

# Air Pollution in Europe

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In this short critical perspective, we outline the serious problems caused by air pollution in Europe. Using two types of metrics, level assessment and trend assessment, we quantify the contribution of ammonia, NO<sub>x</sub>, SO<sub>x</sub>, non-methane volatile organic compounds, and particulate matter in terms of years of life lost per capita and explain the connection between the various pollutants and their effects on human health and the environment. This is done on the basis of data collected by in-

dividual European Union (EU) member states as well as by the EU as a whole. We examine general emission trends as well as sector-specific emissions and discuss the effectiveness of current legislation in reducing health risks and environmental damage. By combining these results with a cost-benefit analysis, we show that a further reduction in NO<sub>x</sub> emissions is the most urgent and potentially the most beneficial.

## Introduction

Air pollution affects all of us. It is one of our greatest social and environmental problems, with terrible consequences. In 1952, a large cloud of sulfate aerosols covered London for just 2 days, yet killed about 12 000 people.<sup>[1]</sup> More recently, a 5 day smog period in 1985 in North-Rhine Westphalia put an estimated 4000 Germans in the hospital as a result of respiratory and cardiovascular failure.<sup>[2]</sup> Unfortunately, these are not stand-alone incidents. Even by conservative estimations, air pollution reduces the average life expectancy in Europe by nearly a year (a total of 7 million life years are lost annually).<sup>[3]</sup> With the rise in urbanization, the dangers of air pollution are increasing. Identifying the problem is easy, but treating it is much harder because air pollution is highly complex. There are many types of pollutants, both anthropogenic and naturogenic. Moreover, quantifying the effects of specific pollutants is difficult because of periodical variations in pollution levels and correlation effects between pollutants.<sup>[4]</sup> Choosing the right way to tackle air pollution is no mean task.


The European Union (EU) identifies seven main pollutants (excluding greenhouse gases, GHGs): ammonia (NH<sub>3</sub>), nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), particulate matter (PM), sulfur dioxide (SO<sub>2</sub>), ozone, and non-methane volatile organic compounds (NMVOCs). These pollutants have been under rigorous scrutiny since the 1980s, and their mitigation is in prog-


ress. Table 1 lists the main pollutants together with their cause, effects, and magnitude.

Current efforts on curbing emissions are mainly directed towards ambient air concentrations as well as the introduction of ceilings to the total output. The main tools for pollution prevention and mitigation in Europe are provided by the Air Quality Directives (AQD) and the National Emission Ceilings Directive (NECD).<sup>[7–9]</sup> However, emission ceilings were introduced under transatlantic agreements, whereof the so-called Gothenburg Protocol is the latest. It has set ceilings for SO<sub>2</sub>, NO<sub>x</sub>, NMVOCs, and NH<sub>3</sub> for 2010, 2020, and thereafter.<sup>[10]</sup> Twenty-six parties plus the EU have already ratified this agreement. Ambient air quality, however, remains solely under local governmental control, and ambitions differ significantly amongst members. The European Commission (EC) called in 2013 for a new Clean Air Policy Package (CAPP). This policy underlines current legislation up to 2020 and aims to improve air quality by hardening the stance on emissions cutbacks through 2030 and thereafter.<sup>[11]</sup> Table 2 lists all the relevant EC/European Economic Community (EEC) legislations with their respective targets.

Ideally, we should strive for a completely pollution-free environment. Pragmatically, we must make some compromises. Quantifying and understanding emission data is the key for determining which pollutants should be targeted to maximize the benefits of emission-reduction programs. A pollutant can be highly toxic, but if its total output and thereby the exposure of the public is limited, the relative benefits of fighting it are small. The selection can be done by analyzing the emission data of individual states and the EU as a whole. Data of all members of the Convention on Long-Range Transboundary Air Pollution have been accumulated by the United Nations Economic Commission for the EU. Here, we quantify the risks air pollution poses to public health and the damage it causes to the environment. We study emission trends and determine the effectiveness of current legislation. Finally, we analyze the total output of EU member states, highlighting through a cost-ben-

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**Table 1.** The seven main categories of air pollutants.<sup>[a]</sup>

Pollutant	Chemical formula	Cause	Main effect	Magnitude [Mt]
ammonia	NH <sub>3</sub>	agriculture	eutrophication	3.9
carbon monoxide	CO	commercial, institutional, and household fuel combustion	global warming	21
nitrogen oxides	NO <sub>x</sub>	transport and energy sectors	shortening of life expectancy acidification	7.8
non-methane volatile organic compounds	C <sub>n</sub> H <sub>2n+2</sub> (n > 1) <sup>r</sup> , C <sub>n</sub> H <sub>2n</sub> <sup>r</sup> , C <sub>n</sub> H <sub>2n+1</sub> Cl, C <sub>n</sub> H <sub>2n+1</sub> OH	industry	precursor to PM and ozone	6.7
ozone	O <sub>3</sub>	NMVOCs, NO <sub>x</sub>	damage to crops	–
particulate matter <sup>[5]</sup>	SO <sub>4</sub> <sup>2-</sup> , NO <sub>3</sub> <sup>-</sup> , NH <sub>4</sub> <sup>+</sup> , C, C <sub>n</sub> H <sub>2n</sub> , C <sub>n</sub> H <sub>2n+2r</sub> , Si, Na <sup>+</sup>	transport sector commercial, institutional, and residential	shortening of life expectancy	3.1
sulfur dioxide	SO <sub>2</sub>	energy sector	acidification	3.1

[a] Output data estimate of EU28 based on fuel sold in 2014.<sup>[6]</sup>**Table 2.** Air-quality legislation in Europe.

