Upgrading Europe’s Air:
How a strong Industrial Emissions Directive can save lives and money

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CREA
Centre for Research on Energy and Clean Air

CREA is an independent research organisation focused on revealing the trends, causes, and health impacts, as well as the solutions to air pollution.

Key findings

- The power, industrial and agricultural sectors are major sources of air pollutant emissions. In the EU27 and the UK, emissions from power and industry are responsible for 80, 27 and 74% of SO_2, NO_x and mercury emissions, while agriculture accounts for 94% of ammonia emissions (EEA, 2021; AMAP/UNEP, 2019).
- Emission control performance in Europe's industrial sectors is far behind best international practices and best available techniques (BAT). The reasons are "best available technique" requirements weakened by lobbying, as well as lenient application of the requirements and prevalent use of derogations on the national level. Agriculture has been largely excluded from emissions regulation despite its major contribution to $PM_{2.5}$ pollution through ammonia emissions. The revision of the Industrial Emissions Directive is a once-in-a-decade opportunity to address these issues.
- Air pollutant emissions from power and industry are responsible for an estimated 17,000 annual deaths due to exposure to $PM_{2.5}$, ozone and mercury. The largest polluting sectors are thermal power, oil & gas refineries and the iron & steel sector, and the countries whose emissions cause the greatest impacts are Germany, Poland and France.
- Application of best available end-of-pipe techniques in the power and industrial sectors would avoid an estimated 10,000 deaths and external costs of €28 billion per year. These improvements can be accomplished by requiring large combustion plants to comply with the more stringent end of current best available technique definitions, with a high bar for exemptions, while the iron & steel and cement sectors would additionally require an update to the definitions of BAT to reflect best international practices.
- Emissions from agriculture are responsible for an estimated 72,500 annual deaths due to exposure to $PM_{2.5}$. The countries whose emissions cause the greatest impacts are Germany, France and Italy.
- Improvements to agricultural practices could reduce ammonia emissions by 1.27 million tonnes by 2030, avoiding 27,000 deaths per year from air pollution and economic costs of €75 billion per year. Fully realizing these improvements requires defining the scope of the revised Industrial Emissions Directive to fully cover industrial-scale livestock and manure operations.

- There is an urgent need to improve reporting on emissions from industrial facilities in the EU. The current system provides very limited data, and even that with a delay of up to five years, hampering both enforcement and research.

Introduction

Air pollution from industry and agriculture

Although often regarded as a global leader in environmental protection, Europe's pollution regulation has been eroded through the implementation of weak standards and loopholes, introduced by industry and national lobbyists and a permitting culture in most member states that seeks to impose the most lenient limits that are legally possible. As a result, the performance of emission controls in manufacturing industry and power plants fall far behind what is technologically feasible at the expense of public health and environmental protection.

Fine particles with aerodynamic diameter smaller than 2.5 µm ($PM_{2.5}$) are one of Europe's leading environmental risks to public health (Landrigan et al., 2018). Once inhaled by humans, this pollutant can lead to health outcomes including ischaemic heart disease, chronic obstructive pulmonary disease and lung cancer (Lelieveld et al., 2019). Scientific research is continually identifying additional (Shi et al., 2020) and more potent (Di et al., 2017) negative health impacts of these pollutants. Recently, the World Health Organisation (WHO) halved the recommended guideline value from 10 to 5 µg m^{-3} (WHO, 2021) due to recent epidemiological studies revealing a higher $PM_{2.5}$ toxicity as compared to previous studies (Di et al., 2017). Achieving this updated $PM_{2.5}$ guideline value will lead to major improvements in public health, but it will be challenging as currently only 0.001 % of the global population live in environments that comply with this value (Yu et al., 2023). Despite being regulated both nationally and internationally, $PM_{2.5}$ remains a major environmental and public health burden in Europe (COMEAP, 2010), with relatively poor progress observed in recent years (Vohra et al., 2021; EMEP, 2021).

Humans contribute to the formation of $PM_{2.5}$ through a variety of different activities. $PM_{2.5}$ is both directly emitted into the atmosphere and formed in the atmosphere from precursor species, those being nitrogen oxides (NO_x), sulfur dioxide (SO_2), and ammonia (NH_3). Many of these species are emitted from the power sector (e.g., combustion plants) and the industrial sector (combustion, iron & steel production, refineries, cement plants).

Agriculture is also an important source of $PM_{2.5}$.However, this sector is poorly regulated. Emissions of ammonia (NH_3) are dominated by the agricultural sector. Emissions of NH_3 from this sector can be minimized through a range of different strategies, including changes to livestock feeding, manure storage, animal housing, and the use of mineral fertilizers (Oenema et al., 2012). While the cost of implementing these strategies is outweighed by the benefits to human and ecosystem health (Giannakis et al., 2019), many of these emission reductions strategies are, however, just guidance (DEFRA, 2018; Hicks et al., 2022) as opposed to legislation. For many countries across Europe, both the historical trend (Richmond et al., 2020) and governments' commitments to future reductions (UNECE, 2017) of NH_3 emission are much weaker when compared to SO_2 and NO_X. For instance, in 2020 and beyond, the UK commits to large reductions in emissions of SO_2 and NO_X (55-59%), but only marginal reductions of NH_3 (8%) compared to 2005 emissions (UNECE, 2017).

