 2.5 levels within the last decade and Vienna achieved the greatest reduction of 51%.

Abstract in German

Der verheerendste Luftschadstoff unserer Zeit ist das sogenannte PM 2.5, welches für Feinstaub mit einem aerodynamischen Durchmesser von weniger als 2.5 Mikrometern steht. Er ist die letzte Ergänzung zu weltweiten Luftqualitätsgesetzen und -vorschriften, und innerhalb Europas ist seine jährliche Konzentration seit 2015 auf 25 μg m^{-3} begrenzt. Allerdings werden auch bei diesen Konzentrationen immer noch negative Gesundheitsauswirkungen beobachtet, und die WHO empfiehlt daher einen Jahresmittelwert von nur 5 μg m^{-3}. Insbesondere Städte, in denen eine hohe Bevölkerungsdichte zu mehr anthropogenen Emissionen führt, haben Schwierigkeiten ihre PM 2.5-Werte innerhalb des gesetzlich vorgeschriebenen Limits zu halten. Die Hauptquellen von PM 2.5 in urbanen Regionen sind Emissionen des Straßenverkehrs sowie die Verbrennung von Brennstoffen im Wohnsektor zum Heizen und Kochen. Diese Sektoren sind diejenigen, auf die die meisten Reduktionsmaßnahmen abzielen. Die problematischste Zeit für die Luftqualität in europäischen Städten ist die Winterperiode. In den kalten Monaten erreichen die PM 2.5-Konzentrationen einen Höhepunkt. Dies ist auf verstärkte Heizaktivitäten, häufigere Nutzung privater Fahrzeuge und die Anwendung von Streusand auf vereisten Straßen zurückzuführen. Auch meteorologische Bedingungen spielen eine entscheidende Rolle. In dieser Arbeit werden die PM 2.5 Niveaus in sechs europäischen Städten (Wien, Prag und Budapest sowie Helsinki, Stockholm und Oslo) untersucht. Die skandinavischen Städte weisen eine deutlich geringere PM 2.5-Konzentration auf. Dies liegt unter anderem an der kleineren Bevölkerungsanzahl sowie an ihrer günstigen Lage direkt am Meer, wo starke Winde die Dispersion von Schadstoffen begünstigen. Die mitteleuropäischen Städte hingegen sind dem weiträumigen Transport von PM 2,5 aus den Hauptemissionsländern in Mitteleuropa ausgesetzt. Die Gesamthintergrundkonzentration ist daher in den mitteleuropäischen Städten höher als in den Städten Nordeuropas. Städte stehen jedoch auch vor individuellen Herausforderungen, die von der politischen und wirtschaftlichen Lage Budapests bis zu Problemen der Spikereifen in Stockholm reichen. Dennoch haben alle Städte ihre PM 2.5-Werte im letzten Jahrzehnt gesenkt, wobei Wien die größte Reduzierung von 51 % erreichte.

1 Introduction

Air quality in general is defined as the degree to which the air in a particular region is pollution free. According to the World Health Organization (WHO) today's global population (99%) breaths air containing so many pollutants, that it exceeds their guideline limits. [1] The WHO nowadays identifies five main categories of air pollutants. These are nitrogen oxides (NO_X), carbon monoxide (CO), particulate matter (PM), sulfur dioxide (SO_2) and ozone (O_3). The cause and adverse impact of these as well as their current limits set by the WHO and the European Union are listed in Table 1.

Pollutant	Cause/ Source	Main effect	Limit/guidelines	
			WHO (2021) [2]	EU (2008) [3]
PM	transport, combustion, industrial processes, construction, wind erosion	shortening of life expectancy	PM2.5(μg m^{-3}): 24-h mean=15 Annual mean=5 PM10(μg m^{-3}): 24-h mean=45 Annual mean=15	PM2.5(μg m^{-3}): Annual mean=25 PM10(μg m^{-3}): 24-h mean=50 Annual mean=40
NO_x	transport and energy sector -specifically combustion processes	shortening of life expectancy, acidification	NO_2 (μg m^{-3}): 24-h mean=10 Annual mean=25	NO_2 (μg m^{-3}): 1-h mean=200 Annual mean=40
SO_2	energy sector	acidification	SO_2 (μg m^{-3}): 24-h mean=15	SO_2 (μg m^{-3}): 24-h mean=125 1-h mean=350
CO	commercial, institutional, and household fuel combustion	global warming	CO (mg m^{-3}): 24-h mean=4	CO (mg m^{-3}): max. daily 8-h mean= 10
O_3	NMVOCs & NO_X	damage to crops	O_3(μg m^{-3}): 8-h mean= 100 Peak season[1]=60	O_3(μg m^{-3}): max. daily 8-h mean= 120

Table 1: major types of air pollutants, their causes, main impacts, and limits set by the WHO and EU [4]

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

Particulate matter (PM) are microscopic particles of solid or liquid matter suspended in our air. The term aerosol refers to both, the PM plus the air. Some particulates are emitted from natural sources, many from anthropogenic ones. More information on PM will follow in chapter two.

Nitrogen and oxygen do not react at ambient temperature. They necessitate very high temperatures to undergo an endothermic reaction to produce NOx. Such temperatures are typically achieved in a combustion process of fuels or naturally as a result of a lighting flash.

Sulfur dioxide is the product of burning sulfur or materials containing it like coal, petroleum oil or diesel.

Carbon monoxide is produced by the partial oxidation or incomplete combustion of carbon containing compounds, like fuels. Naturally it is released into the atmosphere by volcanic activity or wildfires.

Ozone is formed when sunlight causes a chemical reaction between NOx and volatile organic compounds (VOC). VOCs stand for a broad classification of organic gases, that have no strict definition other than that they are compounds paired with a high vapor pressure and low water solubility. Meaning that they can easily evaporate into the air at room temperature. Non- methane volatile organic compounds (NMVOCs) are identical to VOCs, but with the exclusion of methane. Although a very potent greenhouse gas methane is often disregarded in the air pollution context, as it is not toxic.

Additionally to these five main pollutants, the EU sets air quality limits for two more in their EU Directive 2008/50/EC. [3] One of them is benzene, a typical VOC found in petroleum. Benzene is a known carcinogen, meaning it has the potential to cause cancer in the human body. Another substance under strict EU legislative scrutiny is lead. Lead is a heavy metal that can have serious health effects when entering a human body. It is released into the atmosphere in the metal processing industry and when fossil fuels are combusted. A second EU Directive 2004/107/EC sets limits for arsenic, cadmium, mercury, nickel, and polycyclic aromatic hydrocarbons in the ambient air. [5] Both of

these directives are still enforced today and legally obligate all EU member states to abide to the limits and standards set within them.

Apart from these two ambient air quality directives, the EU implements emission mitigation controls on national totals via the national emissions reduction commitments (NEC) directive. This directive obligates the EU member states to reduce the emission of NO_x, SO_2, NMVOCs, PM 2.5 and ammonia (NH_3). [6] The last pillar of the EU's environmental legal framework are the emission and energy efficiency standards that are set for specific sources or sectors. Examples for these are the EU regulations for vehicles, large combustion plants or the industrial emissions directive. Also, strategic policy directions such as the Clean Air for Europe Programme, or actions taken under international climate strategies like the UN Paris Agreement of 2015, are expected to have a positive impact on air quality and the reduction of pollutant emissions. [7]

The public awareness of air pollutants started to form in the second half of the last century. In London coal and chemical combustion smog transformed into a large sulfate cloud covering the city for two days and claiming consequently 12000 lives in 1952. [8] In 1985 a five-day smog period in North- Reihn- Westphalia forced approximately 4000 Germans to seek up hospitals due to respiratory and cardiovascular failure. [9] The adverse environmental impact of heavy sulfur emissions became visible through fish extinction in Scandinavian waters or forest diebacks across Europe. Acid rain, which crosses borders and cannot be contained as an isolated regional problem, received a lot of public attention. This forced international cooperation as well as political collaboration regarding the topic of toxic emissions and their effect on the air quality or generally life quality. [10]

In 1979 the Geneva Convention on Long- Range Transboundary Air Pollution was opened for signature, counting today 51 signatory parties. At the EU level, the European Monitoring and Evaluation Program (EMEP) implements the obligations raising from the UNECE (United Nations Economic Commission for Europe) Convention. Whereas the focus first laid on sulfur emission reduction, the Convention was extended to include eight further protocols in the following 20 years, listed in Table 2.

Agreement	Content
1984 Geneva Protocol on Long-Term Financing of the Cooperative Program for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP)	Stipulates financial support to the EMEP centers
1985 Helsinki Protocol on the Reduction of Sulfur Emissions	SO_2 control by 30% between 1980 and 1993
1988 Sofia Nitrogen Oxide Protocol	Stipulates no further increase in NO_X emissions
1991 Geneva Volatile Organic Compound Protocol	30% reduction in VOC emissions
1994 Oslo Protocol on further Reduction of Sulfur Emissions	The protocol sets ceilings for SO_2 emissions based on CL (critical load) and IAM (integrated assessment modeling)
1998 Aarhus Protocol on Heavy Metals	Control of a selected number of heavy metals
1998 Aarhus protocol on persistent organic pollutants	A selected number of persistent organic compounds
1999 Gothenburg protocol to abate acidification, eutrophication, and ground-level ozone	Emissions of SO_2, NO_X, Ammonia NH_3, and volatile organic compounds (VOC), Amendment (2012) added fine particulates

Table 2: protocols released under the Convention on Long Range Transboundary Air Pollution and their content

As a rule, the protocols focus on one specific pollutant, set limits for their concentration, and provide policy measure recommendations to comply with the guidelines. At this point the UNECE legal framework made no explicit reference to PM. The scientific world on the other hand was already very much aware of the issue and had started to research long

before. It was only the revised Gothenburg Protocol from year 2012 that incorporated commitments on fine particulate matter. This amended Gothenburg Protocol is still in force today. [11]

Few years prior, the European Union adopted the previously mentioned air quality directive in 2008 that limits the concentration of both PM 2.5 and PM 10 among other air pollutants. Since then, the recognition of PM 2.5 as a very harmful pollutant has increased significantly and the measurement of its concentration has been subject to continuous improvement and scrutiny. Nowadays all EU member states are obligated to regularly report their air quality measurement results to the European Environmental Agency (EEA). Based in Copenhagen, Denmark, the EU agency is responsible for analyzing and storing the submitted data as well as monitoring the member states' compliance with the EU air quality standards obligations. Starting 2015 the annual ceiling for PM 2.5 is not to exceed the value of 25 $\mu g\ m^{-3}$. Despite the laws and limits the EEA still estimates roughly 300 000 premature deaths annually due to fine particulate matter in the European Union. [12] As a reaction to this constant and severe impact on mortality the WHO issued a recommendation to limit PM 2.5 to only 5 $\mu g\ m^{-3}$ annually. A lot of work remains to be done in order to achieve this WHO limit in the cities that this thesis investigates.

Three middle European and three Scandinavian capitals were chosen for the purpose of closer examination and comparison. Important aspects considered in the selection were similar topology, number of inhabitants, climate conditions and access to historical air quality data. First the basics on PM and its impacts are presented, followed by the applied measurement techniques. Then, insights on each city's air quality including specifics of every city's PM level will be presented. Finally, the overall results will be discussed, resulting in some conclusions and outlook.

2 Particulate matter

Particulate matter comes in many sizes and shapes and can have several different chemical compositions. These properties can offer conclusion about where the PM originated from and further offer insight on how it might impact our health or climate.

2.1 Sizes

Generally, particulate matter is divided into two groups, depending on their size. PM 10 describes all coarse atmospheric aerosols with an aerodynamic diameter smaller than 10 micrometers. PM 2.5, accordingly, stands for the group of smaller and finer particles, specifically with a diameter less than 2.5 micrometers. Some scientific papers also investigate PM 1, or PM 0.1, so-called ultrafine particles, however, there are no limits or standards set for these specific particle sizes by the responsible international bodies. As a result, they are hardly measured except for research purposes. [13]

2.2 Sources

Apart from the aerodynamic diameter we can also characterize PM based on its source. Typically, we differentiate between natural and anthropogenic sources and can categorize moreover into primary and secondary particulates.

The so-called primary particles are directly emitted into the atmosphere by a specific source. Primary emissions can generally be solid, liquid, or gaseous. Secondary pollutants, on the other hand, are created in the atmosphere by chemical reactions and are exclusively formed from gases. Precursors for this PM formation include the previously mentioned SO_x, NO_x, VOCs, and ammonia. Pure ammonia or NH_3 is a gas that is typically emitted from agricultural activities. Ammonium, NH_4^+, is formed in the atmosphere by the protonation (or hydronation) of ammonia, essentially the addition of a proton.

Ammonium can contribute to the formation of particulate matter and is often found to be a major component of PM in areas with high agricultural activity. [14]

Natural origins of particulate matter comprise dust storms, volcanic activity, forest fires, living vegetation as well as sea spray. Major anthropogenic sources include the burning of fossil fuels and motor combustion, but also construction, power plants, wood smoke, road dust and various industrial processes contribute to a higher PM concentration. The following graph, taken from the 'European Union emission inventory report 1990-2021', displays the shares of the different sectors contributing to PM 2.5 in the EU. [15] Close to two thirds (64%) of the PM 2.5 emitted in the EU, originates from the so-called 'commercial, institutional and households' sector.

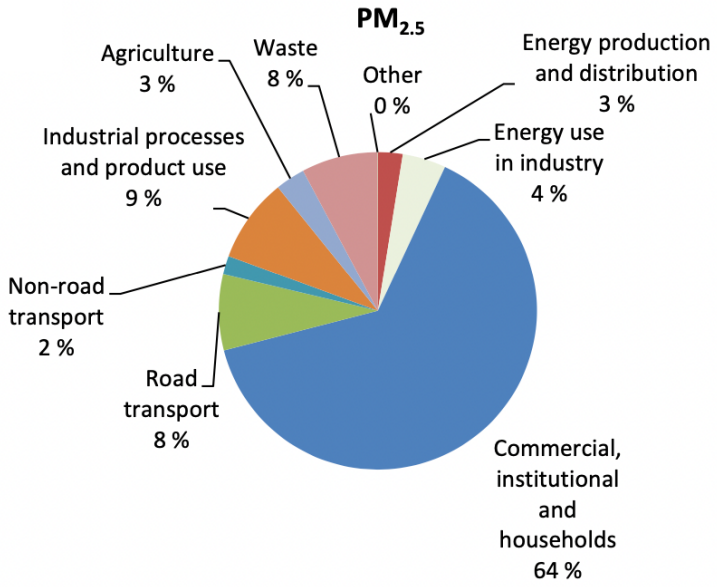


Figure 1: PM 2.5 emissions in the EU in 2021 shared by sector group [15]

This dominant sector groups together the fuel combustion in commercial and institutional facilities as well as households. Within the sector stationary combustion processes in the residential sector with the primary purpose of heating and cooking constitute the key activity.