Legislation	Target
directive 2015/1480/EC directive 2008/50/EC	rules for reference methods, data validation, and sampling locations defined PM2.5 three (PM10), and five years (NO <sub>2</sub> , benzene) delayed compliance limit value
directive 2004/107/EC commission decision 2004/461/EC commission decision 2004/224/EC directive 2002/3/EC directive 2000/69/EC	As, Cd, Hg, Ni, aromatics annual reporting questionnaire obligated submission of plans and programs for threshold zones ozone limit values of benzene and CO
council directive 1999/30/EC council decision 1997/101/EC council directive 1996/62/EC council directive 1985/203/EEC council directive 1980/779/EEC	limit values of SO <sub>2</sub> , NO <sub>x</sub> , PM, and Pb reciprocal data sharing assessment and management air-quality standards NO <sub>2</sub> limit values of SO <sub>2</sub> and PM

efit analysis (CBA) those pollutants and sectors for which gains can be maximized.

$$L_{x,t} = \frac{E_{x,t}}{\sum E_t} \quad (1)$$

## Level Assessment and Trend Assessment

There are two ways to analyze the impact of legislation on the abatement of a particular pollutant. The first reviews the change in the overall output within a certain period. The most recent data is compared to the base year (the earliest data available), is followed over time, and is then related to abatement efforts. In addition, the total output can be separated into specific sectors, and the relative contribution of a specific sector over time can be analyzed. This is known as level assessment. It enables the selection of those sectors that contribute most to air pollution in a particular year. The sectors that together contribute >80% of the level in a specific year should then be the focus of additional abatement efforts.<sup>[12]</sup> Level assessment is done by using Equation (1):

in which  $L_{x,t}$  is the level assessment for source  $x$  in the latest inventory year  $t$ ,  $E_{x,t}$  is the value of emissions estimate of source category  $x$  in year  $t$ , and  $\sum E_t$  is the total contribution in year  $t$ .

The second approach is so-called trend assessment. Consider a situation in which the average pollutant output is declining, but one small sector shows a steep increase. This indicates either increasing activity in that particular sector, or that abatement efforts are ineffective in that specific sector. Such sectors can be identified by weighing the trend of a specific sector versus the trend of the total inventory. This trend assessment [Eq. (2)] pinpoints those sectors with the largest divergence from the overall trend of the inventory.<sup>[12]</sup>

$$T_{x,t} = \frac{E_{x,0}}{\sum E_0} \left( \frac{E_{x,t} - E_{x,0}}{E_{x,0}} - \frac{\sum E_t - \sum E_0}{\sum E_0} \right) \quad (2)$$

in which  $T_{x,t}$  is the trend assessment of source category  $x$  in year  $t$  compared to the base year,  $E_{x,0}$  and  $E_{x,t}$  are the source estimates in year  $t$  and the base year, and  $\Sigma E_t$  and  $\Sigma E_0$  are the sums of the estimates of all the sources at year  $t$  and 0, respectively.

Throughout this paper, we use the terms trend assessment and level assessment to analyze and explain the emission data.

## Regulated Pollutants and Their Sources

We classify pollutants as either primary or secondary. Primary pollutants are released directly to the atmosphere, whereas secondary ones form from precursor gases. All precursor gases are primary pollutants, but not all composed particles are secondary pollutants.

The most common primary pollutants include PM, CO, NMVOCs,  $\text{NH}_3$ ,  $\text{NO}_x$ , and  $\text{SO}_x$  (which represent whole families of nitrogen and sulfur oxides, respectively), and black carbon (BC).<sup>[13]</sup> Their sources vary by geographical origin, year, and pollutant, but the key culprit sectors are energy, industry, and transport (ammonia is the exception, coming chiefly from the agricultural sector).

As the mode of action of specific pollutants often differs, we considered a classification system that distinguishes pollutants that directly impact the environment and human health from those with indirect impact. Some pollutants, such as NMVOCs, are not directly harmful but react in the atmosphere to give harmful products (in this case, ozone). Their impact, thus, depends both on their source and on the meteorological conditions. By including primary and secondary factors, we improve the accuracy and relevance of our risk assessment.

Composite particulate matter (PM<sub>2.5</sub>: diameter < 2.5  $\mu\text{m}$ ; PM<sub>10</sub>: diameter 2.5–10  $\mu\text{m}$ ) is directly linked to asthma, eye and lung problems, and premature death. It can be emitted directly into the air and can be formed in the atmosphere. These particles are multicomponent aggregates, comprising a wide range of substances. In its primary definition, the main sources are car exhaust and road and tire wear. Yet PM has many other sources, both anthropogenic and naturogenic. The main precursor gases that lead to PM formation are  $\text{NO}_x$  (36%), NMVOCs (31%),  $\text{NH}_3$  (18%), and  $\text{SO}_2$  (15%, see discussion below and details in the Supporting Information).