The review of the Industrial Emissions Directive

In the European Union (EU), emissions of pollutants from industry sectors are controlled through the Industrial Emissions Directive (IED) which applies to industrial scale activities, ranging from intensive livestock rearing to waste management activities, listed in its Annex I. The legal framework dates back to the 1996 Integrated Pollution Prevention and Control (IPPC) Framework that was amended for the first time in 2010.

According to the Industrial Emissions Directive, EU member states should set pollution limits in environmental permits on the basis of Best Available Techniques (BAT) conclusions, which are based on an information exchange between industry, member states and the non-governmental organisations (NGOs) promoting environmental protection within the Sevilla Process (EEB, 2022a). Once published in the official journal, operators have a maximum of 4 years to comply with those performance standards. The conclusions typically specify a range of emission levels that can be achieved by the use of BAT. The standards are based on questionnaires by the operators of commercially operating reference plants almost exclusively in Europe.

The ranges given in BAT conclusions are often very wide, with a difference of a factor of 10 or more between the low end (referred to as strict or lower BAT-AEL) and high end (referred to as upper BAT-AEL).

The IED requires, among other things, permit writers to set emission limit values (ELVs) not exceeding those emission ranges associated with the use of BAT, keeping in mind the objective to achieve a high general level of environmental protection as a whole.

In practice, permit writers have consistently aligned pollution limits to the legally allowed maximum levels (the lenient end of the BAT ranges), as well as granted derogations allowing plants to emit more than even the lenient end of the range (European Commission, 2021; EEB, 2021a). The many shortcomings have been highlighted by NGOs in the IED evaluation process (EEB, 2019a, 2019b, 2021b, 2022b).

The European Commission is well aware that the flexibility allowed by the legal provisions has been abused in implementation and sought to address this in a revised IED proposal, published on April 5, 2022 (European Commission, 2022a, 2022b).

The revised IED proposal clarifies that permit writers should set the “strictest possible” emission limits that should be consistent with the performance achieved by applying the stricter range of the BAT conclusions. The plant operator would be required to demonstrate why it is not feasible to meet the strictest end of the BAT range and to demonstrate the best performance the installation can achieve by applying BAT. Member states would be required to assess the feasibility of upgrading national emissions rules to require the more stringent end of the BAT range, leading to the strengthening of national regulations.

There are many roadblocks in the process of revising the IED that can make the difference between a “lost decade” for air quality and public health and accelerated progress:

- How widely will the polluters be required to comply with the stringent end of the BAT ranges of the adopted EU BAT Conclusions under the current IED and whether the burden-of-proof is placed on emitters to justify a less stringent limit or exemption.
- The length of the transition period before compliance to stricter BAT is required. Current proposals of the Council of the EU (2023) allow up to 14 years whilst a practical timeline for carrying out the required retrofits is at most a few years.
- Whether the future process for updating BAT Conclusions for key emitting sectors will reflect actual best available techniques and best practices.
- How much of the agricultural sector is covered, the timing and ambition level of the process to establish BAT requirements for the sector.

Most industrial scale farming activities are currently not covered by the Industrial Emissions Directive: only very large scale pig farms, with more than 2,000 pigs or 750 sows, and poultry farms with more than 40,000 places are regulated, and cattle is completely excluded. The new proposed directive aims to cover all intensive livestock activities starting from a size equivalent to 150 dairy cows (measured in so-called livestock units). The proposal would require the use of BAT for manure spreading, irrespective of whether this occurs off-site. However, the operating rules defining BAT are yet to be decided. In addition, in order to achieve significant improvements, the current definition of BAT would have to be substantially strengthened.

This report assesses the air quality and health benefits under strong mitigation measures for the agricultural sector and implementation of emission limits for the power and industrial sectors that correspond to the use of best available abatement techniques. The scope of the report is limited to end-of-pipe abatement measures; energy efficiency as well as process and fuel changes could yield significant further reductions.

Results

Emissions

Among the studied sectors, thermal power is the largest emitter of NO_x, followed by cement and oil & gas refining. Oil & gas refining is the largest emitter of SO_2, followed by thermal power and iron & steel. Iron & steel is the largest emitter of particulate matter, with thermal power and pulp & paper the second and third largest emitters. Thermal power is the largest emitter of mercury.

Total NO_x emissions from all countries and from all the included sectors amount to approximately 853,000 tonnes per year. Emissions from thermal power plants seem to outweigh the other sectors’ emissions (Figure 1).

