PUBLIC HEALTH CO-BENEFITS OF DECARBONIZING INDUSTRIAL PRODUCTION IN EUROPE

Still preliminary

Laure de Preux[1]
Yixuan Gu[2]
Daven K. Henze[3]
Ulrich J. Wagner[4]

December 7, 2023

Abstract

Decarbonizing the industrial sector presents formidable challenges but is likely to generate sizable ancillary health benefits by reducing air pollution. Knowing which industries are prone to generate significant co-benefits can provide valuable guidance for policymakers called upon to design policies that lead heavy industries on a path towards deep decarbonization through mostly uncharted territory. This paper draws on new data and recent advances in air quality modeling to quantify avoided premature deaths related to $PM_{2.5}$ exposure attributable to industrial precursor emissions. Using this metric, we analyze the health co-benefits of decarbonizing the three highest emitting industrial processes in Europe: cement, steel, and refining. We show that the potential decarbonization benefits are substantial and vary across industries. Our results indicate that decarbonizing cement production should be a priority from a co-benefit point-of-view. The cement industry is not only larger and more pollution-intensive than the other industries, but its emissions also generate marginal external damages that exceed pollutant-specific averages. We plan to extend our analysis along two dimensions: (i) analyze specific decarbonization options for the cement sector and (ii) study the distributional impacts of ancillary health benefits of industrial decarbonization.

Paper prepared for the NBER Workshop on Decarbonizing Industrial Production, December 8-9, 2023. We would like to thank Lint Barrage, Ken Gillingham, and other participants at the NBER Workshop for helpful comments and suggestions. All remaining errors are our own. Support by the German Research Foundation (DFG) through CRC TR 224 (Project B07) is gratefully acknowledged. Wagner received financial support from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement No. 865181). The authors state that they have no ties to the energy industry nor to any of the industries that might be impacted by industrial decarbonization.

---

[1] Imperial College London, United Kingdom. Email: l.depreux@imperial.ac.uk

[2] Department of Economics, University of Mannheim, Germany. Email: yixuan.gu@uni-mannheim.de

[3] Department of Mechanical Engineering, University of Colardo at Boulder, USA. Email: daven.henze@colorado.edu

[4] Department of Economics, University of Mannheim, D-68131 Mannheim, Germany. Email: wagner@econ.uni-mannheim.de

1 Introduction

Decarbonizing the industrial sector presents formidable challenges. The bulk of greenhouse gas (GHG) emissions from industrial production is carbon dioxide (CO_2), which is released not only when burning fossil fuels for heat and power generation but also by specific production processes (e.g., cement clinker or ammonia). Moreover, CO_2 is not the only GHG emanating from industrial production. Other GHGs such as methane, nitrous oxides, HFCs, PFCs, SF_6 and NF_3 all derive from industrial activities. Therefore, decarbonizing industry is expected to be very costly.

At the same time, curbing industrial GHG emissions is likely to generate sizable co-benefits in terms of human health. On the one hand, this is because CO_2 is jointly emitted with numerous air pollutants that damage health directly or are precursors to ozone and fine dust ($PM_{2.5}$) which have dangerous health consequences. On the other hand, some of the above mentioned GHG emissions are known to have detrimental health effects at local and regional scales, in addition to aggravating climate change at the global scale. Therefore, reducing industrial GHG emissions and related co-emissions will likely improve air quality and hence public health.

The goal of this paper is to quantify such public health benefits of decarbonization scenarios for selected industries, and attribute contributions of the various pollutant species to those overall health benefits. To achieve this, we draw on new data as well as recent advances in air quality modeling to quantify avoided premature deaths that can be attributed to emissions of $PM_{2.5}$ precursors from industrial sources. With this metric in hand, we analyze the health co-benefits of decarbonizing the three highest emitting industrial processes in Europe: cement, steel, and refining. Our results indicate that the potential decarbonization benefits are sizable and vary substantially between industries and pollutants. When relating those impacts to carbon emissions, our findings imply that cement production should be a priority from a co-benefit point-of-view. The cement industry is not only larger and more pollution-intensive than the other industries, but its emissions also generate marginal external damages that exceed pollutant-specific averages.

Our work is highly relevant for policy makers weighing the costs and benefits of industrial decarbonization. Decarbonizing the production of steel or ammonia will have major implications for the economic geography of global value chains, shifting the competitive advantage to regions where carbon-free energy is inexpensive and thus threatening to move parts of the downstream value chain in the same direction, away from their historical locations. Against this backdrop, policy makers have begun to implement decarbonization policies as industrial policy, with an explicit objective to prevent such industries from moving overseas (cf. the Inflation Reduction Act). By providing first estimates of the co-benefits of industrial decarbonization, grounded in detailed establishment data and sophisticated atmospheric modeling, our study helps policy makers to compare the net benefits of such policies with those of alternative policy options.

2 Background

2.1 Decarbonizing Industry in the European Union

As a signatory of the 2015 Paris Agreement which seeks to limit global warming to 1.5 degrees Celsius, the EU has pledged to reduce their GHG emissions by 55% by 2030 and to net zero by 2050. The industrial sector will have to play an important role in honoring that commitment. Industry accounted for more than 22 % of EU wide GHG emissions, while also contributing more than 15% to its GDP. Other important sectors called upon to reduce their emissions are energy, transportation, agriculture, and buildings.