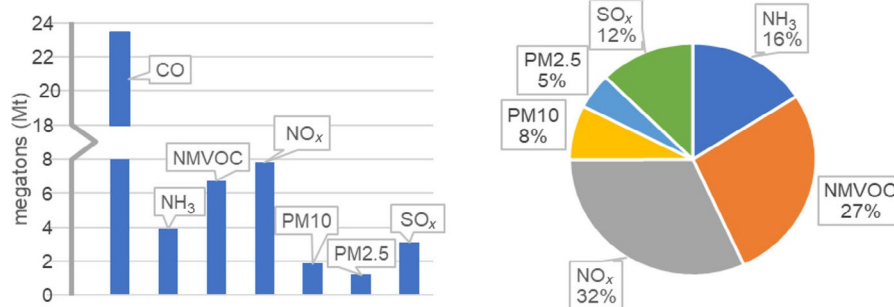
Secondary pollutants, next to PM, are ozone and the  $\text{NO}_2$  formed from the oxidation of nitrogen monoxide. Ozone forms

in the atmosphere as a byproduct of the photochemical oxidation of NMVOCs by nitrogen oxides and ultraviolet (UV) light. Note that only tropospheric ozone is considered an air pollutant, as there it can inflict damage to plants, forests, and crops through oxidation reactions and do harm to humans through breathing.<sup>[14,15]</sup> Especially in areas with dry climates, such as the Mediterranean, ozone can wreak havoc in agriculture during the summer. Ozone is a peculiar pollutant, as its levels peak in bright sunshine and plummet under cloudy skies owing to its dependence on UV light.

$\text{SO}_x$  and  $\text{NO}_x$  are not only primary pollutants but also key components of composite PM. These gases can react with oxygen in the air to form aerosols that build up to acid rain. Acid rain posed a serious environmental problem in the 1980s and 1990s, as it caused damage to large areas of agricultural land and ecosystems across Europe.<sup>[16]</sup> It caused health problems as well, mainly as a result of respiratory tract inflammation.<sup>[17]</sup> A large UK study showed that sulfate ions accounted for 30–35% of the make-up of PM. Nitrate salts—formed upon binding of acidic nitrogen oxides to sodium or ammonium ions—accounted for a further 25%.<sup>[18]</sup> The emission of both gases and especially of  $\text{SO}_2$  was subsequently strictly regulated.<sup>[7,8]</sup> As a result, the levels of both compounds have dropped significantly in the past decade. However, there are increased concerns about the effects of  $\text{NO}_x$  on human health as a primary pollutant. It is associated with premature death, a higher number of hospitalizations due to acute respiratory failure, and longer hospitalization periods. On top of that, exposure to  $\text{NO}_x$  increases the risk of chronic respiratory diseases, especially among children.<sup>[19–21]</sup>

## Contribution by Volume

Examining the emissions in 2014, we see that CO is the largest contributor. With a staggering total output of 21 megatons, it accounts for about half of the output of all seven pollutants combined (Figure 1, left). However, the direct risk that atmospheric CO poses to health is limited and, therefore, of minor concern to policy makers (it only poses a significant risk to public health in cases of high exposure rates for long periods<sup>[22]</sup>). Out of 39 EEA member and cooperating states, only 1 operational station reported CO levels exceeding the World Health Organization (WHO) Air Quality Guideline (AQG) limit in 2013. Thus, we decided to exclude CO emission data, as this



**Figure 1.** Column graph showing the estimated emissions in megatons of pollutants in the EU28 in 2014 (left) and pie chart showing the corresponding vol% contribution of each pollutant if CO is excluded (right). Data is based on the amount of fuel sold in 2014.<sup>[6]</sup>

would benefit the weight attribution to the remaining pollutants and the research as a whole (CO may still pose a threat as a greenhouse gas, but this is out of the scope of our study).

The remaining two largest contributors by volume are NO<sub>x</sub> and NMVOCs. Together, they make up almost two-thirds of the share of the total output of air pollutants (Figure 1, right). That said, although PM accounts for only 13%, it is a strong threat because of its associated adverse health effects. Given that PM is a composite, we treat the share of each component separately. Again, we see that NMVOCs and NO<sub>x</sub> are the largest. Consequently, combating the emission of these pollutants would reduce PM emissions substantially and would also improve overall air quality. However, we still do not understand how the chemical composition of PM affects the potency of the adverse health effects associated with its exposure.<sup>[23]</sup> Although SO<sub>x</sub> and NH<sub>3</sub> play minor roles if solely their total output is taken into account, their relative effect may still be stronger if their toxicity is more significant. To judge the importance of these chemicals, we assess their impact on public health and environment and run a trend assessment (see below).