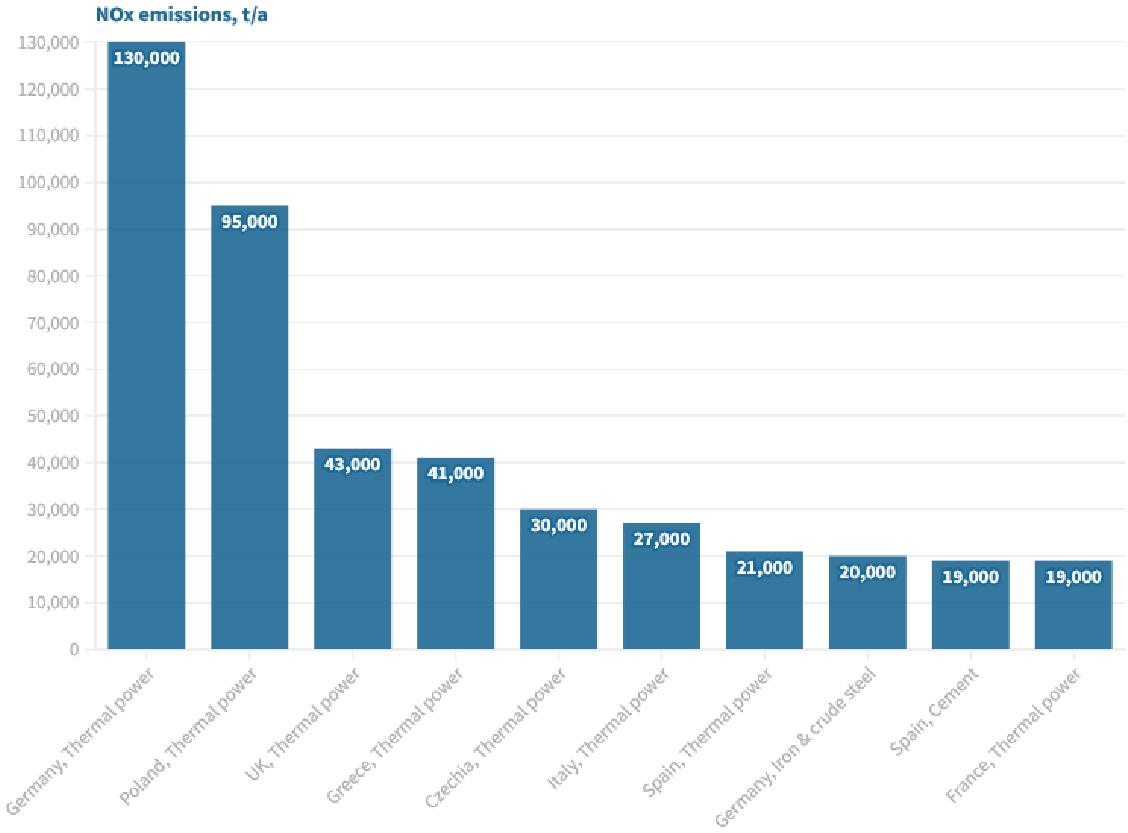

Figure 1. *Top NO_x polluting countries by sector in tonnes per year, based on latest reported year*[1]

Total SO_2 emissions amount to just over 600,000 tonnes per year with Poland’s thermal power sector contributing a sixth of this at 100,000 tonnes per year followed by Germany’s thermal power at 68,000 tonnes of SO_2 emissions (Figure 2). The third largest emitter is again Germany with its oil & gas refineries.

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[1] The latest reporting years vary from 2017 to 2020 depending on the country

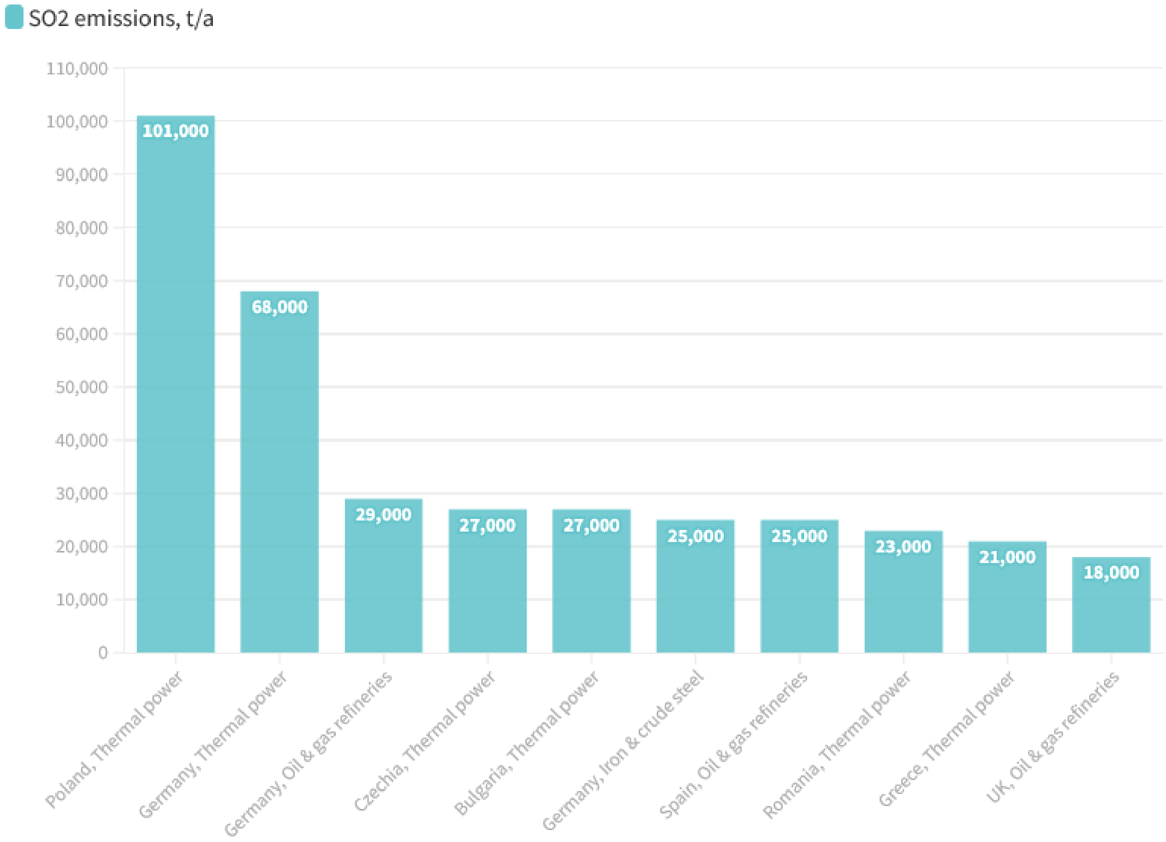

Figure 2. *Top SO_2 polluting countries by sector in tonnes per year, based on latest reported year*