Most (but not all) industrial GHG emissions in the EU are regulated under the EU's flagship cap-and-trade program, the EU Emissions Trading System (EU ETS), which also includes emissions from electricity generation. To get a sense of the magnitudes involved, as well as of recent trends in decarbonization, we look at industrial GHG emissions in the EU ETS. These are reported as verified emissions of CO_2 and other GHGs, converted to tons of CO_2 equivalent, in the EU ETS registry known as the European Union Transaction Log (EUTL).[5] For brevity, we shall refer to those emissions as carbon emissions.

Figure 1 plots the evolution of carbon emissions over time by sector, following the EUTL classification, and sorted in decreasing order of contribution in 2015. Emissions reductions between 2007 and 2017 were largely driven by combustion activities and not industrial processes. Since the EUTL combustion sector also covers steam and electricity generated by industrial plants,

[5] We describe the data sources in Section 3.1 below.

this suggests that emissions abatement by those plants so far has focused on energy related emissions rather than process emissions.[6]

[Figure 1 about here]

Figure 2 displays the trends in carbon emissions from the seven largest industrial emitters: (i) refining & oil, (ii) cement & clinker, (iii) steel & iron, (iv) bulk chemicals, (v) pulp, paper, & cardboard, (vi) lime and calcination, and (vii) ammonia. In the three largest sectors, refining, cement, and steel, where reporting rules were stable over the period, emissions have declined by little more than 15%.[7]

[Figure 2 about here]

For illustration, Figures 3 and 4 plot the corresponding changes in co-emissions of major air pollutants NO_x and SO_x for the same industries. The strongest emissions reductions were achieved by the cement industry (NO_x) and refining (SO_x). In percentage terms, those reductions exceeded contemporary reductions in carbon emissions by a factor of two or more, although they were not as drastic as those in the combustion sector over the same period.

[Figures 3 and 4 about here]

The figures suggest that industrial processes have so far played a minor role in reducing carbon emissions in Europe. Colmer et al. (2023) show that French manufacturing firms reduced energy-related CO_2 emissions by 14-16 percent on average in response to moderate carbon pricing under the EU ETS.[8] Consistent with this, we observe similar changes to air pollution emissions in the above-mentioned industries. This provides additional motivation for our research question how

[6] Trends in industrial emissions depicted in the figure cannot measure adjustments to indirect emissions that industrial plants may have made via the procurement of electricity and intermediate inputs.

[7] As explained in the data section below, both figures rely on emissions information available from the official register of the EU ETS, the EUTL. Regulatory changes in 2008 and 2013 have increased the share of emissions from the production of ammonia and bulk chemicals that are included in the EU ETS. The emissions reported to EUTL increase in those industries and years but do not correspond to actual emissions increases. Our analysis below focuses on industries and time periods with stable reporting rules.

[8] Colmer et al. (2023) also present qualitative evidence from surveys suggesting that abatement efforts targeted energy related emissions (via technology upgrades and improved use of process heat) rather than processes.

large the ancillary health benefits associated with the necessary and still outstanding decarbonization of industrial processes are going to be.

A roadmap for future decarbonization in the industrial sector is provided by the EU Climate Action Plan. It stipulates a EU wide reduction of net carbon emissions by 55 percent from 1990 level targets by 2030. The contribution of the industrial sector towards this goal is expected to be in the range of 18 to 26 percent reduction from 2015 emissions (European Commission, 2020). These estimates are based on top-down simulations with the partial equilibrium model POLES and account for continued improvements in energy efficiency as well as technologically mature options for electrifying heat and steam production for industrial purposes. The projection does not consider demonstration projects for the deep decarbonization of specific processes, however. The POLES estimates are consistent with bottom-up estimates of potential efficiency gains obtained by comparing product specific carbon emissions across plants within an industry (EU Commission, 2020, p. 83). These data show higher efficiency gains in industries that have not yet been subjected to carbon pricing (or not consistently so), whereas industries like steel and iron, cement, or refining offer little cross-sectional potential for reducing energy related emission. None of the scenarios considered by the Impact Assessment anticipates significant reductions in process emissions by 2030. However, by 2050 these scenarios expect significant reductions by switching into electrification, and the replacement of remaining fossil fuel use by hydrogen, e-gas and bioenergy.

2.2 Literature

[to be completed]

3 Methods

Our analysis capitalizes on newly linked data that allow us to measure trends in both CO_2 emissions and co-emissions at thousands of stationary emitters in Europe, including industrial plants. Focusing on the three most pollution-intensive industrial processing (petroleum refining, iron and steelmaking, and cement production), we first quantify the extent of decarbonization in the period from 2008 (the beginning of the second trading phase of the ETS) until 2015. We then analyze how this process has affected co-emissions of air pollutants that are known precursors of $PM_{2.5}$ and ozone. Using a chemical transport model in combination with dose response relationships from the public health literature, we estimate the health benefits of reduced co-emissions of CO_2, expressed as the number of premature deaths avoided because of lower co-pollution emissions. Finally, we apply the same metric to quantify health co-benefits of specific decarbonization pathways that are relevant to the industry in question and proven to be technically viable.