## Health Risks

The health risks of PM have until recently masked the specific risks associated with NO<sub>2</sub>. Given that both pollutants are by and large byproducts of combustion processes, their effects are correlated and are usually quantified together.<sup>[24]</sup> However, increasing evidence shows that NO<sub>2</sub> itself poses a health risk. Since 2015, the EEA has included NO<sub>2</sub> in its multipollutant model study, linking increased morbidity to ambient air NO<sub>2</sub> concentrations.<sup>[3,22]</sup> The impact of NO<sub>2</sub> is four times larger than that of ozone, yet still six times smaller than that of PM. In 2013, an estimate of 723 000 years of life were lost (YLLs) in the EU28 (Table 3) (YLL = weighted average of life years lost compared to life expectancy of a demographic group), with the largest impact observed in Italy.<sup>[3]</sup>

**Table 3.** Years of life lost due to main air pollutants in the EU28 in 2013 and their associated reduction in life span per capita.<sup>[3]</sup>

PM <sub>2.5</sub>	total YLL	per capita	NO <sub>2</sub>	total YLL	per capita	O <sub>3</sub>	total YLL	per capita
4 668 000	—8 months	723 000	—1 month	179 000	—1 week			

These estimates are conservative, because the WHO guideline for the onset of adverse effects for NO<sub>2</sub> ambient air concentrations is 20 µg m<sup>-3</sup>. Correlations between morbidity and NO<sub>2</sub> concentrations are now only modeled for concentrations exceeding this threshold. Consequently, the current model underestimates the impact of NO<sub>2</sub> on public health, because today we know that the threshold should be lower. A comparison of the impact of different legislations on the decline in ambient air pollution levels with the occurrence of premature deaths can influence policy makers to choose one goal over another. As largest gains in workforce could be achieved for

PM<sub>2.5</sub>, we considered four different EEA scenarios, ranked from conservative to most optimistic:

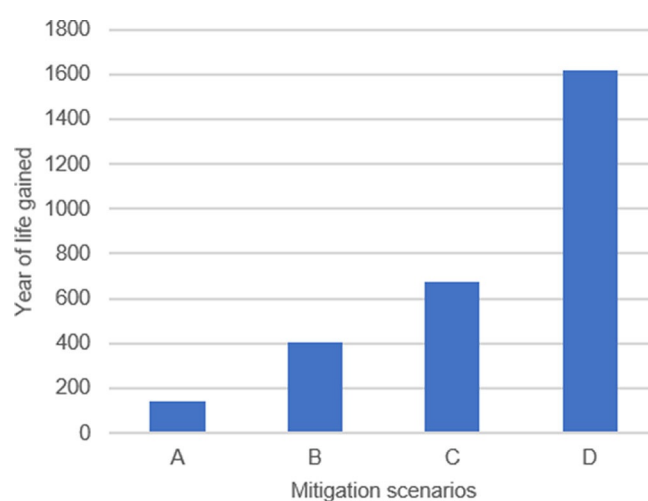
Scenario A: The annual EU limit value of 25 µg m<sup>-3</sup> is met

Scenario B: The WHO 3 year average exposure concentration limit of 20 µg m<sup>-3</sup> is met

Scenario C: The country-specific emission reduction targets (ranging from 0 to 20%) are met

Scenario D: The annual WHO AQG of 10 µg m<sup>-3</sup> is met

Each scenario showed gains in life expectancy with the most optimistic one showing major gains throughout the EU (Figure 2). However, scenario A showed only limited gains, which could be explained by the fact that the EU limit value was only exceeded in 9% of the stations in 2013, and thus, attaining this limit by 2015 would not give much benefit.<sup>[22]</sup>



**Figure 2.** Total number of years of life gained in the EU in each of the forecast scenarios A–D impacting the emission of PM<sub>2.5</sub>.

Interestingly, the current effect of the ambient (outdoor) air concentration limit of NO<sub>2</sub> (40 µg m<sup>-3</sup>), the only legislation in effect, outweighs the effect of the impact of scenario A for the curbing of PM<sub>2.5</sub> emissions by > 25%. This suggests that if the NO<sub>2</sub> WHO limit value is met, which was exceeded in 14% of the operational stations across Europe, it would outperform the attainment of PM<sub>2.5</sub>, which is significantly lower. It also highlights the cost effectiveness of NO<sub>2</sub> legislation, even on short timescales. Achieving even the “softest” scenario for NO<sub>2</sub> would still outperform the morbidity gains of PM reduction.

An increased relative risk (RR) of hospital admissions as a result of respiratory problems is correlated with short-term exposure to ambient NO<sub>2</sub> concentrations.<sup>[25]</sup> For a 24 h average exposure, the RR of hospitalization due to respiratory disease increased by 1.56% per 10 µg m<sup>-3</sup> NO<sub>2</sub>. Specifically, hospitalization due to asthma amongst children (aged 5 to 14) showed increased risks (2.45% per 10 µg m<sup>-3</sup> NO<sub>2</sub>). The latest data for respiratory disease hospitalization showed an average 8.5 days admission and an incidence rate of 1165 per 100 000 inhabitants (Table 4).



**Table 4.** Respiratory-related hospitalization in 26 EU countries from 2005 to 2011.

Respiratory-related hospital admissions, all ages	Average stay length [days]	Cases per 10 000
average	8.5	1165
minimum	4.5	528
maximum	14.5	2170

The length of hospitalization and YLLs are a measurable quantity of loss of workforce. They can be included in a CBA for abatement policies. However, owing to fears of double counting, healthcare costs of NO<sub>2</sub> exposure have not been included in the latest CBAs of the CAPP, nor were they included in the implementations of the recommendations of the Health Risks of Air Pollution in Europe project.<sup>[26,27]</sup> Although the EEA had confidence in the robustness of the YLLs as a result of long-term exposure to NO<sub>2</sub>, it has yet to be included in CBAs. Up to 33% of the adverse effects of NO<sub>2</sub> are included in the quantification of particulate matter.<sup>[28]</sup> This implies, however, that two thirds of the additional healthcare cost is being neglected as a direct result of the underestimation of these adverse effects. A striking example of the directness of impact on health of NO<sub>2</sub> mitigation is the case study of the Beijing 2008 Olympic Games, for which the concentration dropped by 43% in the same year as a result of abatement. This sudden decrease in ambient air concentrations was directly linked to improvement in cardiovascular disease markers.<sup>[29]</sup>