Agriculture is by far the largest ammonia emitting sector with total emissions of the gas from the sector amounting to approximately 3.5 million tonnes a year in the EU27+UK. Germany's agricultural activities emit 650,000 tonnes of ammonia per year making it the largest European emitter, with France accounting for 570,000 tonnes of annual emissions and Spain emitting 430,000 tonnes of the gas.

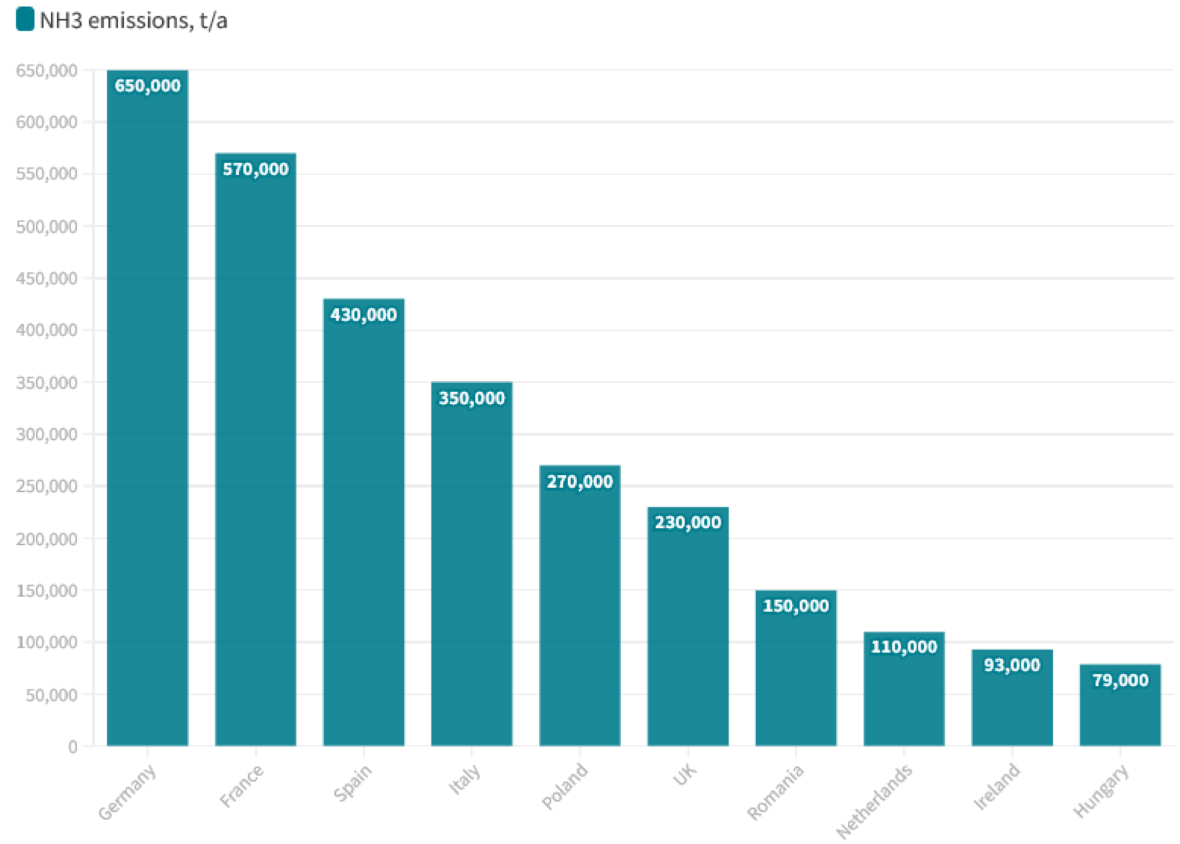

Figure 3. *Ammonia emissions in tonnes per year from agriculture, 10 most polluting countries*

These countries and sectors are also large emitters of mercury (Hg), a neurotoxic pollutant that harms the development of fetuses, and increases the risk of chronic diseases in adults. More than 1.8 million babies are born each year in the EU with unsafe levels of mercury exposure during pregnancy (Bellanger et al., 2013). The mercury emissions from all the sectors and countries for the different reporting years amount to 21 tonnes per year.

Table 1 shows the annual pollutant emissions for each sector compared to the emissions under the BAT scenario. For all sectors and pollutants, the BAT emissions are lower than actual emissions, most times half the amount of actual NO_x, SO_2 or mercury emissions. The largest absolute emissions reductions are realized in the thermal power sector, while the iron & steel, cement and refining industries have the largest potential for reductions in percentage terms.