When regarding the remaining sectors, the overall transportation sector contributes to a share of 10% of the PM 2.5 in the EU. With a share of 9%, 'industrial processes and product use' sector groups together emissions from the production of iron and steel, cement and glass, chemical products, wood processing or generally construction, among others. The sector 'waste', which contributes 8% of the PM 2.5 in the EU, includes the emissions from composting, waste incineration or domestic and industrial wastewater handling. Other sources of PM 2.5 pollution include the energy use in the industry sector, the energy production as well as distribution and lastly agriculture.

Within urban areas the anthropogenic emissions usually outweigh the PM originating from natural sources. More specifically, the PM 2.5 in cities usually comes from one of two sectors. The major source remains the same as in the overall EU (Figure 1). Emissions from combustion processes in the residential sector with the purpose of heating and cooking, typically magnify in an area of high population density. The second major source of PM in cities is road traffic, which includes the pollutants emitted by internal combustion engines as well as particles emitted by road or tire abrasion.

2.3 Chemical composition

The overall chemical composition of PM can vary locally and depends directly on the source it originated from. Generally, however the major constitutes are inorganic ions, mineral dust, sea salt and carbonaceous aerosols. The inorganic ions are mainly nitrate NO_3^-, sulfate SO_4^{2-} and ammonium NH_4^+, formed in the atmosphere by their precursors. The significance of each of these components is graphically illustrated in Figure 2, which is an edited version of Figure 10 in the paper by Fuzzi et al. [16] It shows how the chemical composition differs both in rural versus urban areas, but also compares central Europe to the northern locations.

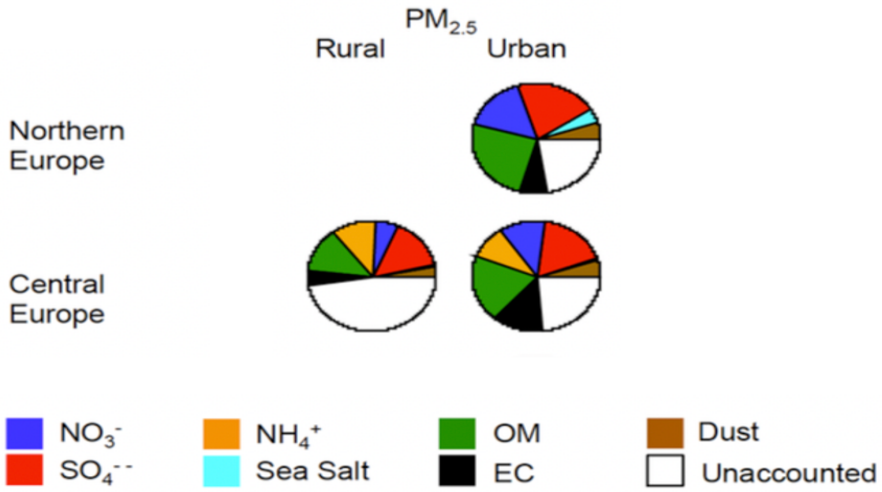


Figure 2: average chemical composition of PM 2.5 at urban and rural sites across Europe. OM (= organic matter) is calculated OC 1.4. This is why OM contribution to PM is probably underestimated, and it explains part of the unaccounted mass. [16]*

Although Figure 2 supports some following conclusions, it typically makes little sense to investigate an average composition of PM 2.5 over such a large spatial distribution and an unspecified time period. It is typically of greater importance to underline the significant variation in emission of most PM components throughout the different months and seasons.

The precursor of nitrate is represented by nitrogen oxides, which are emitted in combustion processes such as those in vehicles or power plants. Nitrate is formed by the oxidation of NO_2. As Figure 2 shows, it is clearly visible, that the concentrations are higher in the urban region, which agrees with the dense traffic cities typically have compared to rural sites. Generally, the highest nitrate concentrations can be found during winter, when these anthropogenic emission sources are at their peak.

Sulfate particles in PM are formed in the areas of SO_2 emission sources. Sulfur dioxide released into the atmosphere can undergo oxidation reactions, forming sulfuric acid, which finally leads to sulfate particles, that contribute to the PM concentration in the atmosphere. The rate of this conversion process increases with both rising temperature and higher relative humidity. [17]

Ammonia is mainly emitted by agricultural activities, which typically peak in spring when the diverse fertilizers are distributed into the fields. NH_3 acts as a precursor for ammonium, found in PM. According to Figure 2, ammonium found in PM 2.5 is predominately a Central European trait. This is in agreement with the data from the 'European Union emission inventory report 1990-2021', which claims that the major NH_3 emitter countries in 2021 within Europe were France, Germany, Spain, Italy, and Poland. [15] The emissions of every one of these countries increases the presence of ammonia in the ambient air within Central Europe. Due to geographic location, however, the ambient air in northern countries does not feel the impact of the pollutant in the same magnitude.

Mineral dust contributes primarily to coarse particles in the atmosphere and is therefore of less significance when looking at the composition of PM 2.5. Mineral dust usually travels from the Sahara Desert to Europe, dominating however in the more southern parts of the continent. Here a strong seasonal dependance prevails with higher dust concentrations in the summer months due to more frequent and more intense dust transport episodes from Africa and overall drier meteorological conditions. [18]

The sea salt concentration in PM exhibits a large decreasing gradient with the growing distance from the sea. [18] Therefore, sea spray is only relevant in the composition of PM in the areas that lie directly at the coastline. This conclusion can be also drawn by looking at Figure 2. Sea salt affects the PM 2.5 composition in North European cities, but can only be seldomly found in Central Europe, due to absence of sea access.

Carbonaceous aerosols have two main components, elemental carbon (EC) or generally black carbon (BC) and organic carbon (OC). BC is called "black" because of its light absorbing properties, which makes it appear black. EC is essentially a subset of BC that consists of nearly pure carbon in graphite like structure, that is the most refractory. These carbonaceous atmospheric aerosols are typically emitted via combustion processes. Organic carbon refers to the carbonaceous particulate matter other than black carbon and is a mixture of many different organic compounds and species. OC in fine particles is associated with both direct emissions from combustion sources and secondary aerosol from natural and anthropogenic sources. Carbonaceous aerosols generally show a

significantly higher concentration in winter than during the summer months, where residential heating is at a minimum and the meteorological conditions favor quick dispersion of the particles. [16]

3 Impacts on and of PM

3.1 Meteorology

Particulate matter, especially fine PM, can be suspended in the atmosphere for several days. The lighter particles are more susceptible to thermal motion of the surrounding gas molecules, and they are therefore more prone for long range transport than coarser PM. This, however, is only possible if the meteorological conditions allow it. Wind speed or precipitation play an obvious role but also temperature, humidity and mixing height are significant factors. In a paper by Megaritis et al. [19] the influence of each of the mentioned parameters on the PM 2.5 concentration throughout Europe is investigated. Using a three-dimensional chemical transport model, the paper quantifies the individual impacts and presents the following findings, graphically shown in Figure 3 below (corresponds to Figure 9 in the paper by Megaritis et al.). Showing three modeled periods summer, fall and winter, Figure 3 summarizes the sensitivity distributions of average PM 2.5 to the various meteorological parameters.

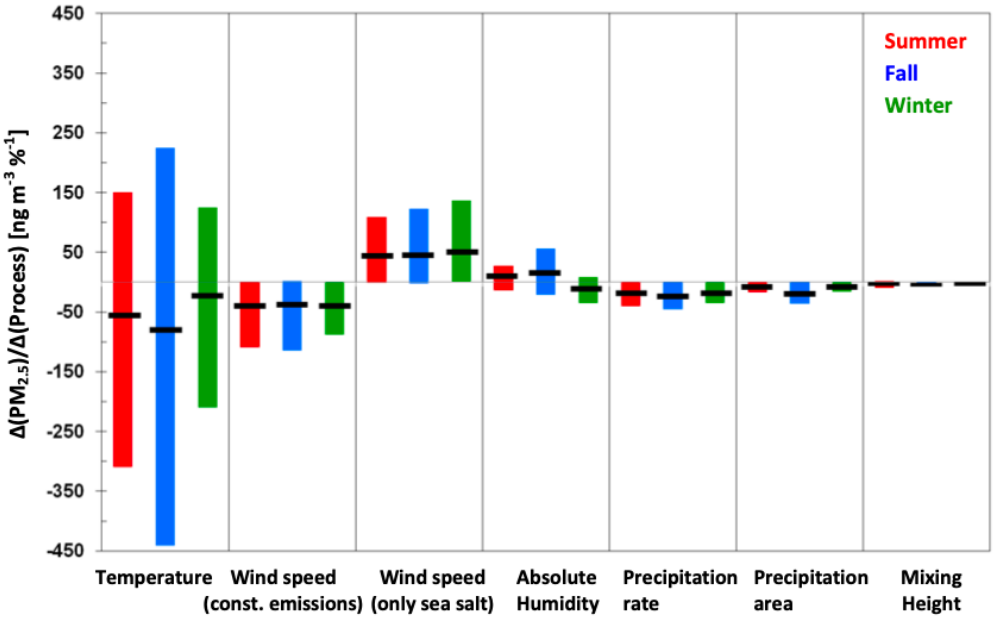


Figure 3: Predicted simulation-average sensitivities of total PM2.5 to changes [%] in different meteorological parameters during the three modeled periods: summer, fall and winter. Each colored bar represents the range between the 10th and 90th percentiles and the black line in every one of them shows the mean PM2.5 sensitivity over the domain. [19]

Based on the simulation findings temperature has the biggest impact on the PM 2.5 concentration. According to Figure 3 a rise in temperature will lead to a decrease of PM 2.5, the effect being the strongest in the fall and the weakest in winter. However, when investigating how a rise in temperature affects the different components of PM, it becomes apparent how intricate the relationship really is. The increased summer temperatures enhance the evaporation of ammonium nitrate, a key component of PM 2.5, causing it to shift to the gas phase. This volatilization results in a substantial reduction in nitrate levels within the particulate phase, contributing significantly to the observed decrease in overall PM 2.5 concentrations during the summer season. However, as the particulate nitrate decreases, cloud acidity rises, accelerating the formation of sulfate particles in the liquid phase, potentially contributing to an increase in PM. Increases in temperature have also been shown to lead to higher biogenic emissions, releasing more VOCs into the atmosphere. This opposes the net negative effect temperature typically has. In conclusion, the effect that increased temperature has on PM 2.5 can vary substantially depending on location and season, but the semi- volatile PM 2.5 evaporation seems to dominate over the opposing effects during all seasons.

A decrease of wind speed, without allowing any change in sea salt or dust emissions, results in an increase of PM 2.5 levels throughout all seasons. Lower wind speeds negatively affect advection, which refers to the horizontal transport of air masses, and might cause pollutants to accumulate in a specific area rather than being transported away. Dispersion, too, is hindered by less wind speed, allowing pollutants to linger in the vicinity of their emission sources. Wind also facilitates the vertical mixing of air masses in the atmosphere. Decreasing wind can trap harmful particles near the ground and limit their vertical dispersion. Moreover, wind speed influences dry deposition of PM 2.5 by affecting the rate at which the particles settle. Megaritis et al. [19] found that a simulated 10% reduction in wind speed led to 7- 13% less PM 2.5 leaving the atmosphere via dry deposition.

On the other hand, reduced wind speed leads to less erosion and fewer sea salt particles are lifted from the ocean into the atmosphere. As a result, lower PM 2.5 levels can be

measured. The predicted decreases are found to be highest during winter, when conditions typically favor sea salt emissions. However, this effect focuses on coastal areas, whereas in continental Europe the influence of marine aerosol emissions is less significant.

Absolute humidity has variable effects, depending both on seasonal and spatial variation. In summer and fall, increased absolute humidity positively impacts PM 2.5 concentrations, predominantly driven by elevated nitrate levels. This can be explained by the shift in the equilibrium of the ammonia–nitric acid system, created by the increased humidity. Megaritis et al. [19] found that a 5% increase in absolute humidity leads to 15% more nitric acid moving to the aerosol phase, resulting in higher particulate nitrate concentrations. Over the oceans, in contrast, the PM 2.5 levels decrease as absolute humidity increases. Increased humidity promotes the coagulation and growth of particles, leading to larger sizes, which then again lead to accelerated dry deposition and an overall decrease of PM 2.5. This effect that humidity has on sulfate and sodium chloride, which are major components of sea salt aerosol, is especially dominant in the winter months and determines the negative response PM 2.5 concentrations have on increased humidity in that period.

Precipitation has an obvious impact on air pollution by removing particles from the atmosphere via wet deposition. Unlike temperature, which is complex due to different effects on different components, precipitation impacts all the PM 2.5 components in the same way. Megaritis et al. [19] predict that an 10% increase in precipitation rate led to a 2-4% and 5-12% increase in both, PM 2.5 wet deposited mass, and wet deposition of PM 2.5 gas precursors, respectively. Moreover, they conclude that not only precipitation intensity, but also the precipitation area affects the total PM 2.5 levels.

Lastly the impact of the mixing height is discussed. In Figure 3 it is visible that, compared to the other parameters, its effect is pretty small, but clearly negative. An increase in the mixing height leads to total PM 2.5 reduction in all seasonal periods. This decline can be attributed to enhanced dispersion and pollution of particulate matter with greater mixing heights.

Additionally, to these main meteorological parameters there are other weather phenomena that can greatly impact the PM 2.5 levels. Here reference is made to heavy storms, heat waves or temperature inversions. A temperature inversion happens when the normal vertical temperature profile of the atmosphere is reversed, and a layer of warm air is trapped above a layer of cooler air near the surface. This can act like a lid above the affected region, limit vertical mixing, prevent air pollutants from being dispersed and diluted and therefore trap them near the ground level. Inversions usually happen in winter due to the more favorable conditions during cooler seasons. Largeron et al. [20] link the high PM pollution during the wintertime to these persistent inversions. In their investigated area, namely French Alpine valleys, the reversed temperature profile of the atmosphere persists 35% of the time between the time span of November to February, significantly impacting the dispersion of air pollutants.