3.1 Data on Carbon Emissions and Co-emissions

Our analysis is based on a novel dataset linking air pollution emissions from the European Pollutant Release and Transfer Register (E-PRTR)[9] and GHG emissions from the European Union Transaction Log (EUTL) which we built in de Preux, Kassem and Wagner (2022). This unique dataset comprises over 6,000 stationary emitters located in more than 30 European countries all of which are regulated under the European Union Emissions Trading Scheme (EU ETS). Mandatory emissions reporting comprises up to 50 different air pollutants at any given facility, subject to reporting thresholds. Focusing on ETS-regulated facilities allows us to work with more complete CO_2 emissions data than would be available from E-PRTR, where the reporting threshold for CO_2 is high. The combined dataset contains information on annual emissions of CO_2, other GHGs and more than 90 co-pollutants overall. We compute two key ingredients for our analysis; (i) GHG emissions in a base year (2015) and (ii) specific pollution intensities for each pollutant and each installation, expressed as mass of co-pollutant emitted per ton of CO_2 equivalent. Appendix Tables A1-A3 report descriptive statistics for emissions of CO_2 and other GHGs, as well as the main precursors to $PM_{2.5}$ pollution in the cement, steel, and refining industries in 2015.

3.2 Modeling Atmospheric Dispersion, Population Exposure, and Mortality Impacts

A well-known challenge with quantifying the health co-benefits of decarbonization policies derives from the fact that the place of emission is not necessarily equal to the place of impact. Topography, weather, and pre-existing air pollution suspended in the local atmosphere all influence in major ways how the emissions of primary pollutant species, once released from the

[9] See https://ec.europa.eu/environment/industry/stationary/e-prtr/legislation.htm

smokestack, translate into ambient concentrations of secondary pollutants such as ozone and $PM_{2.5}$. To gauge the impact of industrial decarbonization scenarios on human exposure to air pollution, it is necessary but not sufficient to know the location of polluters (geo-coded industrial sites in our dataset) and the population exposed to pollution (density on a 1km-by-1km grid for Europe). A chemical transport model is needed to quantify how changes in point-source emissions map to ambient pollution concentrations, taking due account of the highly non-linear atmospheric transport and chemical conversion processes that govern this mapping.

We compute ambient concentrations of $PM_{2.5}$ using a nested GEOS-Chem Adjoint model that was recently developed for the European domain (Gu et al., 2023a). The model is calibrated to 2015 weather and emissions data. Based on primary pollution emissions of, among others, NO_x, SO_2, and NH_3 it generates exposure to both primary $PM_{2.5}$ (organic carbon, black carbon, and fine dust) and secondary $PM_{2.5}$ (e.g., sulfate, nitrate, ammonium) on a 0.25° × 0.3125° grid for the European domain.

Thanks to adjoint modeling, this model allows for source appointment of secondary $PM_{2.5}$ health effects at no additional computational cost. Source appointment helps us to analyze counterfactual decarbonization scenarios by providing a direct mapping from local changes in emissions to public health, summarized in a single but highly policy relevant metric: the total number of premature deaths associated with the prevailing $PM_{2.5}$ concentration levels in each grid cell. This is defined as the total number of $PM_{2.5}$-related premature deaths in all the European countries listed in the Global Health Data Exchange[10] and for health outcomes[11] that can be affected by $PM_{2.5}$ pollution suggested by the Global Burden of Disease Study (GBD) 2019 (Murray et al., 2020). Figure 5 displays the geographic distribution of premature mortality predicted by the model at the 2015 baseline.

[Figure 5 about here]

We examine the impacts of several decarbonization scenarios for the industrial sector, or subsets of it, on $PM_{2.5}$ and ozone related mortality. In addition to computing aggregate mortality impacts,

---

[10] https://ghdx.healthdata.org/

[11] Chronic obstructive pulmonary disease, ischemic heart disease, lung cancer, type-2 diabetes, and stroke.

we analyze the geographic distribution of those impacts and their distributional implications. The first part of the analysis will rely on computationally inexpensive source attribution provided by the adjoint model. For the second part, we will conduct forward runs of the GEOS-Chem model to obtain the spatial distribution of pollution in selected counterfactual scenarios as well as the health impacts associated with them. The next section describes the scenarios in detail.

3.3 Scenario Analysis

We consider decarbonization scenarios for specific industries that are intensive in carbon emissions, including, but not limited to, the industrial production of steel, cement, and refining. We can distinguish between three types of scenarios.

3.3.1 Historical decarbonization

The first scenario looks backwards and tracks the historical emissions reductions in CO_2 and co-emissions. Because plant-level emissions data have been collected and published only recently, our observation period starts in 2008 which marks the first year of emissions trading after the ETS pilot phase. As the last year of observation, we choose 2015 for two reasons. First, the chemical transport model we use is calibrated on emissions inventories and meteorology for 2015. Thus, our assessment of the health benefits of reduced co-pollution until 2015 is coherent with this calibration. Second, the industrial decarbonization targets of 18% to 26% by 2030 under the EU Climate Action Plan, discussed in Section 2.1 above, are formulated in terms of 2015 emissions.

Across industrial emitters in our sample, carbon emissions fell by 15.4% during this period, driven by the cap-and-trade regulation for CO_2, the expansion of renewable energy supply, or economic factors such as the great recession. Moreover, air quality regulations that were introduced or enforced during this period may have had an impact on emissions, particularly those of co-pollutants. When assessing the public health impacts of those emissions changes, we want to distinguish between decarbonization and local pollution control. We get at this by computing not only the observed co-emissions reductions but also the predicted reductions that result from multiplying the observed changes in carbon emissions by with the co-emission ratio, defined as emissions of pollutant *p* per ton of CO_2 equivalent, held fixed at its initial value in 2008. This decomposition tells us to what extent the actual change in emissions is driven by CO_2 reductions vs. pollution control or other factors.