Table 1. *Sectoral emissions by pollutant, actual compared to BAT*

	Emissions							
	NO_x, t/a		SO_2, t/a		$PM_{2.5}$, t/a		Hg, t/a	
Sector	**Actual**	**BAT**	**Actual**	**BAT**	**Actual**	**BAT**	**Actual**	**BAT**
Cement	141,000	28,500	26,500	6,440	577	118	2.5	0.3
Chemicals	29,300	16,800	9,050	3,390	463	270	0.7	0.6
Iron & Steel	72,900	29,600	71,200	19,000	9,890	3,140	2.1	0.95
Oil & gas refineries	78,700	37,700	143,000	31,300	809	809	0.4	-
Pulp & paper	24,200	9,390	5,160	2,030	1,230	265	0.89	0.6
Other industries[2]	8,160	4,580	3,710	1,015	148	90	2.8	1.6
Thermal Power	499,000	252,000	347,000	55,400	8,630	3,400	11.8	5.6

Gaps in emission reporting

Work on this report has made apparent that the EU's current system for reporting on pollutant emissions from industrial facilities, the EEA Industrial Reporting Database and Industrial Emissions Portal, is not fit for purpose (EEB, 2022c) and far behind best international practice. The system is further undermined by incomplete and grossly delayed reporting by many member states. There are multiple issues:

- Only annual data is reported, making comparisons to daily and other short-term emission limits, as well as detailed air quality modeling, impossible.
- Only annual mass emissions (kg or tonnes per year) are reported. The stack emission concentrations, the values that would be directly comparable to regulated standards and emission limit values, are not reported.

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[2] Other industries include food processing, non-ferrous metals, processing of ferrous metals and waste

- Permit conditions in force and compliance information are not integrated with emissions data.
- Activity or output data that would enable emissions benchmarking or assessment of the performance on pollution prevention and reduction across facilities is not reported.

Timely and complete reporting of emissions and environmental compliance would provide a more accurate picture of good and bad performers, leveling the environmental playing field and improving public accountability.

Health and economic impacts

We modeled the health impacts and costs under two scenarios, the “Actual” scenario with latest reported air emissions by each sector, and the “BAT” scenario taking into account emissions under stricter BAT values and estimated mitigation measures. We estimate that air pollution from all the assessed sectors is responsible for 89,600 (95% CI: 66,900 – 102,000) deaths a year in the EU and the UK with a corresponding economic burden on the countries amounting to €248 billion (95% CI: €183 – €286 billion) every year. These figures could be reduced almost by half if all the countries followed the best performance identified in BAT conclusions, and BAT conclusions reflected best international practices. Note that further air emission reductions could be achieved by the implementation of other BAT measures such as strict energy efficiency performance or electrification of combustion processes which have not been considered in the modeling.

We find that the agricultural sector alone contributes the most to annual deaths and associated health and economic costs in the EU27+UK. Therefore, the gains from the agricultural sector if it were to follow stronger emission mitigation measures are huge — approximately 27,000 deaths could be avoided every year and €75 billion in costs could be saved (Table 1). The gains from the industrial manufacturing and power generation sectors combined are 10,000 avoided deaths annually with €28.5 billion in total avoided economic costs. The total avoided deaths for the thermal power sector would be 5,000 per year, with the avoided health costs worth approximately €13.7 billion. Decreased agricultural emissions of NH_3 are due to a combination of measures, most importantly low emission application of manure and covered housing of livestock.

Table 2. *Deaths and total economic costs of Actual and BAT emissions by sector (95% confidence intervals in parentheses)*

Sector	Scenario	Deaths	External Costs (Bln €)
Agriculture	Actual	72,500 (54,400 – 81,600)	202 (149 – 230)
	BAT	45,500 (34,100 – 51,200)	127 (93.5 – 144)
Cement	Actual	1,870 (1,360 – 2,330)	5.0 (3.66 – 6.19)
	BAT	412 (301 – 495)	1.12 (0.81 – 1.33)
Chemicals	Actual	551 (404 – 673)	1.50 (1.10 – 1.82)
	BAT	311 (226 – 396)	0.84 (0.61 – 1.06)
Iron & steel	Actual	2,570 (1,900 – 3,050)	7.05 (5.17 – 8.38)
	BAT	895 (658 – 1,080)	2.45 (1.79 – 2.95)
Oil & gas refineries	Actual	2,690 (2,010 – 3,060)	7.46 (5.50 – 8.57)
	BAT	855 (638 – 966)	2.37 (1.74 – 2.70)
Pulp & paper	Actual	251 (176 – 351)	0.66 (0.47 – 0.90)
	BAT	94 (63 – 153)	0.24 (0.17 – 0.37)
Other industries	Actual	191 (115 – 422)	0.45 (0.30 – 0.95)
	BAT	104 (60 – 251)	0.24 (0.15 – 0.55)
Thermal power	Actual	8,930 (6,520 – 11,000)	24.3 (17.7 – 29.6)
	BAT	3,930 (2,860 – 4,870)	10.6 (7.75 – 13.1)

The country with the largest contribution to the health impacts of agricultural ammonia emissions is Germany, with attributable annual deaths reaching nearly 22,000, followed by France which is responsible for an estimated 9,500 annual deaths and, at third place, Italy with approximately attributable 7,400 deaths. The corresponding economic costs related to the health impacts of agricultural air pollution from these countries' emissions are €59.2 billion, €26.7 billion and €20.6 billion, respectively. If we combine all the deaths from the industrial sector as a whole with the power sector, Germany's industrial and power activities contribute to the largest number of deaths again amounting to around 6,000, with Poland's activities causing over 2,000 annual deaths and France nearly 1,700 deaths.