3.2 Health effects

A grown person breaths approximately 11,000 liters of air each day. Ideally this air is clean and free of pollutants. However, this is seldomly the case. Our lungs therefore have a self- clearing mechanism of the airways in the respiratory system, called mucociliary clearance. In this protective process inhaled particles including pathogens are removed before they reach the delicate tissue of the lung. PM 2.5 however is smaller than most inhaled particles and tends to stay in our lungs, making up 96% of the particles found in the deep lung tissue. [21] PM 2.5 can not only reach into the gas-exchange region of the lungs, but also pass through the respiratory barrier, enter the bloodstream, and hence spread throughout the entire body. The greater specific surface area of PM 2.5 allows them to attach themselves to toxic compounds, such as transition metals and harmful polycyclic aromatic hydrocarbons. [22] Due to its ability to both penetrate deep into our bodies and carry toxic particles, PM 2.5 is more closely linked to negative health effects than any other air pollutant nowadays.

As the initial site of deposition, the lung is one of the primary victims of adverse PM 2.5 health impacts. Several studies have shown that PM 2.5 can cause airway inflammation, decline in lung function and incidence as well as exacerbation of asthma. [23] Moreover, studies have shown that chronic PM 2.5 exposure also correlates to cardiovascular morbidity and mortality. [24] Long term PM 2.5 exposure was also found to enhance the development of diabetes mellitus. Even at low levels (lower than in the enforced standards) of PM exposure, it has been identified to increase the risk of mortality attributable to diabetes mellitus. [25] Another highly concerning impact of PM 2.5 exposure is the one it can have on pregnant women. Epidemiologic evidence suggests that PM exposure during pregnancy is linked with adverse birth outcomes. This includes preterm- birth, lower birth weight as well as post-neonatal infant mortality. [26] [27] [28]

Generally, inhaling PM 2.5 can negatively impact a human's health and ultimately lead to premature death. The relevant factors of determining the severity of this impact, are the

duration and concentration of exposure, as well as the size and chemical composition of the particulate matter entering the body.

3.3 Climate impact

Atmospheric aerosols, including PM, not only negatively influence one's personal health but also affect things on a larger scale like the overall air quality, visibility, and climate.

Aerosols affect the climate both directly and indirectly. The direct effect refers to the radiative forcing that describes the interaction of aerosols with radiation. The indirect effect, known as the cloud albedo effect, involves the influence of aerosols on cloud formation and cloud properties, which in return impacts the overall climate.

Radiative forcing is defined as the perturbation in the earth's energy balance due to a change in concentration of greenhouse gases and aerosols present in the atmosphere. Greenhouse gases such as carbon dioxide (CO_2) or methane (CH_4) trap heat energy from the sun and the earth's surface and therefore lead to a warming effect in the atmosphere. Aerosols, on the other hand, can have both, either a cooling or warming effect on the climate. Certain aerosols, like black carbon, absorb sunlight and contribute to warming. Many other aerosols, like sulfate particles, scatter and reflect radiation back into space and thus lead to a cooling effect. The net impact of aerosols on radiative forcing depends on various factors, including their concentration and composition. However, it is widely acknowledged that aerosols, including PM, tend to have an overall cooling effect on the atmosphere. [29]

The cloud albedo effect is closely related to radiative forcing. Aerosol particles can serve as cloud condensation nuclei (CCN) and as water condensates onto these, clouds are formed. The cloud albedo, which is essentially the reflectivity of a cloud, therefore depends on the particles that formed it. Not only their chemical composition is relevant,

but also the size of the particles as well as their concentration influences both the overall earth's energy budget as well as the local climate and weather. Generally, a larger number of cloud droplets, originating from CCN, leads to a higher cloud albedo as well as a longer cloud lifetime. Consequently, the cooling effect of clouds is enhanced as air pollutants, such as PM 2.5, and the number of CNN sized particles increases. [30]

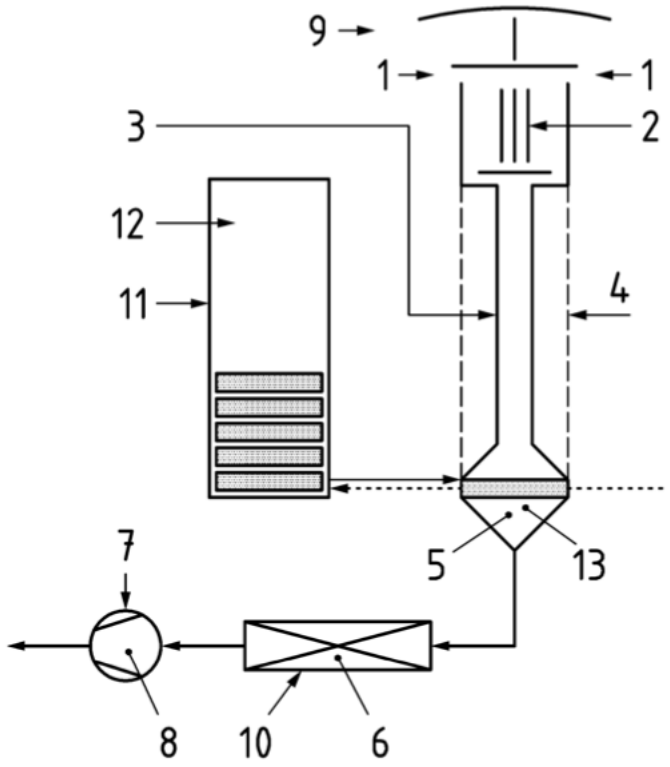
In conclusion, aerosols, including PM, exert various influences on the earth's climate. These effects are often regional and depend on the type and number of aerosols present. Although certain aerosols can have warming effects on the atmosphere, generally they tend to have a negative effect on the overall global energy balance. [31]

4 Measurement techniques

Within the EU, the member states are obliged to apply standardized measurement techniques and procedures to assess air quality on a uniform basis. In the case of particulate matter, a standard reference technique is mandatory, which is laid out in the EN12341 norm. The norm describes the gravimetric measurement method in great detail, facilitating a harmonized practice of the PM reference measurements throughout Europe. [32] However, as discussed later in this chapter, this gravimetric measurement technique is not ideal for routine and continuous monitoring networks. As a result, the responsible entities resort to additional devices, using different techniques. In the European standard EN 16450 the approved automated measuring systems for PM are discussed. [33] The most common ones rely on either oscillating microbalance, beta-ray attenuation or optical methods. All of them are presented in further detail, after first circling back to the gravimetric standard technique.

4.1 Gravimetric method

For a long time, the gravimetric measurement of particulate matter was the standard and only technique available. The simple concept is based on exposing a filter, typically out of glass or quartz fibers, to the ambient air and thereby letting it collect the wanted particles onto it. At a constant flowrate, set at 2.3 m^3/h by the EU standard, air enters the measurement chamber through a size specific inlet. The size selection process of a size specific inlet or impactor relies on the principle of inertia. As particles are drawn into the inlet or impactor by the flow of air, their motion is influenced by their size and mass. Larger particles have more inertia and tend to continue traveling in a straight path, while smaller particles are more easily diverted from their original trajectory. By adjusting parameters such as nozzle size, airflow velocity, and geometric configurations, the device can be tailored to capture particles within a specific size range, which in our case are particles with aerodynamic diameters of 2.5 micrometers or less. In Figure 4 the components of the whole sampling device are schematically illustrated.



1. Air sample
2. Impactor
3. Connecting tube
4. Sheet air
5. Filter holder
6. Flow measurement
7. Pump
8. Flow regulator
9. Measurement of sample air temperature and pressure
10. Measurement of temperature and pressure
11. Filter storage
12. Measurement of storage temperature
13. Temperature measurement next to filter

Figure 4: Scheme of a gravimetric PM standard sampling device from [32]

After sampling for 24 hours the filter is kept in a specific environment, where parameters like temperature and relative humidity are strictly regulated in accordance with the EU standard. The filters stay in this specific environment for a minimum of two days before they can be weighted the first time. As a next step they are carefully stored again for at least another day until they are weighted again and compliance with the first measurement is checked. The filter's average weight is then finally compared to the control filters weight. The difference in mass is a direct indicator for the mass concentration of particulate matter present.
Specifically, the PM concentration c, which is given in $\mu g/m^3$, is calculated using the following formula:

$$c = \frac{m_s - m_0}{\varphi * t}$$

Where m_s stands for the mass of the sampled filter and m_0 for the mass of the control filter, both given in μg. The flowrate $[m^3/h]$ under ambient conditions is described by φ and t stands for the duration of the sampling time in hours.

Although this technique is still used as a reference method throughout diverse European cities, there are obvious disadvantages to it. The whole method relies on manual labor, which is always a potential source of error and uncertainty. More relevantly, the technique does not provide real time data but requires time before delivering results. This makes it impossible to recognize high air pollution in the moment and inform the public as well as act on it. Another drawback is the relatively long sample times, usually 24 hours, that force the averaging of potentially high and low concentrations throughout the day. Information about concentration spikes of short duration might get lost. Therefore, other instruments and techniques are needed. The most commonly used automated dust monitors in Europe are based on one of the three following principals. [34]

4.2 Tapered element oscillating microbalance method

A tapered element oscillating microbalance (TEOM) is an instrument that draws ambient air through a filter, continuously weighing this filter and at the same time calculating real time mass concentrations. In a way it is an automated, continuous gravimetric measurement. Looking at the flow system, shown in Figure 5, the operation principle of this dust monitor is illustrated.

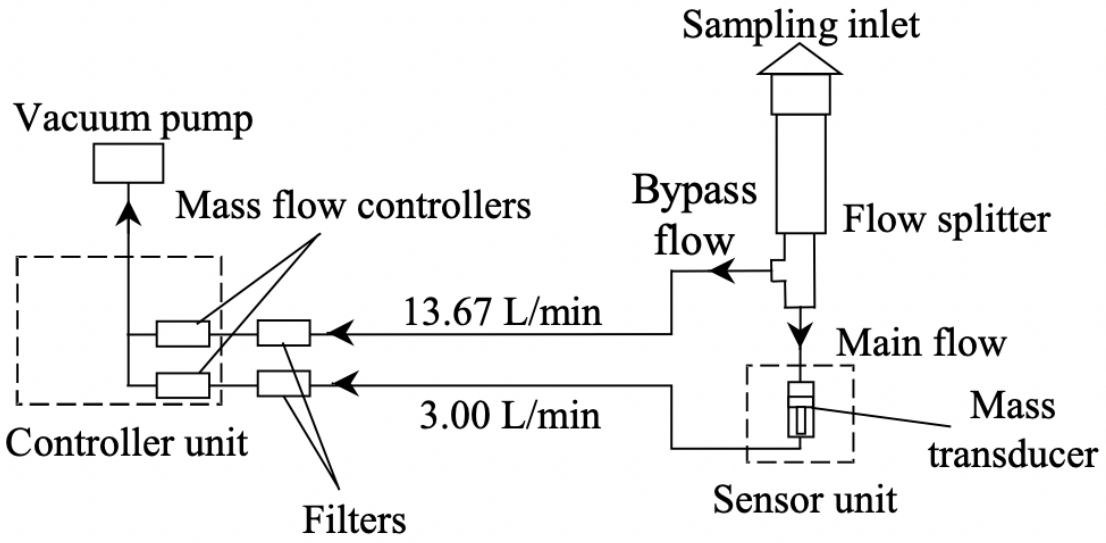


Figure 5: schematic flow system of the TEOM from Lim et al. [35]

A vacuum pump draws air into the instrument at a constant flow rate of 16.67 liters per minute. To enter the instrument the sample air must pass through an inlet, designed to only allow particles of the wanted size range inside. The air stream is then divided at the flow splitter into the so-called main flow of 3 l/min and the rest is sent via a bypass to exhaust. The flow rate is controlled by mass flow controllers, which have to be adjusted for temperature and pressure in order to maintain the constant volumetric flow. The main flow now enters the sensor unit through a sample tube. The mass transducer (or tapered element) is located inside this sensor unit, which is heated to 50°C in order to minimize humidity effects. The tapered element consists of an exchangeable filter cartridge, that is placed on top of a hollow glass tube. The base of the tube is fixed, but the tip is free to

vibrate at its natural frequency, much like the tine of a tuning fork. An electronic circuitry senses this oscillation and can add energy to the system to overcome losses and therefore maintain a constant amplitude. A counter measures the systems frequency every two seconds. Now, as soon as additional weight, in the form of particles, is deposited onto the filter, the frequency, at which the tube oscillates, changes. The mass transducer has a minimum detection limit of 0.01 μg, making the TEOM sensitive to low variations of deposited mass. This decrease in frequency, which is directly dependent on the magnitude of mass deposited, is sensed by the electronic circuitry. The automatically calculated and smoothed out mass rate [g/sec] is essentially the change in the total mass between the current reading and the next one. Dividing this particle mass rate by the flow rate provides a continuous result for the particle mass concentration in $\mu g/m^3$. [36] [37]

4.3 Beta attenuation monitoring

Beta attenuation monitoring (BAM) is a technique that utilizes beta decay and beta ray absorption to continuously measure ambient particle mass concentrations. The so-called BAM 1020, which is an approved and certified PM 2.5 monitoring device in the USA as well as in the EU, uses the radioactive isotope carbon- 14 to do so. [38]

Carbon-14 forms naturally in the atmosphere by the interaction of cosmic rays and nitrogen. Compared to the other naturally present two carbon isotope, it only occurs in trace amounts. Carbon-14 has a half-life of 5730 years and undergoes beta decay to form stable nitrogen-14. During this decay process energetic electrons are released with an average energy of 49keV. These electrons can travel up to a maximum of 22cm through air before their energy is completely absorbed. The long half-life of ^{14}C makes it a convenient source for beta absorption measurement because the source will easily outlast the service life of the instrument.

Generally, the operation of the BAM 1020 relies on the ^{14}C element inside the instrument providing a constant source of beta rays. These travel through a glass fiber filter tape before reaching a scintillation detector. Figure 6 is a photograph that shows the components needed for understanding the operating principal of the BAM 1020.