3.3.2 Naïve decarbonization scenarios

The second type of scenario maps a percentage reduction in CO_2 emissions for an industrial installation of a given type into a corresponding reduction in co-pollution which is governed by the installation-specific pollution intensities. This is isomorphic to a reduction in the economic activity level, multiplied by the average pollution intensity per unit of output or per ton of CO_2.

3.3.3 Detailed decarbonization scenarios

The third type of decarbonization scenario takes into consideration the specific technical decarbonization options that currently are - or may soon become - commercially viable in each industry. A straightforward example in steel production is to replace a blast furnace with an electric arc furnace powered by renewable electricity, which is expected to reduce CO_2 emissions and fossil-fuel related co-pollutants on site. In the fertilizer industry, different decarbonization scenarios will have very different implications for co-pollutant emissions, depending on whether grey hydrogen is replaced by blue hydrogen (where the CO_2 from cracking and energy feedstocks is captured and stored, but co-pollution is released) or green hydrogen (where no pollutants are being released).

Given the need to focus on industry specific cases, we investigate scenarios for the cement industry for several reasons. First, given the nature of the final product, outsourcing to non-European location is not a substitute for decarbonizing cement production in Europe.[12] Second, we have very good of this industry in our dataset. Third, cement offers the highest potential ancillary public health benefits of decarbonization, as we document below. Last, we can identify likely decarbonization options drawing on recent work by Glenk et al. (2023) which examines incremental abatement costs of various decarbonization options.

[12] In contrast, steel or fertilizer production could be outsourced to places with unlimited supply of carbon free electricity.

3.4 Health Co-Benefits of Recent Trends in Industrial Decarbonization

We start our analysis by looking at recent trends in carbon emissions and co-emissions by the three most emission intensive industries, cement, steel, and refining. The first two columns of Table 1 report emissions in 2008 and their absolute change by 2015, by industry. Carbon emissions from cement and steel production fell by about 17%, but just over 10% in refining. While co-emissions for CO and NH_3 followed a similar trend, reductions in NO_x and SO_x emissions were significantly larger, averaging 32% and 39%, respectively, across the three industries. This highlights the influence of direct regulations of air pollution over this period.

[Table 1 about here]

To isolate the part of observed reductions in pollution emissions that can be explained by carbon abatement, we report in column 3 the imputed change in co-emissions if the plant specific co-pollution intensity (mass per ton of CO_2 equivalent emitted) had remained at its 2008 level. This yields smaller reductions for NO_x and SO_x, in line with the more modest carbon abatement observed in this period. The difference between observed and imputed emissions can be attributed to factors other than carbon abatement, such as the installation of end-of-pipe pollution control equipment. For our counterfactual analysis, it will be important to not attribute such abatement efforts to decarbonization. In further columns, we provide estimates of the co-emissions changes when using plant specific pollution intensities for 2015 (column 4), or the median pollution intensity observed over the sample period (column 5). The latter provides a robustness test against outliers in reported pollution intensities, which could have large impacts on aggregate emissions. These measures lie between observed and imputed co-emissions reductions.

[Table 2 about here]

Table 2 reports the $PM_{2.5}$ related health damages associated with industrial emissions of the precursors NO_x, SO_x, and NH_3. Emissions reductions between 2008 and 2015 have avoided 1,715 premature deaths due to $PM_{2.5}$, most of which come from the cement and refining industries which contribute about 740 avoided deaths each. Our decomposition exercise attributes significant shares of that mortality reduction to factors other than carbon abatement. This is true in particular for refining where only 27% of avoided deaths can be explained by carbon abatement, whereas it is 50% and 65% in the cement and steel industries, respectively. The robust estimation of avoided deaths leads to a somewhat lower mortality reduction of 1,407 avoided deaths across sectors.

This provides some perspective on the ancillary health benefits that can be expected to arise from future decarbonization in those industries. As we have seen, cleaning up air pollution emissions has already provided significant benefits in terms of reducing $PM_{2.5}$ related mortality in Europe, which contrasts with relatively modest carbon abatement. This limits the potential for more ambitious industrial decarbonization strategies to deliver significant ancillary health benefits. The next section explores the potential magnitude of those ancillary benefits in more detail.

3.5 Health Co-Benefits of Future Decarbonization Options

To gauge the potential magnitude of ancillary health benefits arising from industrial decarbonization strategies, we assume a sweeping 80% emissions reductions across all pollutants. While such a scenario likely oversimplifies the relationship between abating carbon emissions vs. co-pollution emissions, it helps us understand which industries should be targeted, from a public health point-of-view, with decarbonization strategies that also reduce co-emissions of CO_2 (e.g., electrification). As we shall see below, this is not obvious from an inspection of co-emissions alone, as it depends critically on the location of the industrial plants which determines the human health impact due to heterogeneity with topography, atmospheric chemistry, and population density.