## Environmental Damage

Air quality has multiple effects on our environment. For example, a rising ground-level ozone concentration can lower the yield of agricultural crops and damage vegetation by decreasing growth rates. Other pollutants, such as NO<sub>x</sub>, SO<sub>x</sub>, and NH<sub>3</sub>, contribute to the acidification of soil and groundwater. Ammonia can counter acidification, but together with NO<sub>x</sub> it causes eutrophication. The excess nutrient build up on the earth's surface impairs biodiversity and facilitates the invasion of alien species. Eutrophication has a large impact: in 2012, 63% of EU28 member states' ecosystems were under immediate risk of eutrophication, and 73% of the 2000 EU Natura Area was exposed to it.<sup>[30]</sup> The risk of eutrophication is measured as an exceedance of a critical load (CL), a limit value set to represent the amount of excess nutrients an ecosystem can manage without significant changes to its diversity.<sup>[31]</sup>

For acidification, the CL is determined as the maximum decrease in pH a particular system can sustain. Since 2005, the risk of acidification of the ecosystems of the EU28 has declined by 40%, and the risk to the EU 2000 Natura Area has decreased by 30%. This is attributed to a decline in SO<sub>2</sub> levels over the past decades. As a result, NO<sub>x</sub> and NH<sub>3</sub> have become the largest influencers in acidification throughout Europe. Moreover, NH<sub>3</sub> output has declined only marginally since 2000. Unfortunately, quantifying the risks of eutrophication and acidification is difficult, as assigning values to the biodiversity

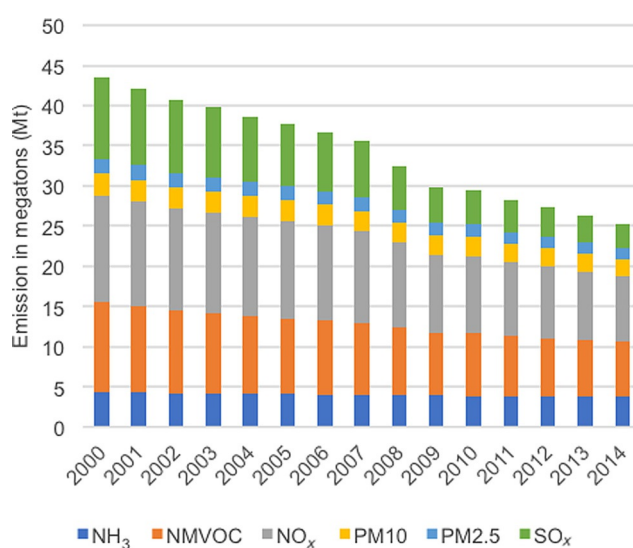
and the sustainability of ecosystems is impractical. Measures, however, were taken to battle these phenomena. For instance, annual critical levels of NO<sub>x</sub> and SO<sub>2</sub> for the protection of vegetation in rural areas were set as 30 and 2 µg m<sup>-3</sup>, respectively.

Conversely, ozone is directly linked to damage to agricultural crops and is, therefore, included in cost estimates. A 2011 study calculated a €3.2 billion loss in wheat production in the EU27 plus Norway and Switzerland in 2000 solely through damage caused by ground-level ozone.<sup>[32]</sup> Unfortunately, concentrations depend on multiple factors: volume fractions of NO, NO<sub>2</sub>, and NMVOCs as well as the levels of sunshine. This makes it difficult to pinpoint a measure that benefits agricultural yield the most. Therefore, a more generalized legislation is in place, targeting each component individually. This includes the annual limit level of NO<sub>x</sub> and reduction targets for NMVOCs.

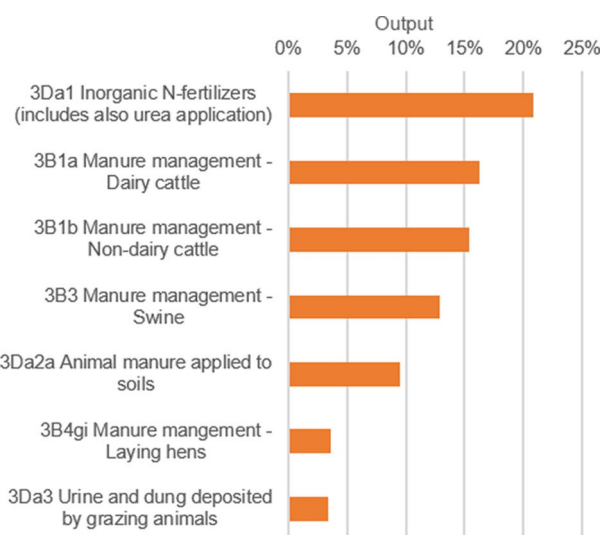
## General Emission Trends

Since the implementation of the NECD and the AQDs, ground-level concentrations of almost all pollutants have declined steadily (Figure 3).<sup>[7–9]</sup> The two most notable trends concerning emission reduction are the decline of SO<sub>x</sub> levels and the almost unchanged total output of ammonia. The total output of SO<sub>x</sub> for the EU28 member states decreased by 69% in the period of 2000 to 2014, following the implementation of the EU AQDs. Similarly, NMVOC emissions were cut by 39% (see the Supporting Information for more details).