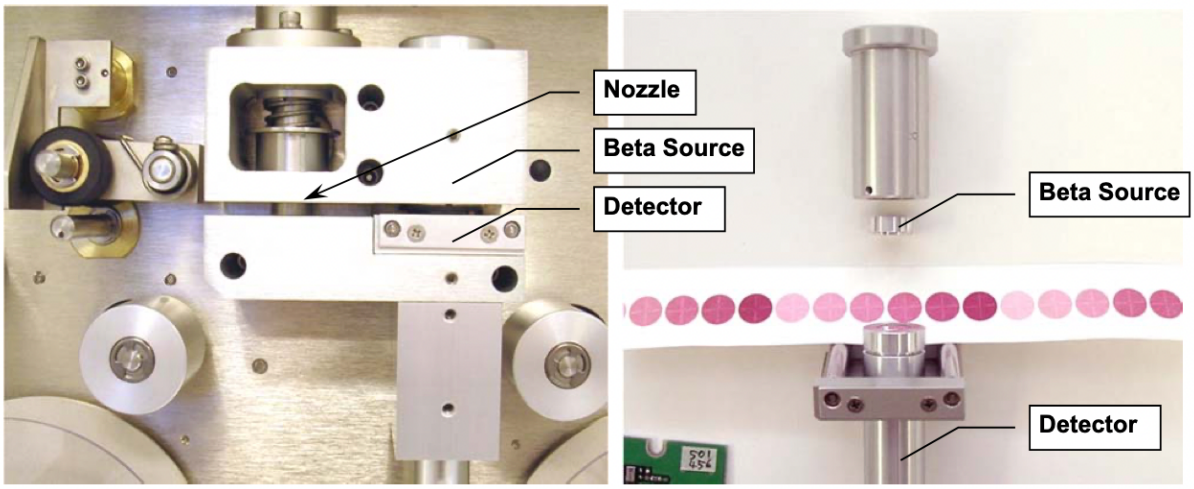


Figure 6: BAM 1020 sample and measurement stations [38]

At the beginning of every measurement cycle, which typically lasts an hour, a clean new spot of filter tape is placed between radiation source and its detector. This beta ray count (I_0) is recorded for 8 minutes. As a next step the tape is moved, and the previously exposed spot is positioned directly under a nozzle. A vacuum pump is turned on and a particulate laden air flow is generated with 16.67 liters per minute. This air flow travels through exactly the same tape spot for roughly 42 minutes. Then the pump is turned off and the tape is moved back to its initial position between the radiation source and detector. The beta attenuation monitor now counts the beta particles passing through the dirty spot of tape for 8 minutes (I_1). The particle concentration is calculated using the ratio of I_0 and I_1 and with the advancement of a new fresh spot of tape the cycle begins again.

This beta ray absorption process by matter can be described with the following relationship:

$$I_1 = I_0 \exp\left(-\frac{\mu M}{S}\right)$$

As previously mentioned, I_1 is the measured flux, or counts, across the aerosol laden filter tape and $I_0$the one across the clean tape. M stands for the mass deposited on the tape in mg, S is the spot area in cm^2 and μ is the beta ray absorption cross section given in cm^2/mg. The whole exponential term represents the attenuation or reduction in beta particle flux due to the higher absorption of beta rays by the additional particles on the dirty filter tape. By measuring I_1 and I_0 and knowing μ and S, one can solve the equation for M to determine the mass of the particles deposited. Along with the sampled volume and other calibration related factors the final concentration can then be provided. The absorption cross section μ primarily relies on the mass of the absorbing material rather than its chemical composition. This means that for commonly encountered substances in ambient particulate matter, such as soot, iron oxide, silica, or salt, the absorption cross sections are approximately equivalent. As a result, one does not necessarily need prior knowledge of the chemical makeup of the aerosol being sampled to conduct precise mass measurements using instruments like the BAM 1020.

4.4 Light scattering

The last measurement principle discussed in this thesis is based on the well-known concept of light scattering. The most commonly used dust monitor in the EU using this technique is the so-called GRIMM EDM (environmental dust monitor) 180 model. [39] Particles over a size range from 0.25 µm up to 32µm can be detected with the EDM 180. Additionally to their detection, also the particle size distribution can be determined.

This optical particle counter detects particles using the measurement principle displayed in Figure 7. A semiconductor laser serves as a light source. Illumination optics are used to focus the laser beam to a flat elliptical strip, achieving uniform illumination within the measurement volume. A light trap positioned directly across the laser source, absorbs the unscattered light. The scattering interaction itself is initiated by the introduction of sample air into the measuring cell. A pump is responsible for generating the air flow through the cell, while always controlling the accurate sampling volume of 1.2 liters per minute. The sample air is perpendicularly directed onto the laser beam.

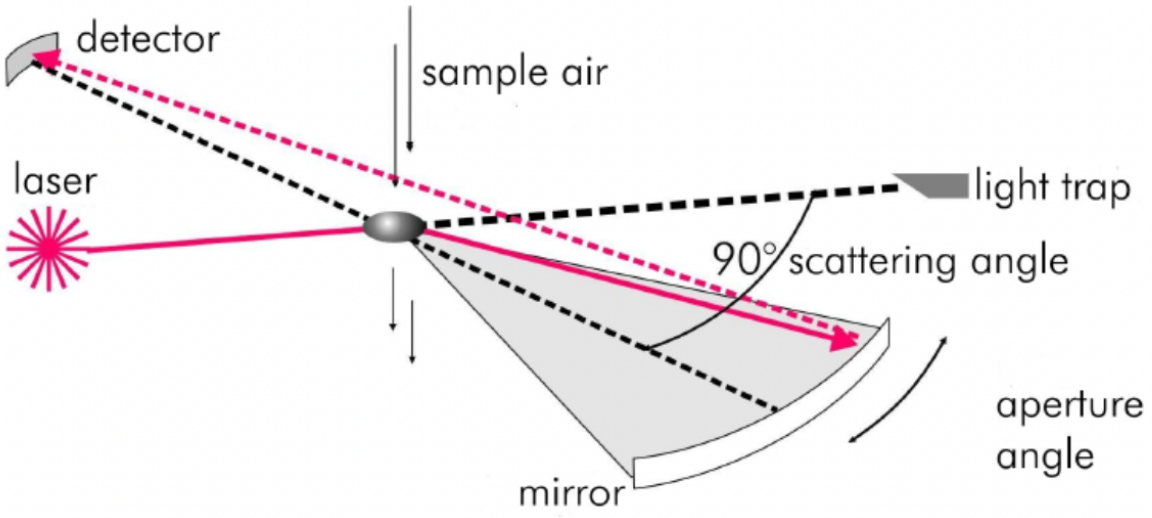


Figure 7: schematic measurement principle of the EDM 180 from manual [39]

The interaction of the light particles and the aerosols leads to a scattering process. The scattering light emitted by every particle is captured by a secondary optical system at a 90° angle. In it the scattered light is directed to a receiver diode (detector) using a wide-angle mirror. Positioning the detector at a 90° angle minimizes the influence of the aerosol particles refractive index for determining the particle size. The refractive index of particles refers to how much they bend light, affecting scattering intensity. It is crucial for accurate particle size determination, but often unknown due to diverse particle compositions and atmospheric variability. The scattering light pulse of every single particle is counted and its intensity, which is proportional to the particle size, is being measured. More specifically, the signal of the diode is first adequately amplified and it then passes a multi-channel size classifier. The EDM 180 model provides 31 channels within the size range from 0.25 μm to 32μm, into which the signal of each particle is categorized. The PM 2.5 concentration is inferred from the measurement by utilizing the particle size distribution information provided by the instrument. By summing up the particle counts within the channels that capture particles in the PM 2.5 range, one can estimate the concentration of PM2.5 particles in the sampled air.

The property of additional size distribution information provides a distinct advantage of this technique compared to TEOM or BAM. Another advantage is the lack of consumables in the optical particle counter. There are no filters or filter tapes that need to be exchanged on a regular basis. Moreover, in contrast to BAM, the EDM 180 does not rely on a radioactive source, for which's handling a special license might be required.

5 Central European cities

The three chosen middle European cities have many similarities; however, their air quality differs significantly. All capital cities have a population of a similar magnitude. They also share geographic resemblance, as well as the fact that a major river runs through each of them. Vienna, Budapest, and Prague all reside within the same time as well as climate zone. Prague is the most northern city with the highest elevation and Budapest the most southern with the lowest elevation. The average mean temperature difference between those two capitals is approximately 3°C (with Prague being the colder one) and Vienna lies pretty accurately in the middle of these two as regards both the temperature and the geographics.

Austria joined the EU in 1995, whereas Hungary and the Czech Republic became a member in 2004. This means that Austria had a mandatory head start in implementing the European air quality standards and was obligated to take measures towards a cleaner air before the other two counties did.

In the following section the PM 2.5 monitoring network of each middle European city is introduced. Every chapter includes a subsection, where an individual aspect or issue regarding the city's air quality is discussed. For Vienna this subchapter is about background pollution and for Prague the consequences of historic developments and the relevance of coal are discussed. In the last section of this chapter Budapest and the impact economy might have on air quality is presented.

5.1 Vienna

The capital of Austria has a population of about 1.9 million people.
The responsible entity in charge of taking the air quality measurements is the city of Vienna itself, specifically the municipal department for environmental protection. In 2010 there were two stations across the city measuring the PM 2.5 values. One year later there were already six monitoring stations and nowadays there are 13. The city of Vienna uses mostly optical particle counters in their monitoring network and does reference measurements using the gravimetric filter sampling method. [40]

Compared to the other two middle European cities, Vienna stands out because of its good air quality and specifically its lower PM 2.5 values. This is even more remarkable, considering the so-called Aquella study showing in 2005 that only one fourth of the fine dust present originated from the city itself whilst the rest was caused by long range transport. [41] During the last two decades the city of Vienna took many measures to reduce their share of the PM 2.5 emissions and thanks to cooperation with the neighboring countries the PM 2.5 levels were reduced by approximately 50% within 2010 and 2020. This equals the highest reduction out of all the investigated cities in the considered time span. To answer how Vienna was able to reduce its PM 2.5 levels so significantly an interview with an expert (Dr. Tizek, who works for the municipal department of environment in Vienna and is responsible for the air quality measurements) was conducted. In our talk it soon became clear, that it is nearly impossible to pinpoint one measure taken or one reduction strategy that has been the most effective. Especially for PM 2.5 a complex interplay of many factors needs to be regarded and measures are and need to be taken in every aspect possible. The measures put in place range from more sustainable domestic heating options (e.g., district heating), new construction concepts, traffic emission regulations by lowering speed limits, greater investments in public transportation to reducing and changing the type of winter road grit used to tackle snow and ice on the Viennese streets.

5.1.1 Background pollution

Dr. Tizek, however, highlighted again that the majority of PM 2.5 in the ambient air in Vienna is not emitted in the city itself. He presented an interesting graph, of which an edited version is shown in Figure 8.

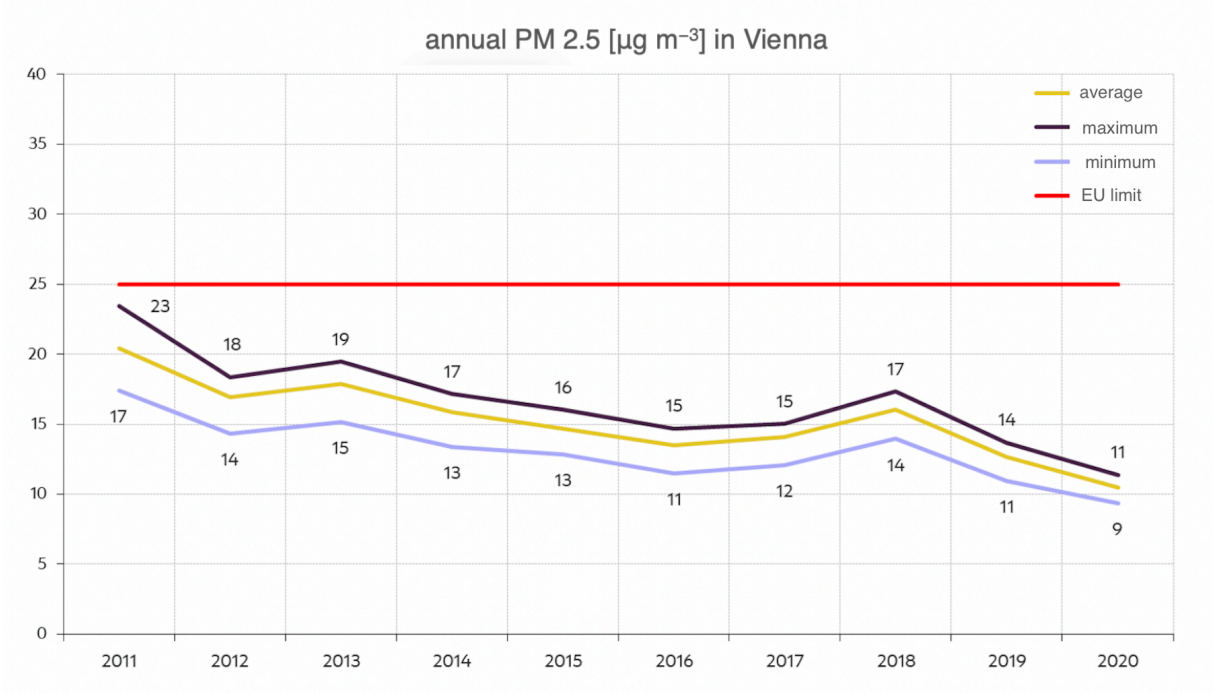


Figure 8: annual PM 2.5 concentrations in Vienna from 2010 – 2020 [42]

In Figure 8 one can see the annual evolution of the difference in PM 2.5 values. The dark line represents the annual average from the monitoring stations in the most polluted area of Vienna, indicating the maximum values. The lilac line represents the minimum values measured, which typically come from stations located furthest away from any emission source. Their average and the EU limit are also shown in the graph. What is interesting, is that the measurement stations next to highly trafficked roads or construction sites do not deliver much higher annual averages than the stations that essentially only measure background pollution. This offers evidence to the conclusion that the pollution in Vienna, is still only for a little part self-made and the rest of the PM 2.5 concentration is imported background. In 2011 the gap between the highest annual average and the lowest is three times as big as it is in 2020, indicating, that the city is making progress to reduce their

own emissions so much, that they will be indistinguishable from the background pollution someday.

Background pollution is an issue that can only be tackled at international level. Continental European countries share similar climate conditions, meaning they also share the consequences of each other's emissions. Although each city can make a difference with every measure they take towards cleaner air, entities like the European Union are crucial in the regard of setting pollutant emission limits improving thereby air quality not only locally but on the whole continent.