[Table 3 about here]

Table 3 reports, in Panel A, the magnitudes of an 80% cut in emissions by pollutant as well as the resulting impact on $PM_{2.5}$ related premature deaths, by industry and air pollutant. Panel B of Table 3 summarizes the total public health impact, in terms of avoided premature deaths due to $PM_{2.5}$, of this scenario, by industry.

The total potential health benefits associated with an 80% decarbonization amounts to 2,913 avoided deaths, two thirds of (1,870) are due to NO_x, just under one third to SO_x, and the rest to NH_3. It is enlightening to further decompose these numbers. Looking across industries, potential health co-benefits of an 80% decarbonization are largest in the cement industry (1,327 avoided deaths), followed by refining (957) and steel (629). This ranking is the same as ranking these industries by size, but this is not the only reason. Cement production in Europe is relatively more intensive in NO_x and NH_3 emissions than the other industries, both of which are more lethal than SO_x. Averaging impacts across plants and locations in our sample, the avoided premature deaths are 20.3 for one kiloton of NH_3, 4.9 for one kiloton of NO_x and only 2.5 for one kiloton of SO_x. Notwithstanding its relatively low marginal impact, SO_x emissions from refining are large enough to drive more than half of the total health impact of that pollutant.

Notice that, because of different locations, a kiloton of the same pollutant has different marginal health effects depending on the industry that emits it. For example, a kiloton of NO_x emitted by the cement or steel sectors causes more premature deaths (6.5 and 6.9, respectively) than when emitted by a European refinery (5.1). Similarly, reducing one kiloton of NH_3 in the cement (steel) sectors avoids 26.7 (23.8) premature deaths but only 19.0 in refining. The avoided deaths per kiloton of SO_x are 3.5 in cement, 3.7 in steel, and 2.8 in refining. The consistently lower social external damages of refinery pollution suggests that their location is more conducive to avoiding health impacts. Cleaning up steel and cement production offers higher marginal health benefits.

Given our interest in ancillary health benefits of decarbonization, it is instructive to relate these marginal benefits to carbon emissions. Abating one megaton of carbon emissions from the cement industry avoids 12.1 premature deaths compared to only 9.8 in refining and 8.9 in the steel industry. So not only does the cement industry offer the largest potential for reducing GHG process emissions, but it also provides the highest marginal ancillary health impacts due to its intensity in lethal co-pollutants in combination with unfavorable locations that lead to above-average marginal impacts of those co-pollutants. As we have seen, the clean-up of cement production in recent years has progressed faster than in the steel industry, but slower than in refining. For all these reasons, decarbonizing the cement industry offers a high promise of reaping ancillary benefits to public health. This warrants a more detailed investigation of technically and commercially viable decarbonization options for this industry.

3.6 Health Co-Benefits of Decarbonizing the Cement Industry

[slides]

4 Distributional analysis

[tbc]

5 Conclusion

[tbc]

6 References

Colmer, J., M. Muûls, R. Martin, and U. J. Wagner (2022). Does Pricing Carbon Mitigate Climate Change? Firm-Level Evidence from the European Union Emissions Trading Scheme, CEPR Discussion Paper No. 16982. https://cepr.org/publications/dp16982

de Preux, L., D. Kassem and U.J. Wagner (2022). Air Pollution Trading on the European Carbon Market. *Mimeograph*, University of Mannheim.

European Commission. (2020, September 17). COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people. (Report SWD/2020/176 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020SC0176&qid=1700007973943

Fennell, P.S., S.J. Davis, A. Mohammed (2021). Decarbonizing cement production. *Joule*, 5(6), 1305 – 1311.

Glenk, G., A. Kelnhofer, R. Meier, and S. Reichelstein (2023). Cost-efficient pathways to decarbonizing Portland cement production. *SFB Transregio 266 Working Paper No. 120*. University of Mannheim.

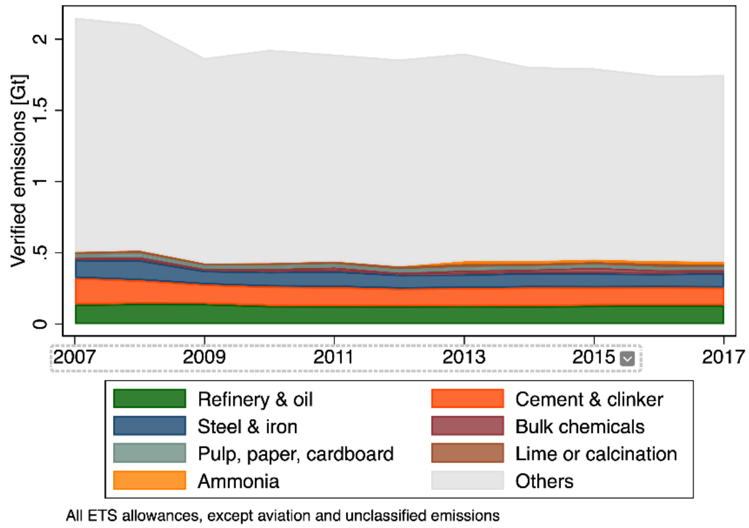
Gu, Y., D.K. Henze, M.O. Nawaz, C. Hansen, and U.J. Wagner (2023a). Sources of PM2.5-associated Health Risks in Europe and Corresponding Emission-induced Changes during 2005-2015. *GeoHealth*, 7(3): DOI: 10.1029/2022GH000767

Gu, Y., D.K. Henze, M.O. Nawaz, and U.J. Wagner (2023b) Response of the ozone-related health burden in Europe to changes in local anthropogenic emissions of ozone precursors. *Environmental Research Letters*. DOI: 10.1088/1748-9326/ad0167

Murray, C. J. L *et al.* (2020). Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, 396, 1223–1249.