The marginal decline in NH<sub>3</sub> can be understood by considering its main source: in 2010, 94% of the ammonia emissions originated from agriculture.<sup>[30]</sup> The decline can mostly be attributed to the local decrease in the number of livestock, as manure management is the largest contributor to NH<sub>3</sub> release. Next to that, optimization of the use of nitrogen-containing fertilizers should be assigned to the remainder of the reduction (some fertilizer is always needed, as it directly affects production capacity).

**Figure 3.** Emission trends in the EU28 on the basis of fuel sold.<sup>[6]</sup>

Our level assessment points out seven sectors that had a considerable influence on the total output in 2014 (Figure 4). All the key categories are in the agricultural sector and are of manure-management origin, with the exception of the chief contributor. With a 21% total share, the distribution of inorganic nitrogen fertilizers had the largest impact on the environmental state if  $\text{NH}_3$  was considered.

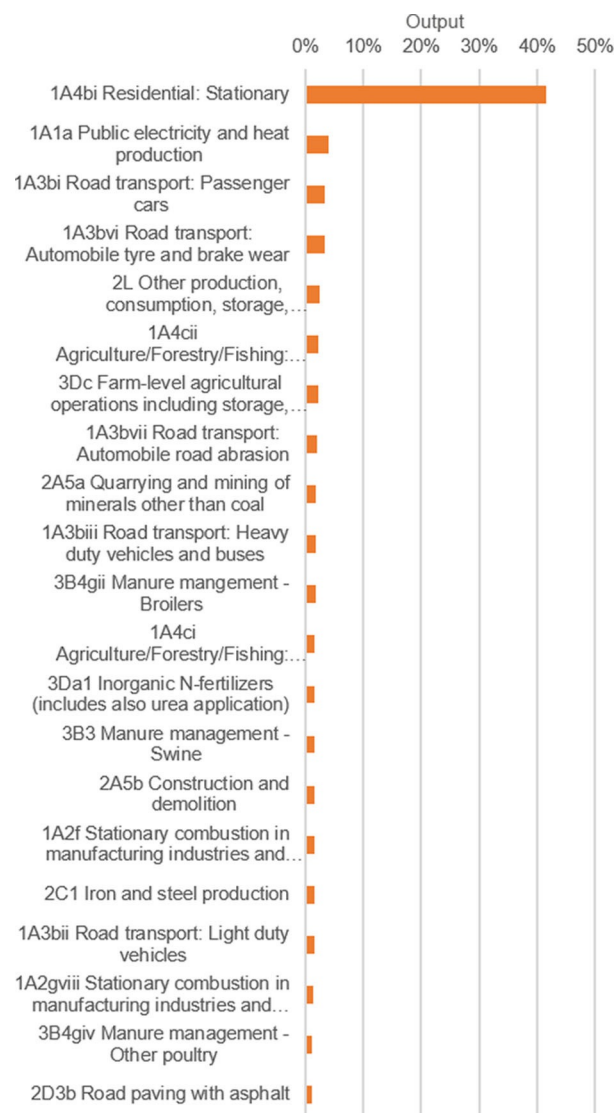


**Figure 4.** Level assessment of relative sector output of  $\text{NH}_3$  in 2014. The sum of the contributions adds up to 80% of the total output.

Both  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  declined by about a quarter between 2000 and 2014 (Figure 3). The gains were mostly achieved in the energy sector owing to switching from coal-powered plants to natural gas (Figure 5). The most polluting sector was the residential stationary combustion sector, with a 51% share for  $\text{PM}_{2.5}$  and a 36% share for  $\text{PM}_{10}$  in 2014. Many additional small sectors are required to reach the total of 80% for level assessment.

If we compare the share to the total output in 2014 to that of 2000, we see an increase in contributions of 41 and 36%, again emphasizing the importance of this single sector. Furthermore, upon comparing the emission data of Germany with that of a new EU member state such as Romania, we see that large gains can still be made with the measures currently in place. Romania had only a 30% smaller total  $\text{PM}_{10}$  output in 2014 than Germany, whereas it had a 75% smaller population.<sup>[33]</sup> Even more so, it had a larger  $\text{PM}_{2.5}$  output of 11.5 kilotons. Germany reduced its output from 2000 to 2014 with 34% for  $\text{PM}_{2.5}$  and 20% for  $\text{PM}_{10}$ .