5.2 Prague

The population of the Czech capital stands at approximately 1.3 million people. Here the responsible entity for taking and reporting on air quality measurements is the Czech Hydrometeorological Institute (CHMI). Over the span of the 10 years, they measured the PM 2.5 concentration using five to seven different stations. The network in Prague mainly uses Beta radiometry as an automated measurement method for the PM 2.5 particles, in addition to the gravimetric measurement for reference purposes. [43]

5.2.1 Historical aftermath

Air quality has been a sore topic in the Czech Republic for several decades. After the Second World War, Czechoslovakia was a centrally planned economy with a politically set priority to develop heavy industries. The natural abundance of coal in the region lead to the construction of massive coal combustion power plants. Power produced by such plants impacted the air quality and environment significantly. Sulfur is naturally found in coal to a varying extent, depending on the region and coal type. When a coal combustion power plant was operating, 50- 95% of the sulfur compounds present in coal were emitted into the air. The SO_2 annual mean concentration ranged in the order of hundreds of μg m^{-3} and daily values went up even one more order of magnitude. Together with Germany and Poland, the border region of the three countries constituted the so-called black triangle in the 1980s. This region was known for its extremely high levels of air pollution. The industrially produced pollutants, mainly sulfur dioxide, water pollution, acid rain and other effects impacted the population and the environment greatly. However, the negative impacts did not only show up locally but effected the whole continent. "*The then Czechoslovakia, as a major emitter country, also contributed substantially and was blamed for air pollution export and consequent acidification problems elsewhere*." [44]

After the Velvet Revolution in 1989 and the conversion of Czechoslovakia into a parliamentary republic the nation quickly acted to cut emissions and within 10 years the Czech Republic was able to reduce their SO_2 emissions by an unpreceded 90%. [44] Even though air quality has continued to improve since 2000 throughout the country and the monitoring network of CHMI is one of the densest in Europe, Prague still struggles to keep their pollutant concentrations within the EU limits. One reason for that is the topology of the capital. The Prague basin, where the city is located, negatively affects the climatic conditions and dispersion of pollutants. During colder periods of the year, temperature inversions are often formed, leading to the accumulation of pollution. The most problematic pollutants, that mainly originate from traffic and domestic heating, are nitrogen dioxide, PM 10 as well as PM2.5. [45]

To this day coal continues to play an important role within the Czech Republic's energy mix. In 2017, almost 50% of the country's electricity was produced by coal combustion power plants, with even a higher share of 75% of heating generated by it. [46] Situated roughly 40km outside of Prague, the massive Melnik power plant, which started operation in 1960, still remains the main source for delivering heat and electricity to the capital city. [47] However, this power plant, along with all others that utilize coal are planned to retire within the next ten years at the latest.

The UN Paris climate agreement as well as the legally binding EU clean energy package call for a coal exit date in 2030. Although the Czech Republic will most likely overshoot 2030, steps into the right direction are taken. Given the country's history with coal as well as their reliance on it, their coal phase out commitments stand out in comparison to some other European countries, who have not even started discussing their coal exit. [48] Switching to more sustainable energy sources will not only help combat the global climate warming, but also positively affect the local regions. Improved air quality, vegetation and biodiversity can be expected. [49]

5.3 Budapest

1.8 million people live in the capital of Hungary. In Budapest the responsible entity for measuring and monitoring air quality values is the so-called Hungarian air quality network. In the first years of the decade there was roughly one station that measured the PM 2.5 concentration. In the years 2014 and 2015 there are even time periods of a few months where no data was recorded. In the second half of the decade the number of measurement stations grew up to approximately 8 in 2020. The Hungarian air quality network uses both beta attenuation and light scattering in their PM 2.5 monitoring instruments. [50]

5.3.1 Economic and political impacts

Out of all the examined cities Budapest is the one with the overall poorest air quality. The city's PM 2.5 values started to show significant reduction first in 2016 (see Figure 12). There are several reasons for this, topological, economical as well as political. Budapest is situated in a valley, which means that they are also prone to inversion and accumulation of air pollutants in the winter months. This does not put the city apart from Vienna or Prague, as all three have similar topology and experience the same phenomena. On the other hand, there are distinct economic differences between the neighboring countries. The gross domestic product (GDP) per capita is noticeably lower in Hungary than in the others. [51] This directly impacts the air quality. [52] The city's poorer public transport system (compared to Prague and Vienna) might force people to use their own cars. The cars tend to be older, less fuel-efficient vehicles, built at a time where emission standards were less strict or non-existent in some places. As traffic, specifically combustion, is a major source of pollutants in urban regions, this contributes negatively to Budapest's air quality and PM 2.5 concentration.

There are several known and implemented techniques, that have proven to increase the use of cleaner vehicles or ideally even reduce the use of private vehicles in urban areas.

There are continuous advances in making public transport more effective as well as sustainable. The significance of investing into these sectors is acknowledged and understood, seeing as cities are continuing to grow rapidly. [53] [54] However, it is up to the local politicians and national governments to activate these bans and policies as well as make these investments. Budapest's public transportation company (BKV) just released their first sustainability report in 2023, having made improvements starting in 2017. The slow progress towards providing a greener service and the main challenges can be attributed to political issues and pressures, as a state company can be influenced by governmental changes, according to Taksas' thesis. [55]

Another sustainability aspect that seems to be influenced by the political regime in Hungary is the energy generation, specifically the lack of renewable energy sources. Wind power, solar photovoltaic electricity, heat pumps or geothermal energy can provide electricity or heat without combustion and its potentially harmful byproducts. An EU directive sets goals and targets for its member states to achieve a major switch towards renewable energy sources since 2009. [56] However, since 2010 Hungary has continuously been at the bottom of the list that displays the share of renewable energy consumption in the EU member states. [57] Topologically Hungary is not an inhospitable place for wind and solar energy, having on average more sunny hours than e.g. Germany. [58] Also, economic reasons for the low level of investment in renewable energy are shallow since Hungary is not the poorest country in the EU. Romania and Bulgaria both have a lower GDP per capita, and still achieved a 24 % and 23 % share of total energy consumption derived from renewable energy sources in 2020. Hungary on the other hand only had a renewable energy share of 14%.

Instead, Hungary has four nuclear reactors generating about half of the country's electricity. The parliament has expressed its overwhelming support for the construction of two new power reactors, the main contractor of which is Russia's Rosatom. *"In September 2023 Rosatom director general Alexei Likhachev announced that first concrete would be poured in early 2025*." [59] In one of his papers Antal explains how the political regime in Hungary was able to delay and hinder the adoption of solar and wind energy. He suggests that the nuclear industry and government act as a single regime, influenced

by early regime actions, limited media discourse, weak landscape pressures, and characteristic features of an illiberal state. [60] All these factors reflect on the progress and investments made towards cleaner energy and cleaner air, which compared to the other investigated countries have been slower and lower, respectively.

6 Northern European cities

Scandinavian cities are known for their cold climate but also for a great living standard, which includes a good air quality. The better air quality, compared to the middle European cities, is not only due to smaller population wise or being lucky in their geographics, but because the three countries realized the relevance of the topic early on and started acting ahead of time. Several of the air quality protocols that were implemented in the last decades of the previous century carry the name of a Scandinavian city (see Table 1). Finland and Sweden joined the EU at the same time as Austria did, in 1995. Although Norway is no member state, it has been a driving force in research since the beginning of the recognition of air pollutants.

The open sea access of all the capitals influences the weather conditions significantly and therefore also the air pollutants present. The fact that they are all situated in the most northern countries of Europe correlates with the overall colder climate. In average the temperature difference between the Scandinavian cities and the middle European ones lies at 4°C.

After each cities measurement network is introduced in this section, the role of wood burning and studded tires on the PM levels are presented in the chapter of Helsinki and Stockholm, respectively. The chapter on Oslo includes a little discourse on the topic of urban overheating.

6.1 Helsinki

The greater city area of Helsinki is populated by roughly 1.3 million people. The Helsinki Region Environmental Services Authority (HSY) is responsible for measuring and monitoring the air quality values of the area. The HSY monitoring network is spread throughout the greater city aera of Helsinki, which includes the outer cities Vantaa, home of the Helsinki airport, Espoo and Kauniainen. 2010 there were eight stations in place and since 2016 they use eleven stations to observe the PM 2.5 concentrations. Unlike some other cities they use many different monitoring instruments, that are based on one of the three measurement principals, TEOM, beta attenuation and light scattering. [61]

6.1.1 Wood burning

Major sources of PM 2.5 in Helsinki include the typical urban emissions from vehicle traffic, construction, and domestic heating. An interesting aspect, however, is the part wood burning plays in the PM 2.5 levels. In the year 2000 it has been proposed that residential wood burning produced 25% of the total primary PM 2.5 emissions in Finland. [62]

"Fine particles are the greatest environmental health risk and in Finland they are estimated to claim 1600- 1800 premature deaths annually. Wood burning is estimated to be responsible for about 13% of them." [63]

According to the HSY about 80% of the smaller houses in the city area use wood burning as a secondary heating source. [64] The more you move away from the capital city the higher this percentage typically gets. Wood burning has always been regarded a sustainable heating option, which is why not only people in Helsinki but traditionally all of Scandinavia, heat up their wooden stoves or fireplaces as soon as it starts to get colder, in order to minimize the bills that come from the primary heating system. Another source of pollutants that originates from wood burning is the Finnish sauna culture. It is

estimated that there are 3.3 million saunas in a country where roughly 5.5 million people live. The HSY therefore puts in great efforts to educate the population on good wood burning, which emits many times less pollutants than “badly” burned wood. The most important aspect to consider for clean burning is the usage to dry wood and a good fireplace, that gets sufficient intake air and does not produce too much smoke, which would indicate poor combustion. [65] A closed firebox, where combustion and air intake are controlled, will emit up to 50 times less PM than an open fireplace. [66] However, also parameters like the batch and log size might influence the overall emission of particles. [67] What makes the residential wood burning so harmful, is not necessarily the amount or type of particles being emitted, but more the fact that it happens in the residential aeras, inside people’s homes, where they typically spend the most time. In contrast to most other PM 2.5 emission sources, that have been regulated and restricted over the last decade, residential biomass combustion, in the form of wood burning, is actually increasing. [68]

6.2 Stockholm

The capital of Sweden is home to approximately 1.6 million people. The entity that is responsible for measuring and monitoring the air pollutant concentrations in this area is the Stockholm Air and Noise Analysis (SLB). For the PM 2.5 measurement they use seven monitoring stations throughout the city. Both TEOM and optical particle counters are being adopted as automated air quality monitors. [69]

Since 1990 Sweden has been able to reduce PM 2.5 emission by 65% at national level. The different sector's share in the overall PM 2.5 emission in the year 2021 are presented in Sweden's Informative Inventory Report (IIR) and are shown in Figure 9. [70]

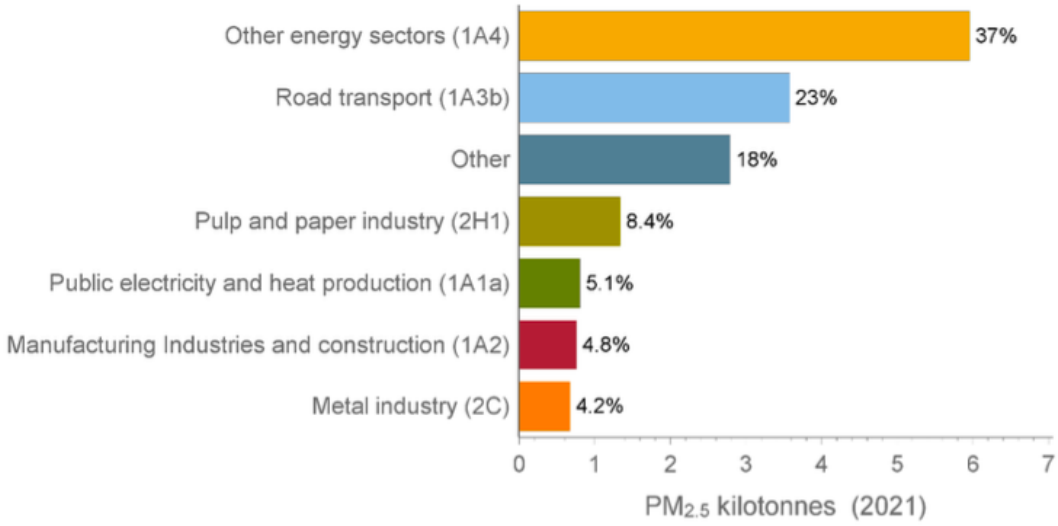


Figure 9: Distribution of PM 2.5 emissions among contributing sectors in 2021 in Sweden [70]

The abbreviations in the brackets next to the sector names in Figure 9 refer to the NFR (nomenclature for reporting) format used in the EU for dividing different emission sectors and sources. So-called "other energy sectors" were Sweden's largest source of PM 2.5 in 2021. The main part of emissions in this sector came from stationary biomass combustion in the residential sector. Emissions from road transport accounted for 23% of the total PM emission in Sweden. The IIR reports that the emissions in this specific sector have been already reduced by 45% since 1990. This can be explained by the stricter standards

for heavy good vehicles and buses, which lead to an emission reduction of 95% and 96% since 1990, respectively. Also, diesel passenger cars specific emissions of PM 2.5. have decreased by over 76%. However, the particle emission from road abrasion has increased with 26% between 1990 and 2021. These non-exhaust traffic emissions are composed of several wear sources (road, tire, and brake) but may also contain emissions from traction sanding or road salt. The increase can be explained by the overall larger average number of vehicles on the roads, whereas the majority of these emissions is closely related to the use of studded tires in Nordic countries. [70]

6.2.1 Studded tires

In Sweden the use of studded tires is allowed between the 1st of October and 15th of April each year. Although needed for the Scandinavian icy winter roads, studded tires significantly contribute to air pollution. Snilsberg et al. show in their paper that at 60 km/h studded tires produce 30 to 40 times more total suspended particles than non-studded tires would. Moreover, they find that studded tires generate dust with a finer particle size distribution. [71] In Nordic cities like Stockholm this poses a problem, contributing to higher PM 2.5 concentration in the winter months. In 2010 Stockholm introduced a studded tire ban for certain parts of the city to tackle this issue. The bans are still in force today. In a paper by Norman et al. Swedish and Norwegian scientists used the NORTRIP road dust emission model to assess the impact of traffic measures like the studded tire bans in Hornsgatan, Stockholm. The immediate effect of this ban lead to an estimated PM concentration reduction of 42% for the same year. Overall, the ban reduced the studded tire share and traffic in that area, resulting in an observed and modeled net concentration reduction of approximately 50% in the following years (2011- 2014). [72]

However, studded tires are still in use in all northern countries and all major cities struggle with the emissions resulting from these. Helsinki too, has enforced bans on parts of the cities where the adverse impact of studded tires is the highest. [73] In Oslo usage of studded tires is subject to extra fees. [74]

6.3 Oslo

The smallest of the examined cities is the capital of Norway, Oslo, with a population of roughly 1 million people. The Norwegian Institute for Air Research (NILU) is responsible for measuring and storing data about the air pollutant concentrations in Oslo. The monitoring network constitutes of approximately nine PM 2.5 measuring stations. They mainly use TEOM as an automated monitoring technique. [75]
Norway is no EU member state, however, is a signatory party to the amended Gothenburg Protocol under the Convention of long-range Transboundary Air Pollution. The country's air quality values easily comply with the EU standard limits and Oslo's PM 2.5 levels are comparable to those of other Scandinavian cities (see Figure 12).