Table 3. *Deaths from 10 of the most polluting countries by sector*

	Deaths				
Country	**Agriculture**	**Cement**	**Iron & steel**	**Oil & gas refineries**	**Thermal power**
Germany	21,300 (16,000 – 23,900)	463 (338 – 575)	1,110 (826 – 1,290)	835 (625 – 942)	3,450 (2,530 – 4,230)
France	9,590 (7,190 – 10,800)	356 (259 – 421)	357 (263 – 423)	264 (197 – 300)	465 (342 – 534)
Italy	7,400 (5,550 – 8,330)	195 (142 – 224)	210 (153 – 256)	367 (273 – 420)	397 (292 – 457)
Poland	5,500 (4,120 – 6,190)	53 (37 – 78)	149 (109 – 181)	17 (12 – 19)	1,880 (1,370 – 2,390)
Spain	3,630 (2,720 – 4,080)	120 (84 – 152)	62 (45 – 78)	249 (186 – 286)	143 (104 – 170)
UK	5,540 (4,160 – 6,240)	141 (106 – 173)	182 (134 – 233)	288 (218 – 322)	343 (257 – 424)
Belgium	2,620 (1,960 – 2,950)	133 (100 – 165)	158 (120 – 181)	149 (113 – 168)	54 (41 – 59)
Czechia	2,150 (1,610 – 2,420)	49 (36 – 58)	152 (112 – 180)	14 (10 – 16)	681 (488 – 908)
Romania	1,820 (1,360 – 2,050)	111 (80 – 129)	60 (44 – 72)	29 (21 – 34)	419 (307 – 483)
Hungary	2,130 (1,590 – 2,390)	38 (26 – 50)	44 (33 – 50)	21 (16 – 25)	203 (148 – 236)

We estimated the avoided health impacts at the EU level due to reductions in pollutants from the agricultural, power generation and the largest industrial sectors.

There are major health benefits related to the decrease in emissions, especially the reduction in power plant and industrial NO_x and SO_2 emissions, as well as ammonia emissions from agriculture. These gases are important precursors to $PM_{2.5}$, and NO_x is also a key precursor to ozone. $PM_{2.5}$ is of particular danger to human health as it can penetrate deep into the lungs and into the bloodstream when inhaled and consequently increasing the risk of multiple cardiovascular and respiratory diseases. Over 20 million restricted activity days could be avoided due to reductions in the contribution of the agricultural sector to $PM_{2.5}$ levels, and a further 7 million restricted days could be avoided from the power and industry sectors combined.

Interestingly, the reduction in ammonia emissions in the agricultural sector increases ozone (O_3) levels which would worsen some of the health impacts such as cardiac hospital admissions, minor restricted activity days and respiratory medication use by adults, depicted in Table 4 with a negative sign. The reduction in ozone levels happens because NO_x can either react with NH_3 to form $PM_{2.5}$, or with Volatile Organic Compounds (VOCs) to form ozone. Therefore, decreased NH_3 emissions due to implementing BAT in the agricultural sector leads to an increased availability of NO_x to form ozone.

The potential increases in ozone concentrations due to reduced ammonia emissions from agriculture would be more than offset by the reductions in NO_x emissions in the power and industry sectors. These emission reductions could lead to 1,400 avoided preterm births, 1,300 avoided respiratory hospital admissions and 77,000 avoided days of asthma attacks per year in children. Lower $PM_{2.5}$ levels due to emission reductions in the agricultural sector could avoid 207,000 days of unnecessary asthma attacks in children and 27,000 deaths annually.

Table 4. *Avoided health impacts from the application of BAT in the agricultural sector and in the power & industrial sectors combined*

Outcome	Pollutant	Power & industry	Agriculture
Cardiac hospital admissions, all ages	O_3	120,500 (67,700 – 172,000)	-18,300 (-10,300 – -26,100)
Chronic bronchitis[3]	$PM_{2.5}$	3,540 (1,210 – 5,720)	9,520 (3,260 – 15,400)
Chronic mortality	$PM_{2.5}$	10,040 (7,530 – 11,300)	27,000 (20,300 – 30,400)
Minor restricted activity days, ages 18-64	O_3	494,000 (192,000 – 799,000)	-75,100 (-29,300 – -121,000)

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[3] Population aged over 27 years

Preterm births	PM$_{2.5}$	1,420 (662 – 1,510)	3,820 (1,780 – 4,070)
Respiratory hospital admissions, all ages	PM$_{2.5}$	1,340 (-127 – 2,850)	3,620 (-343 – 7,650)
Asthma attacks, children	PM$_{2.5}$	77,100 (16,500 – 140,000)	207,000 (44,400 – 378,000)
Restricted activity days	PM$_{2.5}$	7,530,000 (6,730,000 – 8,490,000)	20,200,000 (18,100,000 – 22,800,000)

How air pollution contributes to death and disease and how the contribution can be quantified

Numerous long-term health studies have shown that people living in areas with higher average levels of pollutants such as PM$_{2.5}$, ozone, NO$_2$ and mercury have a higher risk of a range of negative health outcomes, including death. Each of these pollutants affects the body in different ways.