Our analysis shows that the trend in emissions for this sector declined by 19% for  $\text{PM}_{10}$ , indicating that further legislation for this sector is less practical. However, for  $\text{PM}_{2.5}$  a growth in trend of 37% was measured. Clearly, large gains are still possible in that sector. Gains in the residential combustion sector for both PM pollutants are expected in the younger member states, for which mitigation efforts are still underway. However, gains in  $\text{PM}_{10}$  reduction overall are expected to decline. Only one other large sector exists for this pollutant (the



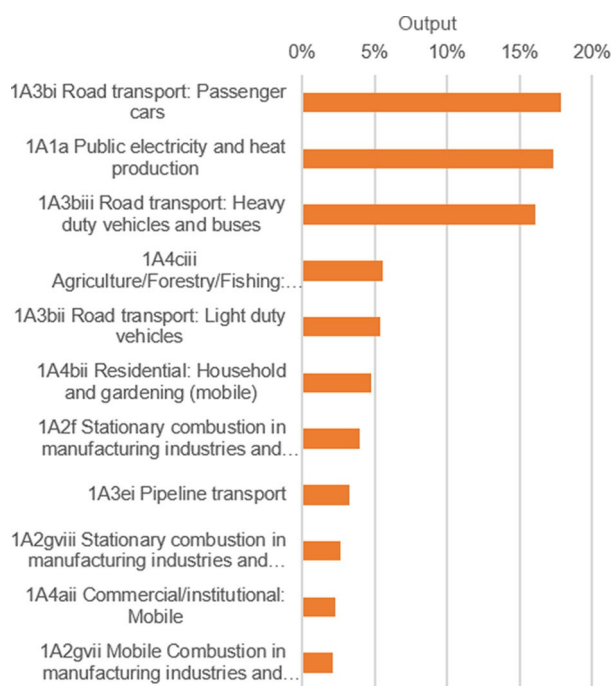
**Figure 5.** Level assessment of the relative sector output of  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  in 2014. The sum of the contributions adds up to 80% of the total output.

energy sector), and only small gains were reported there. The gains that were achieved originated from the aggregated reduction of emission of a larger group of smaller polluters.

$\text{NO}_x$  emissions declined by 39% with the largest gain in the transportation sector as a result of the advent of cleaner fuels and better combustion techniques (Figure 3). The main polluting sector is still "Road transport: passenger cars". In 2014, it contributed 18% of the total  $\text{NO}_x$  release of the EU28 (Figure 6). Other polluting sectors are "Public electricity and heat production" (17%) and "Road transport: Heavy-duty vehicles and buses" (16%).

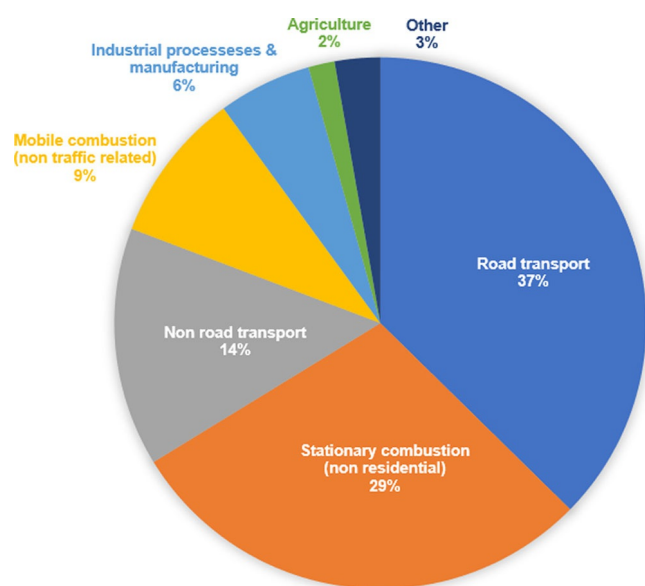
## Sector-Specific Effectiveness

Here, we used a trend assessment to study the effectiveness of the current legislation on curbing emissions in specific sectors. We identified two sectors that had the largest deviation from the overall trend of the inventory, both pertaining to road



**Figure 6.** Level assessment of NO<sub>x</sub> emissions in the EU28 in 2014: 11 categories were identified as key by standards of the EEA (sum contributions larger than 80%).

transport. "Road transport: Heavy-duty vehicles and buses" declined by 22%, and "Road transport: passenger cars" decreased by 15%. Bearing in mind that these sectors contribute a fair share to the total output of NO<sub>x</sub> (Figure 7), this raises a red flag for the total decline in the impact of mitigation efforts on the reduction of NO<sub>x</sub> in the road-transportation sector. The total emissions declined by 31%. This supports our assumption that the impact of reduction measures is reaching its limits.



**Figure 7.** Aggregation of sectors contributing to the total NO<sub>x</sub> output of the EU28 in 2014 to identify the most significant polluters (in this case, "Road transport and Stationary combustion").

Conversely, stationary combustion showed a strong increase in its contribution to the total. Here, five sectors were indicated as key, of which four were of the nonresidential type. The aggregate had a total contribution to NO<sub>x</sub> release of 29% and showed an increase in trend of 11%. These results show that large gains are still achievable in this sector. Stricter regulation of these sectors is desirable.