6.3.1 Urban Heat Island and green infrastructure

Like every other larger city Oslo is a so-called urban heat island. The overheating of cities is the most frequently documented consequence of climate change worldwide. An urban heat island is defined by the increased temperature in the urban area, compared to the lower temperatures in the rural surroundings. The magnitude of this temperature difference can be as high as 10°C, with an average around 5°C. This has, among other things, a serious impact on a city's air quality. [76] The photochemical reactions with VOCs and NOx to form ozone are accelerated and enhanced due to the rise in temperature. The emission of PM2.5 precursors also increases with higher ambient temperature. [77] Moreover, energy production is increased to meet the elevated demand of air conditioning or cooling of water, causing the emission of more pollutants.

Different strategies are being employed worldwide to tackle this issue. Planting trees in the city or increasing green infrastructure have become very popular options. In a paper by Venter et al. their research confirmed that urban landscape units containing tree canopy within Oslo showed lower surface temperatures than the areas with artificial surfaces. The magnitude of these temperature differences was as high as 10°C. By

modeling a counterfactual city of Oslo where no tree canopy exists, based on the model of the measured surface temperatures, they concluded that the temperature would rise in the hypothetical Oslo by roughly 3°C, depending on the district. Their findings are graphically shown in Figure 10. [78]

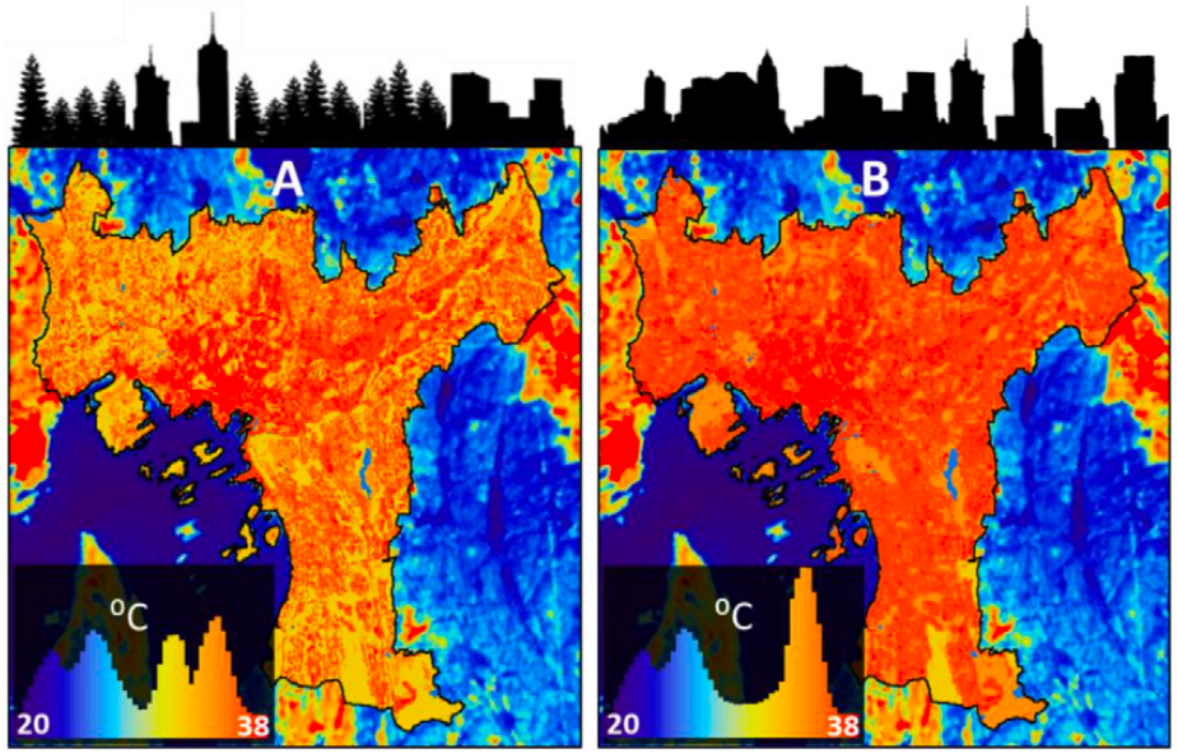


Figure 10: A: Land surface temperatures over Oslo built- up area (limited by the black lines) B: hypothetical surface temperature scenario where all the tree cover is replaced by impervious and artificial surface [78]

35% Oslo's built-up area is covered by trees. [79] Figure 10 shows the remarkable difference these green spaces make in the surface temperature profile of the city. Moreover, the Figure vividly illustrates the initial effect of the city's overheating. The urban heat island is easily distinctable by the rapid change in color, indicating temperature, when moving from the city center across its borders. In addition to the positive effect green infrastructure, bushes, trees and vegetation in general have on a city's overheating issue, they have also been proven to improve air quality in urban areas. Some plants can absorb specific types of air pollutants, or they can form a physical barrier between people and car related air pollution. Barwise and Kumar present a literature

review on how green infrastructure can be used to improve air quality. [80] Their findings revealed that various biological traits of plants contribute to the reduction of different air pollutants. In summary, the ability to remove transport related pollutants is dependent on factors like small leaf size, high leaf complexity and optimal vegetation height as well as density. Generally, taller vegetative barriers are more beneficial for open roads, whereas shorter barriers are more effective in street canyons. [81]

Another measure set in place not only in Oslo but in cities all around the world to tackle transport related air pollution, is to increase the number of charging stations for electric cars or to adopt national tax incentives to encourage the purchase of an electric car. Norway has been a role model when it comes to switching from ICE (internal combustion engine) vehicles to cars, that do not emit harmful pollutants during their operating process. Since 2011 the number of new ICE passenger cars registered in Norway is continuously decreasing, whereas the relative amount of hybrid and electric cars grows from year to year. [82] In 2022 this share of electric cars in newly registered passenger cars, accounted for 89%, which is the highest in all of Europe. [83] Although there are debates on how sustainable electric cars really are and whether they have an overall reducing impact on air pollution, research has shown that the replacement of ICE vehicles with electric cars reduces urban heat island intensity and locally improves air quality. [84]

7 Results and Discussion

All the data used in this thesis were acquired using the websites of the mentioned institutes. They store their PM 2.5 values differently, some in online databanks and others in the form of annual PDF reports. The monthly values were calculated by averaging the data from all available stations. In the absence of uncertainties in the raw data the use of uncertainties was excluded from the calculations. As a result, the calculated monthly or annual averages of the PM concentration comprise no use of uncertainties. The calculations represent a city average, from stations with high exposure and from ones that only measure background. The values were generously averaged spatially and temporally and should therefore be considered a qualitative representation.

On the example of Helsinki, I want to further explain and justify this analysis method. The HSY PM 2.5 monitoring network consists of eleven measurement stations distributed throughout the greater city area. In Figure 11 this network is shown.

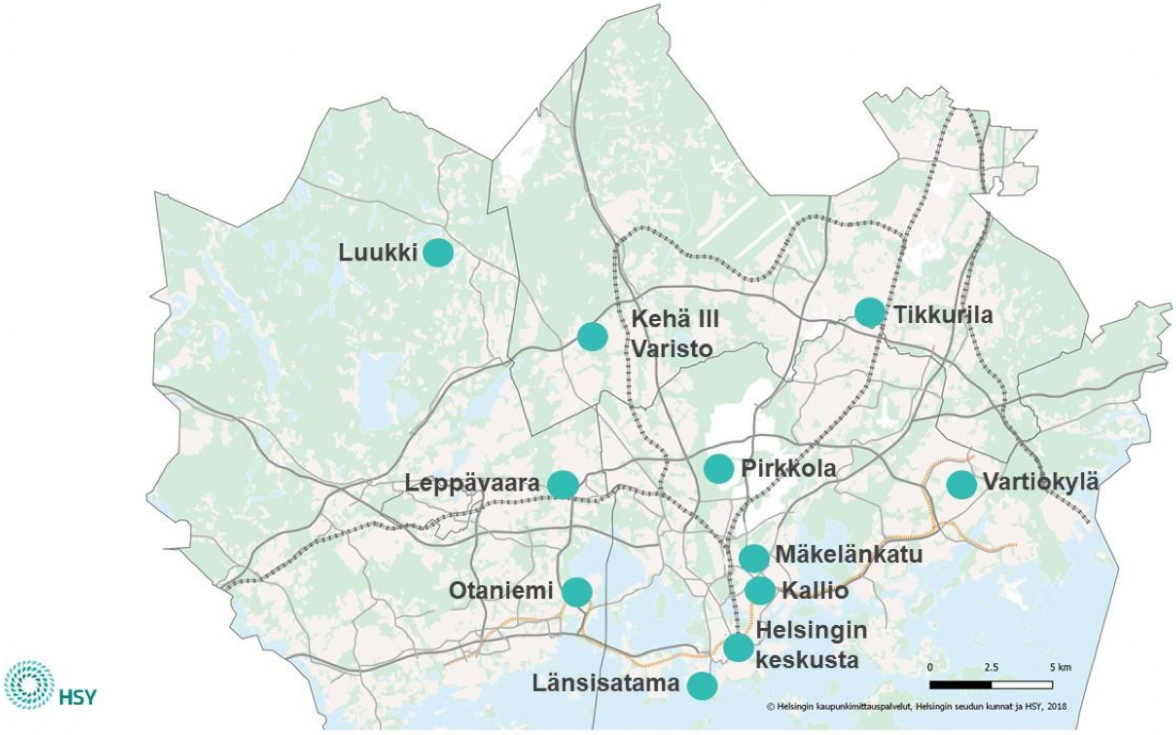


Figure 11: HSY PM 2.5 monitoring network in 2020 [85]

Four of these stations *Helsingin keskusta*, *Mäkelänkatu, Leppävaara* and *Tikkurila* are situated in heavily trafficked and busy areas. *Kehä III* and *Otaniemi* are stations located next to major highways, whereas *Pirkkola* and *Vartiokylä* measure the PM 2.5 levels in suburban residential areas. *Länsisatama* is located at the harbor of Helsinki. *Luukki* is situated on the countryside and is used to measure background pollution. *Kallio* is located just outside the city center but is also used as a background monitoring site. As one can imagine these background stations will generally measure lower PM 2.5 levels than the ones situated within the city center or next to highways.

In the case of Helsinki, the annual air quality reports provided a monthly PM 2.5 average concentration from each station. From these a monthly city average was calculated by the author. Considering that the data used did not have uncertainties to begin with and was presented in the HSY reports in an already averaged form, the monthly as well as annual values presented in this thesis should be regarded a qualitative representation.

7.1 Overall reduction

It is safe to say that my generation breaths in cleaner air than the previous one. Although population is growing and urbanization increases, the number of harmful air pollutants in our ambient air has decreased over the last 30 years and still is. The recognition, that good air quality is not a local trait, but involves the cooperation of the neighboring countries, helped to make remarkable progress. PM 2.5 is the “newest” pollutant that has been added to air quality legislations and guidelines across the world. Naturally, its overall reduction lacks behind when comparing with pollutants, whose emissions have been subject to ceilings for several decades. Between 1990 and 2021 the overall PM 2.5 emissions in the EU member states dropped by 31%. Other regulated pollutants showed following emission reductions during that time period: SO_x 93%, NO_x 63% and NMVOCs 59%. [15] Since SOx and NOx act as major precursors for PM, their reduction consequently leads to a decrease in secondary PM 2.5.

Other reduction techniques that have proven to be effective in lowering PM 2.5 levels within cities are the following:

- Investing in public transport and cycling lanes or supporting the purchase of electric cars helps decrease the number of internal combustion engines cars within the city and their consequent emission of harmful pollutants.
- Adapting vehicle emission standards, banning, or charging "old and dirty" cars that do not comply with these, as well as fuel regulations help achieve the same goal.
- By setting stricter speed limits, expanding the number of pedestrian zones and planting trees, positive effects on the amount of road and tire abrasion present in the air can be achieved. Bans on studded tires have proven to be effective too.
- Having identified energy consumption from the residential sector as a major emitter, supporting, educating, and installing sustainable heating options also has positive consequences on the PM 2.5 levels within densely populated areas.
- Big energy plants are typically located outside of cities, their emissions however, if the meteorological conditions allow it, can impact the air quality over long distances. Switching to sustainable and renewable energy sources will benefit the environment and climate as well as air pollution. [86]
- Designing more sustainable construction projects, while also adapting new construction practices, that help minimize the pollution produced by it. The application of sprinklers that spray water over the construction area is one example of dust control practises during construction. [87]

In the six cities investigated, the Scandinavian cities show less of an overall reduction compared to the middle European cities. However, their PM 2.5 values were low to begin with, and always complied with the EU standard, set at 25 $\mu g\ m^{-3}$. When comparing 2020 with the 2010 baseline values, Vienna is the city with the highest relative reduction, followed by Helsinki, Oslo, Prague, Budapest and lastly Stockholm. The specific values can be found in Table 3. Figure 12 shows the downward evolution of the annual means for all

the different locations, made by the author with the data acquired. Also a general intercomparison of the PM 2.5 levels in the cities can be made.