The scientific basis for quantifying the health effects of different pollutants is the body of epidemiological studies that compare the risk of different health issues in people living in areas with different levels of pollution. In the case of short-term and acute impacts, it is also possible to compare the risk for the same group of people during days with low and high pollution levels.

The findings of these studies have allowed scientists to develop concentration-response functions that show how deaths increase or decrease when air pollutant levels change.

Health impact assessment studies take these relationships, and apply them to observed incidence of different health outcomes, and observed level of exposure to pollution. Based on the concentration-response relationships, we can project how much the risk of e.g., lung cancer or asthma attacks would be lowered if pollution from the studied sources was eliminated, and consequently how many cases of such health outcomes would be avoided. These avoided health outcomes are considered attributable to air pollution.

Many health impact studies use the term "premature" deaths to refer to deaths attributed to air pollution. This terminology is a relic from times when only short-term, acute mortality was linked to air pollution, and therefore the loss of life expectancy associated with deaths from air pollution was measured in days or weeks. According to current understanding, the loss of life expectancy from air pollution-related deaths averages 10–20 years and includes people in their 30s and 40s with a remaining life expectancy of 40 years or more, as well as children with a life expectancy of 70 years or more. We do not, therefore, consider the term appropriate or instructive anymore.

Methodology

Air emissions projections

For all industrial sectors, “actual” emissions data refers to the latest data reported to the EEA Industrial Reporting Database. This database comprises two emissions datasets, one for combustion emissions from Large Combustion Plants (LCP) (“Installations”) and one for both combustion and process emissions from all industrial emitters (“facilities”), with different coverage of emissions species, and different information available. The LCP dataset includes data on fuel use, and only covers the emissions of SO_2, NO_x and dust. The data was screened for implausible data points by calculating the ratio of pollutant emissions to fuel input and CO_2 emissions for each facility and pollutant, and discarding values that were more than five median absolute deviations removed from the median value for the economic sector.

For each sector, a counterfactual emissions projection was calculated assuming the use of best available emission mitigation techniques relating to air emissions, without changes to fuels or production processes, e.g., electrification to substitute combustion and hence preventing on site generation of air emissions. This means that the potential to prevent or reduce emissions through the use of clean energy, energy efficiency or changing production processes is not included in the “BAT” scenario. Other environmental co-benefits on strict BAT implementation relating to other media such as water, soil, waste management and phase out of chemicals of concern substances on site have not been factored into this projection of health benefits.

For all sectors, dust emissions concentration levels of 5 mg/Nm^3 and mercury concentration levels of 1 $\mu g/Nm^3$, based on the lower BAT levels in the LCP BREF for coal and lignite, was taken as BAT. Flue gas streams from other sectors can be treated to these levels using the same abatement techniques such as fabric filter and advanced ESP filters or a combination of those for dust and dedicated mercury control techniques applicable to any flue gas stream, so there is no valid reason to apply less efficient techniques in other sectors. The exception is the refining sector where there was no reliable way to estimate total flue gas volumes, and therefore the effect of applying these limits couldn't be estimated.

For the iron & steel and cement sectors, the definition of BAT for SO_2 and NO_x emission control was based on China's ultra-low emission (ULE) standards, which require SO_2 concentrations below 35 mg/Nm^3 and NO_x concentrations below 50 mg/Nm^3 in flue gas for both sectors.

Conversions between dust, PM_{10} and $PM_{2.5}$ emissions were done using the ratios in the EMEP Guidebooks for each emitting sector, and in the case of combustion plants, for each fuel.

Large combustion plants

For LCPs, BAT was defined as compliance with the lower BAT-aligned emission levels in the LCP BREF document (European Commission, 2021).

Emissions of SO_2, NO_x and dust were taken from the LCP data, and mercury emissions from the facility data.

Calculating annual emissions under the BAT emission levels requires estimating the flue gas volumes of the plants. These were calculated based on reported fuel consumption (C) and specific flue gas volumes (SFGV) for each fuel type taken from Graham et al. (2012). BAT-aligned emissions E^{BAT} then become:

$$E^{BAT}_{pollutant} = \sum_{fuel} \left(L_{fuel,pollutant} \times C_{fuel} \times SFGV_{fuel} \right)$$

where L is the lower BAT-aligned emission level.

In order to avoid double counting with the other sectors, LCPs with their main activity in the iron and crude steel, refining or cement sectors were excluded.

Iron & steel

BAT for iron & steel was defined as compliance with China's ultra-low emission standards (Bo et al. 2021; MEE 2019). South Korea, Taiwan and Japan have equally strict emission control requirements, but China's ultra-low emission standards are by far the most widely applied set of standards, with 240 million tonnes of production capacity retrofitted for compliance by February 2023, and another 460 Mt in the process of completing the retrofits (China Metallurgical News, 2023), in addition to the construction of new plants. This demonstrates the availability of the techniques for compliance.

Given the complexity of the production processes in the sector, emissions were benchmarked on the national level. Steel production through different routes by country was obtained from the World Steel Association annual World Steel in Figures publications (see e.g. WSA, 2022).