## The Cost Effectiveness of Emission Reduction

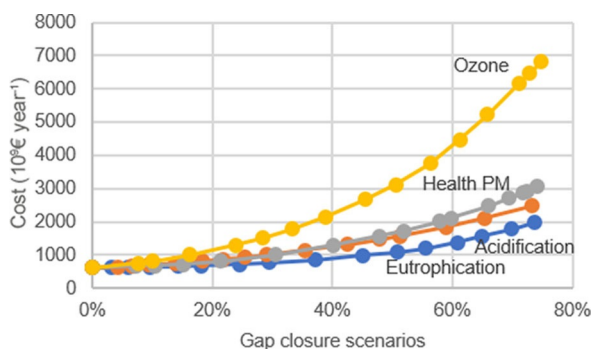
Cost-benefit analyses are used by policy makers to measure the effectiveness of future legislation. They consider economic activity, costs of emission reduction, and adverse effects of air pollution and try to determine the most cost-effective measure to attain a goal. One model that is widely used here is the Greenhouse Gas and Air Pollution Interactions and Synergy (GAINS) model. This model includes impacts on human health by PM and ground-level ozone, acidification and eutrophication of ecosystems, and effects of GHG mitigation, correlating these to national emission estimates of the main air pollutants (SO<sub>2</sub>, NO<sub>x</sub>, PM, NMVOCs, CO<sub>2</sub>, NH<sub>3</sub>, CO, CH<sub>4</sub>, N<sub>2</sub>O, and fluoride-containing gases).<sup>[34]</sup> GAINS relates the effects of a baseline to that of increasingly tighter emission control target packages, up to the maximum technically feasible reduction (MTFR) scenario.

Amann et al. studied such scenarios.<sup>[35]</sup> They examined the emission reduction goals for 2020, set in the Gothenburg Protocol, highlighting the most cost-effective revisions of these measures. With the 2011 legislation as a baseline, they estimated an average of 4.3 months shorter life expectancy per capita for 2020 throughout the EU27 as a direct result of PM exposure (equivalent to 120 million YLLs). In addition, they projected 24000 new cases of premature deaths per year due to ground-level ozone exposure, an immediate eutrophication threat to 1.4 million km<sup>2</sup> of European ecosystems, and unsustainable pH levels in 110000 km<sup>2</sup> of forest. These results show the need for new legislative measures that can target emissions.

After establishing the baseline, they carried out a gap-closure procedure, calculating the effects of various legislation packages in a stepwise fashion. Each new set of legislative measures results in a different reflection of the cost effectiveness of that collection of abatement efforts. By tweaking the relative ratios of each of the impact indicators, an optimal reduction package was selected. Whereas the suggestion of a set of reduction targets is beyond the scope of this research, we studied the sensitivity analysis of each individual impact indicator to help select such a package.

By choosing an arbitrary gap closure scenario for the impact indicators, that is, health effects, acidification, eutrophication, and ground-level ozone, a sensitivity analysis made clear that mitigation costs for ozone were most sensitive towards gap-closure ambitions. For example, if the gap closure targets were increased by 20% on top of an arbitrary overall gap-closure setting of 25%, ozone reduction costs increased by roughly 60% (Figure 8). Eutrophication was shown to be the least sensitive, as costs grew marginally if targets were tightened.





**Figure 8.** Sensitivity analysis of impact indicators considering four gap-closure scenarios. For each scenario, the gap-closure target was increased up to 70% and the growth in costs was estimated while all other impact indicators were kept at a constant value of 25%. Data redrawn from Ref. [35].

A 20% tighter target resulted in a growth of about 20%, showing the near linearity of the impact response curve at lower impact levels for eutrophication.

Ground-level ozone concentrations are cut through the reduction of NMVOCs and  $\text{NO}_x$ , and eutrophication reduction is achieved through mitigation of  $\text{NH}_3$  and  $\text{NO}_x$ , providing an opportunity. To reach the beneficiary effects of ozone reduction, sizeable investments are needed to reduce the concentrations of both NMVOC and  $\text{NO}_x$ . Fortunately, owing to the insensitivity of eutrophication reduction, the minimization of ammonia mitigation could counter the additional costs of  $\text{NO}_x$  reduction. The costs of a relatively higher ammonia output are only marginal compared to those of  $\text{NO}_x$ .

Another cost–benefit analysis by Van Grinsven et al. quantified nitrogen mitigation in Europe as guidance for policy makers to prioritize particular legislation.<sup>[36]</sup> Using standard economic concepts such as estimations of cost of treatment, workdays lost, and willingness to pay to reduce YLLs, they estimated that the EU27 spent between €100 and 300 billion in 2008 on costs related to  $\text{NO}_x$  emissions. For sources of stationary combustion, legislative measures would especially be beneficial, up to 10–20% reduction of the prognoses of emission levels in 2020. This is a strong argument for  $\text{NO}_x$  mitigation legislation for short-term targets. However, for more strict emission reduction targets to be cost effective (cutting emissions by 360 kt and beyond), technological innovations are needed.

## Summary and Outlook

A pollutant's impact must be measured by two criteria. First, the emission should be sizeable. Pollutants may be toxic to humans or bad for the environment, but if their exposure is low, so is their impact. Second, both direct and indirect effects should be considered. Yet even if a pollutant fulfils both requirements, stricter measures may not be needed, so long as current legislation has led to significant risk reduction. However, if the measures prove ineffective, or if the risk was underestimated, additional measures should be applied. The final criterion is cost effectiveness. Emission control legislations will only

be passed by governments that perceive them as cost effective.

Specifically, we conclude that further reduction in  $\text{NO}_x$  emissions is the most urgent and most beneficial. By improving ambient air quality,  $\text{NO}_x$  abatement will benefit both the public and the environment. As the technology required for  $\text{NO}_x$  reduction advances, the gains in workforce and healthcare savings from  $\text{NO}_x$  abatement will outweigh the costs of implementation.

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## Conflict of interest

The authors declare no conflict of interest.

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