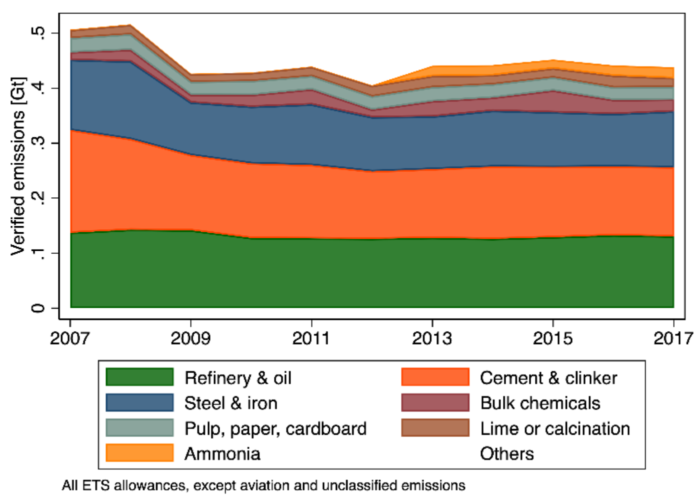
6.1 Tables and Figures

Figure 1: GHG Emissions by industry [in gigatons of CO_2 equivalent]



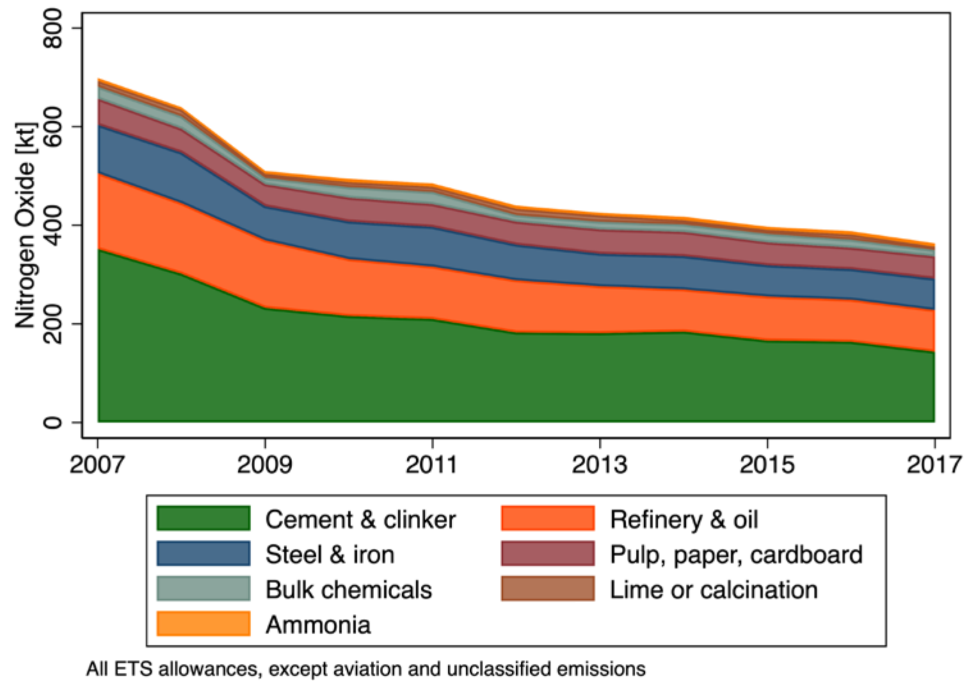
Notes: The figure displays trends in GHG emissions regulated under the EU ETS in gigatons of CO_2 equivalent. Increases in 2013 values for bulk chemicals and ammonia are due to regulatory changes at the beginning of trading phase III in 2013, which broadened the inclusion of greenhouse gas emissions from those sectors.

Figure 2: GHG Emissions by industry [in gigatons of CO_2 equivalent]