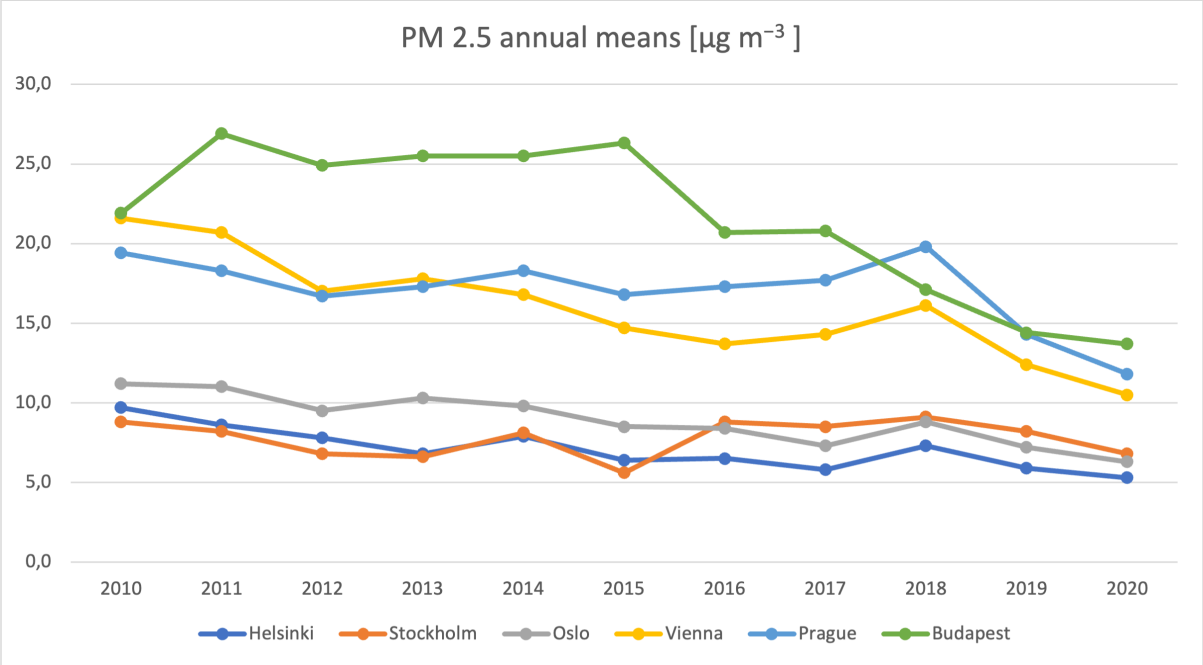


Figure 12: PM 2.5 annual means over the last decade in all six cities

	2010 PM [µg m^{-3}]	2020 PM [µg m^{-3}]	ΔPM [µg m^{-3}]	ΔPM [%]
Helsinki	9,7	5,3	-4,4	45,3
Stockholm	8,8	6,8	-2,0	22,7
Oslo	11,2	6,3	-4,9	43,7
Vienna	21,6	10,5	-11,1	51,4
Prague	19,4	11,8	-7,6	39,2
Budapest	21,9	13,7	-8,2	37,4

Table 3: PM 2.5 values of all cities and their overall reduction

As stressed several times, there are many factors that influence the PM 2.5 levels at local and at national level. However, the main reason as to why PM 2.5 concentrations are so significantly lower in the north of Europe can be explained by looking at the spatial

distribution of the emissions. Figure 13 from the 'European Union emission inventory report 1990-2021' shows the total PM 2.5 emissions in the EU, with the top 10 contributor countries highlighted. [15]

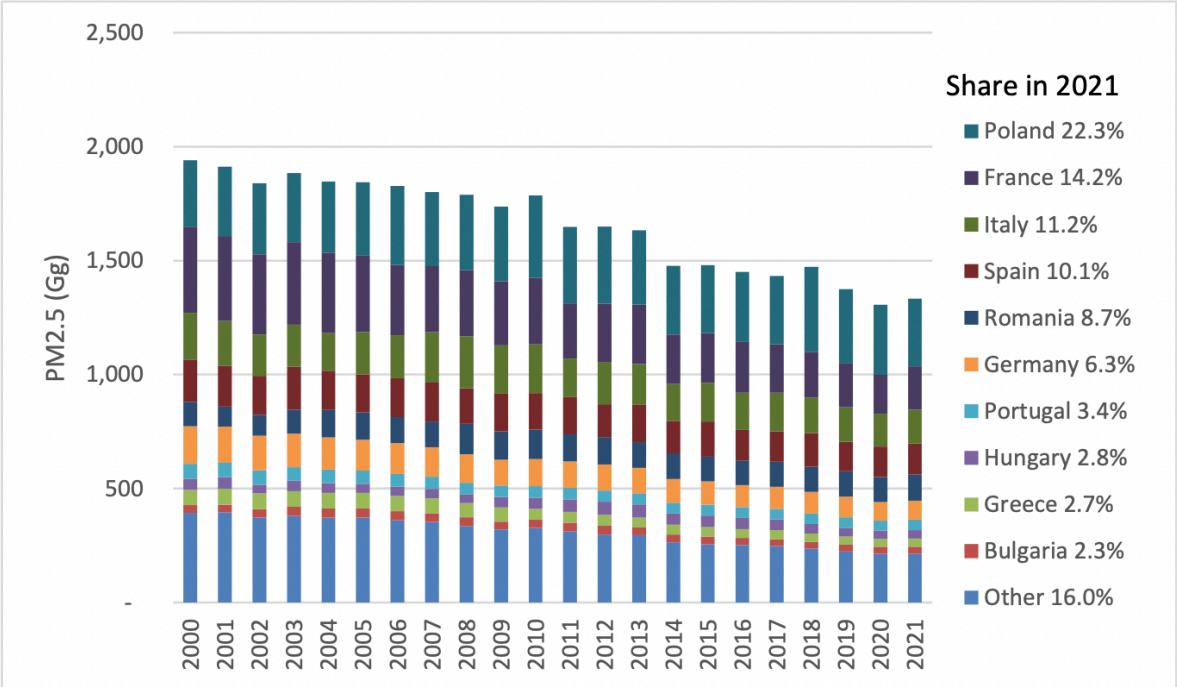


Figure 13: PM 2.5 emission trends in the EU from 2000-2021, with a focus on the top 10 contributor countries. The 17 other EU member states are summed under 'Other'. [15]

The overall downward trend in emissions, correlates with the reduced PM 2.5 values observed in Figure 12. The ten main emitter countries, listed on the right side of Figure 13 lack Scandinavian representation. Although neither Austria nor the Czech Republic are part of the top 10, several of their direct neighbors are. This explains the high background pollution in cities like Vienna compared to substantially lower background PM in Helsinki. The fine particles from Poland have to cross the sea to reach the Scandinavian cities and a majority are deposited along the way. On the other hand, the PM emitted in the South of Poland does not have a long way to travel to reach cities like Prague or Vienna.

7.2 Seasonal variation

When regarding seasonal variation of the PM 2.5 levels and its causes the main reason for the higher PM 2.5 values during winter months is the combination of greater anthropogenic emission and meteorological conditions. Domestic heating increases during colder seasons, private vehicle use is at its peak and particles from winter roads treated with sand or salt enter the atmosphere. In high pressure areas, which are likely to occur in the winter months, atmospheric stability is increased, wind speed is decreased, and dispersion of pollutants is hindered. Especially in the middle European cities, inversions play a big role. They trap the pollutants near the surface leading to higher air pollution. On the example of Vienna one can vividly follow this seasonal trend in Figure 14.

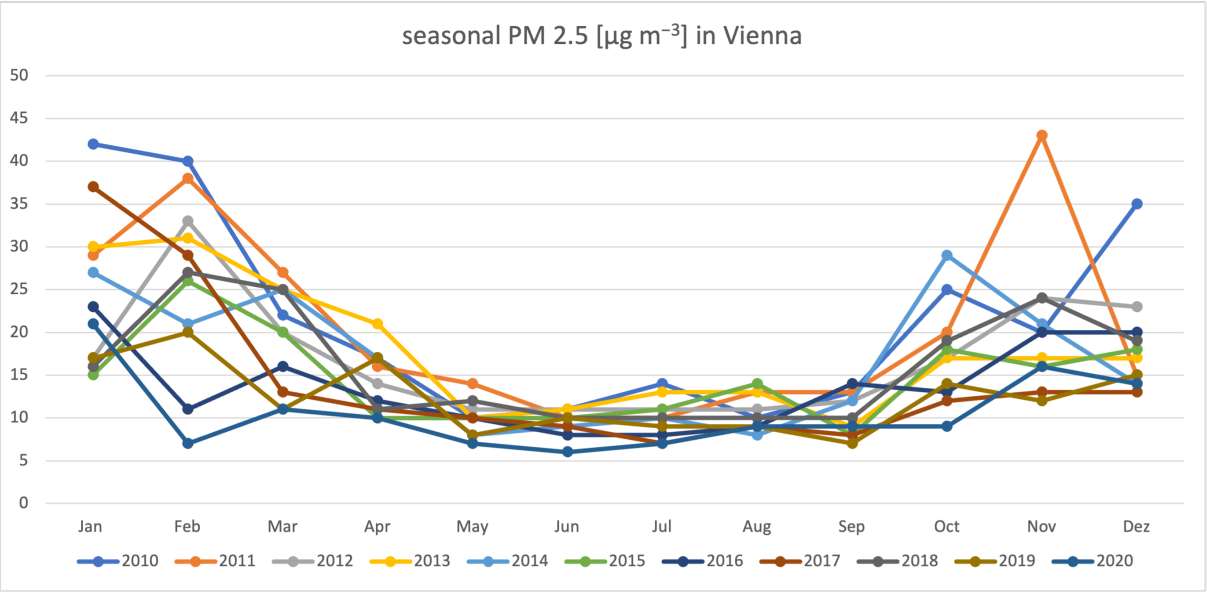


Figure 14: seasonal variation of PM 2.5 values throughout the years in Vienna

Comparing the Viennese PM 2.5 values of June (average of approx. 10 µg m^{-3}) over the last decade to the values measured in January (average of approx. 25 µg m^{-3}), one can conclude that the concentration of PM 2.5 in winter is typically 2 to 3 times higher than in the summer months.

Looking at a Scandinavian city, like Oslo in Figure 15, this seasonal variation is too recognizable, however the trend may not be as distinct in Vienna. In Oslo the June average lies at approximately 7 µg m^{-3} and for January the value is roughly 13 µg m^{-3}. Typically, the seasonal variation factor for the northern cites fluctuates between one and two.

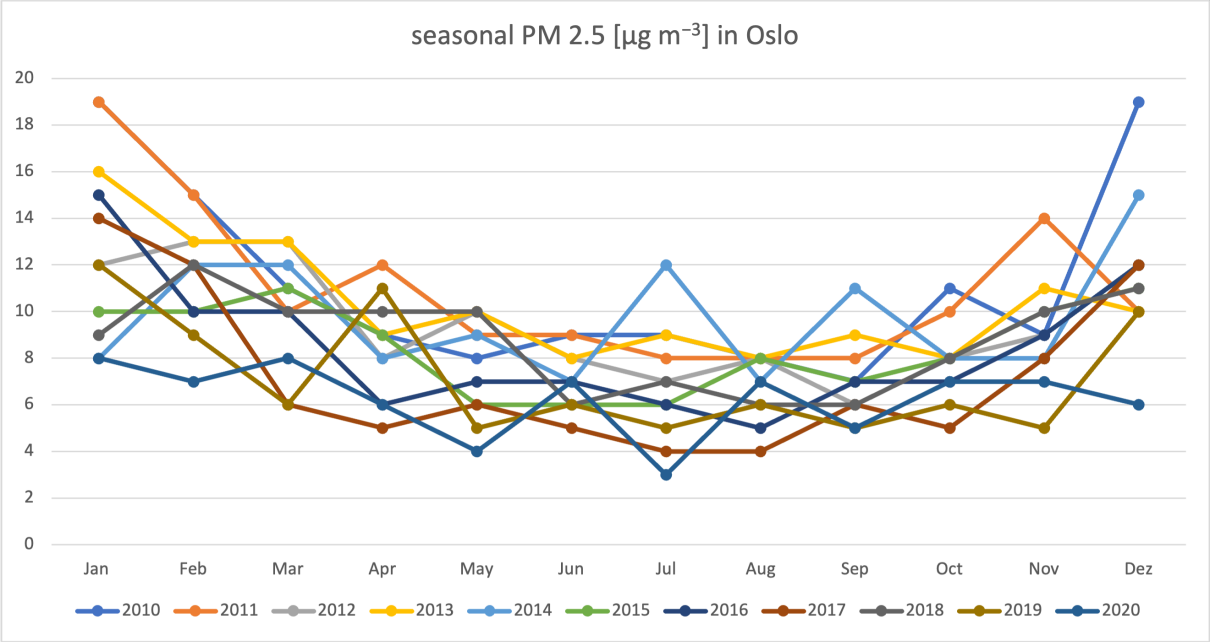


Figure 15: seasonal variation on PM 2.5 values throughout the years in Oslo

The conclusion on how the seasonal variation of PM 2.5 is more dominant in middle or even southern European cities than in the northern capitals is backed up by papers like the one from Aalto et al. [88] In their research they measure the total aerosol particle concentration over a three-year period in five European cities, Augsburg, Helsinki, Stockholm, Rome, and Barcelona. Based on Aalto et al. findings, the winter concentration in Helsinki and Stockholm is higher by a factor of two, compared to the summer months. In Augsburg the factor levels close to three whereas the winters in Rome and Barcelona are 4-10 times more polluted than the summers. Worth noting is that the study period was from 2001 to 2003, and the factors might have been higher than we would expect them to be nowadays. Moreover, the Aalto et. al. paper also considered all airborne particles without distinguish data on PM 2.5.

The high air pollution during the winter months remains a pressing issue that cities and countries in general struggle to tackle. Taking a closer look at Figure 14 one sees that the values between April and September are narrowly distributed, implying relatively constant summer concentration over the period of ten years in Vienna. The PM concentration in winter months, however, shows greater fluctuation. These months are subject to targeted reduction measures resulting in lower annual averages, and overall significant reduction in PM 2.5.

Figure 14 shows that the highest PM 2.5 values measured in February were the ones in 2010, 2011 and 2012, marking the period when the first set of reduction measures were put in place. Roughly five years later, Vienna recorded the lowest February concentrations (years 2020, 2016 and 2019). Implementation of more sustainable heating options throughout the city paired with reduced emissions from vehicle traffic, can be credited for the reduced February PM 2.5 values.