The emission intensity of BF-BOF steel production under China's ultra-low emission standards are taken from Bo et al. (2021), and EAF steel from EMEP Guidebook 2019 (EEA, 2019). Emissions under the application of BAT were then projected as:

$$E^{BAT}_{pollutant} = \sum_{route} \left(O_{route} \times I_{pollutant,route}\right),$$

where I denotes emission intensity per tonne of steel produced, and O is the output of crude steel through each route (BF-BOF and EAF). Mercury and dust emissions intensity from BF-BOF production were calculated using Bo et al. (2021) values for flue gas volumes from the production process, and our uniform BAT emission levels (L):

$$I_{pollutant,BF-BOF} = L_{pollutant} \times FGV_{BF-BOF}$$

Refineries

Given the complexity of the production processes in the refineries sector, emissions were benchmarked on the national level. BAT was defined as the lower end of values for emissions per tonne of crude oil processed given in the IFC EHS Guidelines.

$$E^{BAT}_{pollutant} = T \times I_{pollutant},$$

where T is the throughput of crude oil in each country taken from IEA World Energy Balances.

Cement

China’s ultra-low emission standards for cement were used as a basis. Similar to steel, these standards are being applied to hundreds of retrofit projects as well as newbuild plants, demonstrating the availability of the techniques for compliance. Unlike with power plants and steel, the standards vary by province, but the strictest standards have been adopted by Shanxi, Shandong and Jiangsu (Polaris Network 2021; Shandong DEE 2022). In China’s largest cement-producing province, Henan, alone, 131 cement plants had completed the retrofits by June 2022 (Henan DRC, 2022). In Shanxi, 10 cement plants had achieved compliance by the end of 2021 (Shanxi News Network 2022).

Flue gas volumes calculated on the basis of reported CO_2 emissions in the PRTR data, and ratio of normalized flue gas volume to CO_2 emissions (FGR) from EMEP Guidebook 2019 (EEA, 2019):

$$E^{BAT}_{pollutant} = L_{pollutant} \times E_{CO2} \times FGR.$$

In practice, the ultra-low emission standards require the installation of catalytic NO_x controls, and upgrades to desulfurization equipment. EU cement industry information of 2018 indicates that 240 kilns run on the less efficient SNCR NO_x abatement technique, with just 17 having the more effective catalytic controls (SCR) system (CEMBUREAU, 2021).

Agriculture

We calculate changes in agricultural emissions of ammonia (NH_3) by combining the EMEP emission inventory with results from an integrated assessment model. In the EMEP bottom-up emission inventory, the latest available information on underlying human activity and emission factors are combined with one another. This inventory has been evaluated extensively and is used widely by scientists and policy makers. Because of this, there is confidence in the magnitude and spatial pattern in the emissions of this inventory. To calculate the change in agricultural emissions of NH_3, we scale EMEP emissions by results from an integrated assessment model. The Greenhouse Gas Air Pollution Interactions and Synergies (GAINS) (Amann et al., 2011; Klimont et al., 2017) is a global scale integrated assessment model and has been used to estimate the emissions of pollutants and precursors under a range of scenarios and time periods, and the information is archived in Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants (ECLIPSE) (Amann et al., 2020). The most recent version of ECLIPSE (6b), includes a maximum technical feasibility emission reduction scenario, where all feasible emission mitigation strategies and technologies are implemented into legislation (see the Introduction for an overview of ammonia emission reduction strategies for agriculture). We create a spatially-varying gridded scaling factor from the ECLIPSE dataset that represents the change in agricultural NH_3 emissions between 2020 and 2030 in the maximum technical feasibility emission reduction scenario, and apply it to the EMEP emissions. The advantage of this methodology is that it preserves the accuracy of the EMEP emission inventory in capturing the magnitude and spatial variability in emissions, and combines it with the predictive capacity of the integrated assessment model.

Health and economic impacts

The health and economic impacts of the emissions of major air pollutants from different countries and sectors were assessed using the methodology of the report “Costs of air pollution from European industrial facilities 2008–2012” (EEA, 2014). This framework covers the impacts of exposure to $PM_{2.5}$ and ozone due to the emissions of SO_2, NO_x, dust and ammonia. The impacts of mercury emissions were estimated using the Schucht et al. (2021) methodology, as it provides physical health impacts as well as economic costs.

The EEA (2014) methodology is based on country-level source-receptor matrices derived from detailed atmospheric chemistry-transport modeling simulations. The matrices capture the effect of reductions in the emissions of each of the included pollutants in one country on the exposure to $PM_{2.5}$ and ozone in all European countries. Adjustment factors are applied to emissions from different sectors to account for the differences in the locations of emitting sources, release height and other characteristics. There was no adjustment factor available for the agricultural sector, but since the sector dominates ammonia emissions, applying the source-receptor relationships for total ammonia emissions to the sector is appropriate.

The concentration-response function for $PM_{2.5}$ exposure was updated in accordance with the Chen and Hoek (2020) meta-analysis carried out to inform the update of WHO ambient air quality guidelines.

All economic valuations were updated to 2022 prices using the Eurozone weighted average GDP deflator to account for inflation.

One important shortcoming of this framework is that the health impacts of exposure to NO_2 are not covered. Exposure to NO_2 pollution is responsible for an estimated 136,000 deaths per year in the EU (EEA, 2023). This omission means that the avoided health impacts of emissions reductions from the power and industrial sectors are underestimated.

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