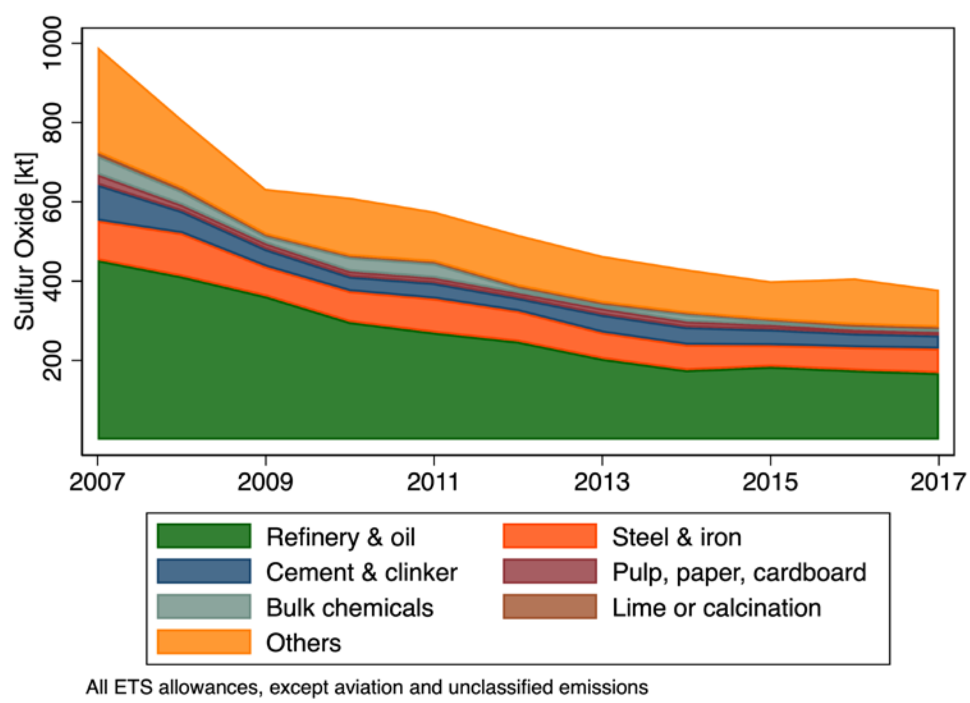
Notes: The figure displays trends in GHG emissions for the seven largest industrial processes (i.e., excluding combustion) regulated under the EU ETS in gigatons of CO_2 equivalent. Increases in 2013 values for bulk chemicals and ammonia are due to regulatory changes at the beginning of trading phase III in 2013, which broadened the inclusion of greenhouse gas emissions from those sectors.

Figure 3: NO_x emissions by industry [in kilotons]



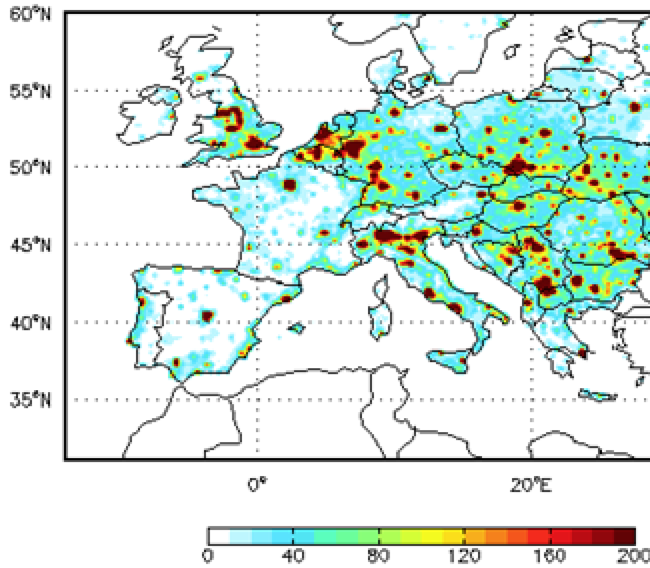
Notes: The figure displays trends in NOx emissions in tons, by industry, based on E-PRTR v.18 data.

Figure 4: SO_x emissions by industry [in kilotons]



Notes: The figure displays trends in SOx emissions in tons, by industry, based on E-PRTR v.18 data.

Figure 5: Premature deaths due to $PM_{2.5}$ in 2015



Source: Gu et al. (2023a).

Table 1: Carbon and co-pollutant emissions between 2008 and 2015 in selected industries

Pollutant	Industry	(1) Emissions in 2008	(2) Observed change 2008-15	(3) Imputed change with 2008 ratio	(4) Imputed change with 2015 ratio	(5) Imputed change, median
CO_2 [kt]	Cement	157,532	-27,382	N/A	N/A	N/A
	Steel	126,764	-22,490			
	Refining	132,750	-14,481			
	Total	**417,046**	**-64,352**			
NO_x [t]	Cement	302,637	-116,044	-64,796	-53,296	-54,423
	Steel	104,307	-23,149	-14,846	-24,645	-14,713
	Refining	144,498	-41,701	-11,887	-12,523	-14,605
	Total	**551,441**	**-180,893**	**-91,529**	**-90,464**	**-83,741**
SO_x [t]	Cement	66,110	-9,715	-1,194	-10,309	-5,220
	Steel	112,291	-34,689	-22,004	-21,687	-20,306
	Refining	414,242	-185,821	-24,517	-33,695	-39,308
	Total	**592,643**	**-230,225**	**-47,716**	**-65,691**	**-64,833**
CO [t]	Cement	467,440	-47,244	-59,747	-111,430	-72,771
	Steel	1,779,864	-376,866	-337,577	-878,075	-287,116
	Refining	3,611	-8,148	-5,553	-9,949	-3,825
	Total	**2,290,916**	**-432,258**	**-402,877**	**-999,454**	**-363,712**
NH_3 [t]	Cement	4,578	-695	-568	-888	-644
	Steel	492	-257	-144	-861	-305
	Refining	791	94	46	-307	-214
	Total	**5,861**	**-858**	**-666**	**-2,056**	**-1,162**

Notes: Only firms with non-missing observations in 2008 are included.

Table 2: Premature Deaths associated with $PM_{2.5}$ exposure due to NO_x, SO_2, and NH_3 emissions from selected industries, 2008-15.