At the same time the February values show no continuous downward trend. The main reason lies in meteorological conditions. February 2018 recorded the lowest average temperature during the 10-years observation period, with exception to 2012. [89] The average temperature was more than 7° C lower than the one measured in Februarys of 2020 or 2016. There was a greater need for heating and energy, resulting in a distinct peak in the pollutant concentration in the seasonal trend for 2018 (represented by the dark grey line). The warmest Februarys in 2020 and 2016, on the other hand, represent local minima in their respective trends. February 2020 was the second warmest recorded in Austria, with the hottest one dating from 1966. [90] A decrease in heat and energy production or usage naturally follows and then directly correlates with the lower PM 2.5 concentrations. Another major source of pollutants typical for winter, which is the use of road sand and salt during cold periods, becomes unnecessary due to the lack of snow and ice. In 2016 the PM minima during the warm February (dark blue line) also stood out because of the additional heavy precipitation, which enhanced the wet deposition of pollutants. [91]

However, this observation also works the other way around. The unusual peak in Figure 15, describing Oslo's PM 2.5 concentration in July 2014 can be explained by another extreme weather phenomenon, that occurred during this time. A heat wave hit Scandinavia summer 2014, Oslo experiencing record-breaking temperatures in July. The hot and dry conditions favor the introduction as well as suspension of fine dust in the atmosphere. The demand for air conditioning in cars and those of buildings rises and the increased energy production also contributes to higher PM 2.5 levels. Generally, heat waves have been linked to increased air pollution in several studies. [92] [93]

7.3 Diurnal behavior

Diurnal behaviour is another aspect that is often investigated, when researching air pollutants. It is especially useful, when trying to work out the locally emitted anthropogenic portion of the pollutants present. The weight of it can be seen by looking at the PM 2.5 concentration of a typical day in Stockholm. In Figure 16 one can see the averaged diurnal behaviour of PM 2.5 in the city on Tuesdays. Eight Tuesdays in the period of November and December 2020 were selected and their hourly mean concentrations were averaged. One can clearly distinguish the morning and evening traffic rush hours when people drive to and from work, by looking at the peaks of the concentration, indicating a direct relation to increased anthropogenic activity at that time. In this Figure the author chose to include error bars that represent the standard deviation of the respective mean values. The magnitude of these error bars supports the previously discussed lack of uncertainties. Here too, the data is only used to describe a qualitative trend.

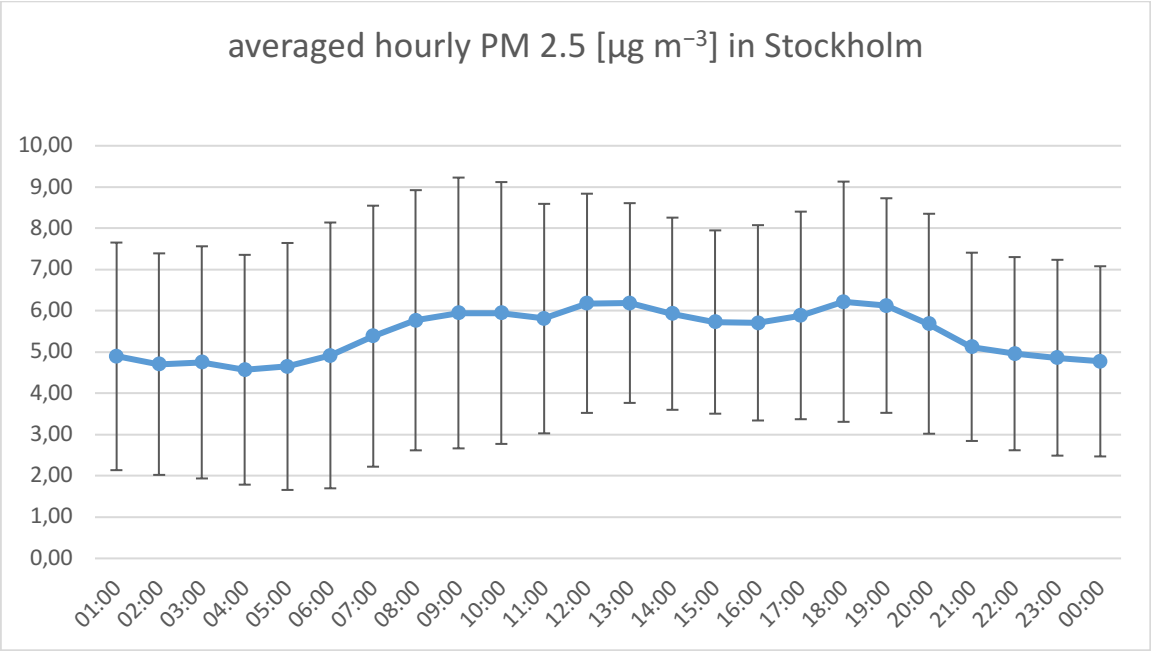


Figure 16: Diurnal behavior of the PM 2.5 concentration in Stockholm on Tuesdays

The findings from Figure 16 strongly support the conclusion of Aalto et al. [88] ,who also investigated diurnal behavior of fine particle concentration in different cities. Aalto et al. found that the daily pattern of particle number concentration is mainly caused by the variation in traffic. During the weekdays this pattern seems to be consistent with the traffic rush hours of the respective city. On weekends however, especially Sundays, Aalto et al. found, that the concentrations are 60- 75% of the weekday concentrations. The noticeable reduction of PM levels on the one day of the week, where anthropogenic activity is typically at a minimum, is a clear indicator for the relevance of traffic in urban air quality.

7.3.1 Impact of a few fireworks

A little more interesting day to look at, regarding fine particle concentration, is the New Year's Eve, shown in Figure 17. It is a widespread tradition to have fireworks at midnight to mark the beginning of a new year. The PM 2.5 data on the night of the 31st of December 2020 and the early morning of the 1st of January 2021 clearly tracks the impact of the celebrations in Stockholm.

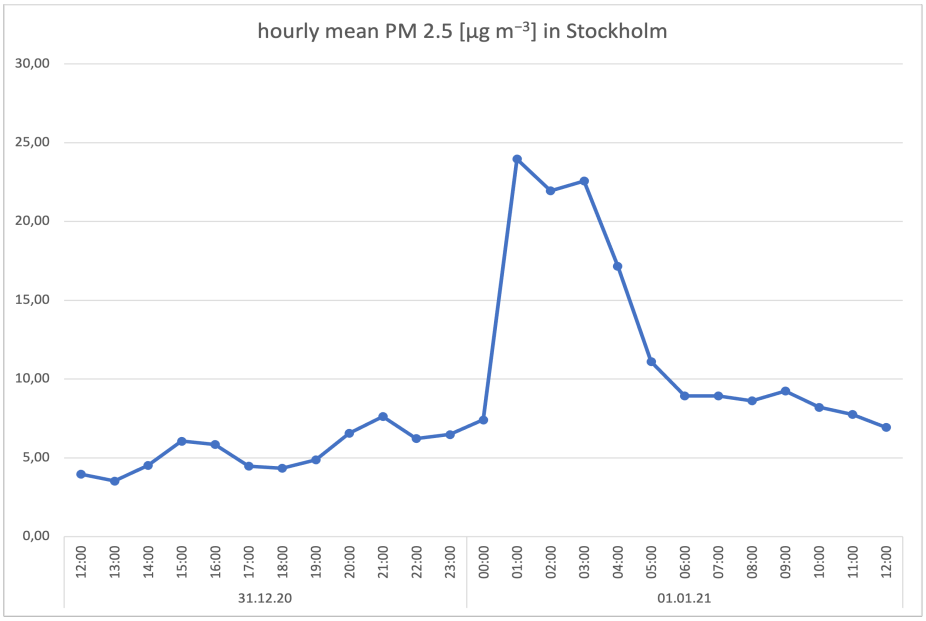


Figure 17: PM 2.5 concentration in Stockholm on New Year's Eve 2020

Between midnight and 1 o'clock in the morning the PM 2.5 concentration in Stockholm skyrocketed by a factor of approximately three. This finding agrees with several similar conclusions made by researchers investigating the impact of fireworks on air quality. Wang et al. measured a rise of PM 2.5 levels by a factor of six, relative to normal days, on a lantern day in Beijing, which involves a big display of fireworks. [94] At the Montreal International Fireworks Competition in 2007 the PM 2.5 values went up by a factor of 50 within the fireworks plume and 2 km of the launch site. [95] On Independence Day, 4th of July, the national average in the whole United States of America recorded a 42% increase in PM 2.5 levels, compared to control days. [96]

However, not only PM levels are elevated, but fireworks typically also lead to increased concentrations of gaseous pollutants (sulphur dioxide and nitrogen oxides) as well as several trace metals. Numerous studies have investigated the consequences of this extremely high short-term exposure caused by fireworks on our health. During the 2010 Deepavali Festival period in India cardiovascular and respiratory mortalities as well as hospital admissions almost doubled at all the investigated sites, correlating with the higher PM concentrations due to the firework displays. [97] A health risk analysis in central London found that during firework events the combined health risks associated with inhaling PM 2.5 and potentially toxic elements, increases by 1.58 for adults and more severely, by 3.0, for children. [98] Chen et al. concluded in their paper, that strict firework regulations, which are enforced in several cities throughout China since 2015, showed effectiveness in reducing ambient PM 2.5 during festival months. Moreover, the firework regulation was found to significantly reduce the internet search intensity for respiratory and cardiovascular conditions, indicating an increase in public well-being. A reduction in the number of related hospital admissions and expenses in these strictly regulated areas was also observed. [99]

Although the impact of fireworks is obviously concerning, the particles emitted by them typically disperse very quickly. This can be seen in Figure 17 by looking at the quick descend of the PM 2.5 concentration. Also in papers, like the one about the Montreal Fireworks Competition, the rapid drop of the high levels is observed. [95] This of course, depends on the specific meteorological conditions at that time and place.

8 Conclusion and Outlook

Many conclusions can be drawn from this thesis, that attempts to summarize and review several different aspects regarding PM 2.5 and its concentrations within Europe.

PM comes in many sizes and compositions. It can originate from natural or anthropogenic sources, and either be emitted into the atmosphere directly or form via chemical reactions as secondary pollutants. Depending on their physical and chemical properties they can be harmful for human health and affect the climate. Vice versa meteorological conditions affect the PM concentration too. Parameters like temperature and wind speed can have significant impacts on the local PM 2.5 levels. The increasing frequency of extreme weather phenomena, which is linked to the progressing issue of climate change, will certainly leave its mark on air quality. [100]

In the EU member states the measurement of PM 2.5 is enforced and limits are set for its maximum levels. Gravimetric measurement is used as a reference method, whereas countries and cities independently build their measurement network of automated monitoring stations.

The six different European cities investigated in this thesis have all reduced their PM2.5 values throughout the last decade. Within the cites the major source of the fine dust is fuel combustion. This can be transportation or heating related. The higher concentration of PM 2.5 in the middle European countries can be explained by the geographic and meteorological conditions and first and foremost by the magnitude of emissions. At the EU level, the central and eastern- European countries are the ones with the highest PM2.5 emissions. Air pollution does not stop at national borders and leads to a relatively high background concentration of particulates in all the central European cities. The Scandinavian cities have a more forgiving location right at the sea, where strong winds favour the dispersion of pollutants. Seasonal variation can be also for one part be attributed to the weather conditions, but mostly to the increase in anthropogenic

emissions during the winter period. Investigating diurnal behaviour of PM 2.5 also leads one to conclude that the rise and fall of pollutant levels in cities is man-made and correlates with traffic rush hours.

The examined cities use different strategies to tackle their individual problematic emission sectors and areas. Generally, there are some methods that have been widely accepted and proven to be helpful in reducing air pollution in urban areas. They are typically targeted at the emissions from road traffic and heating practices within the residential sector.

Not only the primary particle sources can be reduced, but also the controlled emissions of its precursors are of relevance in reducing PM levels. The strict EU limits for the emission of SO_x as well as NO_x or NMVOCs have resulted in remarkable progress. At the same time, the reduction of ammonia, which is mainly emitted by the agricultural sector and is just as relevant a precursor for PM as the others, is hardly progressing. Although its emission is regulated and obligated to reduction, according to the 'European Union emission inventory report 1990-2021', NH_3 emissions decreased between 1990 and 1995 and since then remained stable with minor fluctuations. [15]

Whilst the strategies and policy instruments are in theory simple and straight-forward, it is the implementation where many good plans come to a halt. Policies and decisions are made by national governments, and the goal of improving air quality is not necessarily at the top of their political agenda. Conflicts of interest might hinder the progress, although it is undeniable that progress has been made. Responsible entities, like the EU, continue to take further steps into the right direction. The European Green deal, for example, aims to make Europe the first climate neutral continent by 2050. Among many others, one goal within this Green Deal is to achieve zero pollution for ambient air. In order to do so European Commission proposes stricter rules, specifically that the annual limit value of PM 2.5 should be cut by more than half of what it is now. In the proposed legislation the PM 2.5 limit value of 25 $\mu g\ m^{-3}$ will be replaced by an annual limit of 10 $\mu g\ m^{-3}$ in 2030. Looking at the data acquired for this thesis, this limit already seems achievable in all

Scandinavian cities. Also, Vienna, according to expert Dr. Tizek, will be able to comply with the stricter standards in the future, as the city continuously takes measures towards it. However, big, and densely populated cities in the more southern or eastern parts of Europe will face more challenges achieving the same annual values.

Nevertheless, on a global scale Europe seems to do a pretty good job regarding their air quality legislation. In the Bulletin of the WHO a paper by Nazarenko et al. finds that only 58 countries worldwide have an official PM 2.5 standard. 28 of those countries are EU member states and furthermore Ukraine, Norway, Switzerland, and Russia are included in the European region. This leaves only 26 countries outside of Europe that have an air quality standard for PM 2.5. In other words, more than half of the world's land under national jurisdiction lacks an official PM 2.5 limit and 3.17 billion people live in these areas. The existing standards range from annual limits of 8 μg m^{-3} in Australia to 50 μg m^{-3} in Egypt. [101] The need for strict and universal metrics and standards is substantial. The proven adverse health effects on humans should be a strong enough motivation for all countries to observe, control and officially limit their pollutant emissions. Governments worldwide must overcome the hurdles that currently prevent them from reaching the target values set by the WHO, to ensure a safe and sustainable future. [102]

Finally, the answer to the main research question, which investigates reasons for different PM 2.5 levels throughout European cities can be summarized as follows:
The number and density of inhabitants in a city and these peoples lifestyle plays an important role. Their heating habits and their preferred way of transportation are the most relevant potential contributors. On the next level it is the responsibility of local policy makers to invest towards and prioritize a sustainable future. The government is in charge of making changes on a national level, and entities like the EU hold them accountable for their progress. Then there are the factors that humans cannot influence as easily. The geographic situation of a city as well as its climate or weather conditions cannot be controlled or regulated. Vulcanic eruptions or wildfires occur by the will of nature. All these components can make one region or city more susceptible for higher air pollution than another.

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