	Premature deaths				
	(1)	(2)	(3)	(4)	(5)
Industry	Level based on 2008 emissions	Change based on observed emissions 2008-15	Change based on imputed emissions using 2008 ratio	Change based on imputed emissions using 2015 ratio	Change based on imputed using median ratio
Cement	2,205	-738	-370	-347	-335
Steel	946	-237	-156	-264	-163
Refining	1,889	-741	-205	-180	-198
Total	**5,040**	**-1,715**	**-732**	**-791**	**-696**

Table 3: Effect of an 80% decarbonization on emissions and public health, by industry

	Industry	(1) Level in 2015	(2) 80% reduction of emissions in 2015	(3) $PM_{2.5}$ related premature deaths
A. Emissions				
CO_2 emissions	Cement	136,696	109,357	-
	Steel	88,321	70,657	-
	Refining	122,068	97,654	-
	Total	**347,085**	**277,668**	**-**
NO_x emissions	Cement	196,658	157,326	-1021
	Steel	78,422	62,737	-430
	Refining	103,578	82,862	-419
	Total	**378,657**	**302,926**	**-1,870**
SO_x emissions	Cement	66,408	53,126	-186
	Steel	64,940	51,952	-192
	Refining	229,801	183,841	-521
	Total	**361,148**	**288,919**	**-899**
NH_3 emissions	Cement	5,608	4,486	-120
	Steel	368	294	-7
	Refining	1,121	896	-17
	Total	**7,096**	**5,677**	**-144**
B. Health				
Premature deaths associated with $PM_{2.5}$ exposure due to industrial emissions of NO_x, SO_2, and NH_3	Cement	1,659		-1,327
	Steel	786		-629
	Refining	1,196		-957
	Total	**3,641**		**-2,913**

Notes: Based on data from EPRTR v. 18 linked to EUTL data. Aggregates are computed using all ETS regulated facilities for the selected sectors that also report to EPRTR in 2015. Emissions of CO_2 are reported in kilotons, air pollution emissions are reported in tons. Panel A reports baseline emissions as well as predicted reductions in emissions and $PM_{2.5}$ related mortality for each industry and pollutant. Panel B reports the level of and changes in the total number of $PM_{2.5}$ related premature deaths in Europe that can be appointed to sources of NO_x, SO_2 and NH_3 emissions in our dataset, disaggregated by industry.

Table A1: Descriptive statistics based on 2015 data: Cement plants (excluding lime)

Variables	Facilities	Mean	Std Dev.	Min	Max	Units
GHGs						
CO_2	320	435.09	429.36	0.53	4,100.00	kt
CH_4	7	588.14	636.96	125.00	1,920.00	t
N_2O	58	28.66	37.10	10.10	263.00	t
HFCS	2	0.30	0.19	0.16	0.43	t
Co-Pollutants						
NO_x	272	723.01	606.35	101.00	4,120.00	t
SO_x	127	522.89	844.91	150.00	7,160.00	t
NH_3	170	32.99	31.32	10.15	227.00	t
PM_{10}	62	114.47	162.71	51.30	1,280.00	t
CO	203	2,510.13	7,968.12	506.00	91,600.00	t

Notes: Based on data from EPRTR v. 18 linked to EUTL data. Descriptives are computed using all ETS regulated facilities in the sector which also report to EPRTR in 2015. GHG emissions reported in kilotons, co-pollution emissions reported in tons.

Table A2: Descriptive statistics based on 2015 data: Petroleum refineries

Variables	Facilities	Mean	Std Dev.	Min	Max	Units
GHGs						
CO_2	120	1,039.95	1,042.66	0.11	6,590.00	kt
CH_4	23	346.24	476.98	102.00	2,090.00	t
N_2O	54	40.38	35.99	11.00	188.00	t
HFCS	22	0.31	0.26	0.10	0.97	t
Co-Pollutants						
NO_x	101	1,025.52	913.90	103.00	4,290.00	t
SO_x	102	2,252.95	2,037.67	157.00	11,000.00	t
NH_3	22	50.93	75.22	10.10	275.00	t
PM_{10}	52	105.38	59.07	50.90	319.00	t
CO	36	1,388.65	1,529.66	512.00	7,930.00	t

Notes: Based on data from EPRTR v. 18 linked to EUTL data. Descriptives are computed using all ETS regulated facilities in the sector which also report to EPRTR in 2015. GHG emissions reported in kilotons, co-pollution emissions reported in tons.

Table A3: Descriptive statistics based on 2015 data: Iron and steel plants

Variables	Facilities	Mean	Std Dev.	Min	Max	Units
GHGs						
CO_2	176	525.99	1,509.48	0.00	8,650.00	kt
CH_4	8	464.06	267.38	193.00	868.00	t
N_2O	10	85.95	111.21	10.90	361.00	t
HFCS	7	0.33	0.27	0.10	0.71	t
Co-Pollutants						
NO_x	115	681.93	1,400.94	101.00	6,650.00	t
SO_x	50	1,298.80	1,829.69	152.00	7,450.00	t
NH_3	9	40.89	23.00	17.70	84.10	t
PM_{10}	45	317.20	464.83	51.50	2,080.00	t
CO	94	13,013.30	30,099.92	508.00	133,000.00	t

Notes: Based on data from EPRTR v. 18 linked to EUTL data. Descriptives are computed using all ETS regulated facilities in the sector which also report to EPRTR in 2015. GHG emissions reported in kilotons, co-pollution emissions reported in tons.