Assessing the climate and health impacts of energy consumption in European Union countries

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(The paper is a non-peer reviewed preprint submitted to EarthArXiv)

Abstract

Burning fossil fuels for energy generation emits greenhouse gases (GHGs) that are the major driver of global climate change and its cascading health impacts. Combusting these fuels also generates air pollutants that pose an immediate health burden. Carbon and GHG emissions are routinely counted in climate policies and energy-efficiency standards and targets, yet the health burden of air pollution emission is rarely quantified. Here, we developed a modeling framework to estimate climate *and* health impacts of energy consumption in European Union (EU) countries. Our findings show that both climate and health impacts exhibit notable variations among EU countries depending on their energy source mix. For example, in Sweden the climate (0.5 €/MWh) and health (1.4 €/MWh) impacts of electricity consumption were significantly lower than the climate (15.3 €/MWh) and health (995 €/MWh) impacts in Bulgaria. In countries where coal or oil dominates energy supply, the health impacts can be larger than climate impacts by a factor greater than 10. For instance, Greece had 23.8 €/MWh in climate impacts and 654 €/MWh in health impacts. We also found that using fuel sources that can be "carbon neutral", like biomass, can yield dramatically different health impact results. For example, Estonia and Poland had comparable levels of climate impacts (32.4 and 28.4 €/MWh, respectively) due to their similar shares of solid fossil fuels and renewable energy for electricity production. However, the health impacts in Estonia (1508 €/MWh) were five times that in Poland (284 €/MWh), and one of the key reasons is the use of biomass in Estonia. Our results highlight the importance of quantifying health impacts when evaluating energy-efficiency and carbon-reduction measures and policies. Energy reports with biofuels lumped into renewables may overlook the potential health burden of combusting biofuels.

Keywords

Energy efficiency; air pollution; greenhouse gas; climate policy; renewable energy; biomass

1. Introduction

Developing energy-efficiency strategies across sectors such as buildings, transportation, and industry is a key step to combat energy, climate, and environmental challenges. Combusting fossil fuels for energy generation emits greenhouse gases (GHGs) that are the major driver of global climate change. The European Union (EU) has published the European Climate Law that EU countries must reduce GHG emissions by at least 55% by 2030 (compared to 1990 levels) and become climate neutral by 2050 [1]. Furthermore, burning fossil fuels generates air pollutants that pose an immediate public health burden. For example, the energy consumption in buildings was responsible for 44 % of emissions of PM_{10}, 58 % of $PM_{2.5}$, 37 % of black carbon, and 46 % of CO in the EU in 2020 [2]. Air pollution in the EU is associated with around 300,000 premature deaths and a significant number of diseases such as asthma, lung cancer, and cardiovascular problems annually [3].

GHG and carbon emissions are routinely assessed in climate policies and energy-efficiency standards and targets, yet the health burden of air pollution emission is rarely quantified [4-6]. This may lead to decisions that overlook potential public health impacts, such as the transition to energy sources with low carbon footprints but high air pollutant emissions, such as biofuels [7]. Nevertheless, there exists few studies and models that provide a holistic assessment of climate *and* health impacts of energy consumption in EU countries. Existing models such as Carbon Risk Real Estate Monitor (CRREM) [8] focus mainly on GHG emissions and do not include analysis for air pollution and health impacts. The Co-benefits of the Built Environment (CoBE) tool [9,10] estimates the GHG and air pollutant emissions as well as health and climate benefits of energy savings, but it focuses on the US. In this study, we present a modeling framework for quantifying the country-specific climate and health impacts of energy consumption in EU countries, called CoBE-EU. The model can be used to evaluate the potential climate and health benefits of energy-efficiency laws and policies, carbon reduction strategies, building and grid decarbonization efforts, and new climate mitigation focused technologies. This information can help incentivize and optimize energy efficiency and climate plans and policies. In this study, we first describe the development of CoBE-EU, and then demonstrate its application by evaluating the climate and health benefits of electricity savings in EU countries.

2. Methods

2.1 Estimating GHG and air pollutant emissions of energy consumption

We calculated the emissions of GHGs (CO_2, CH_4, and N_2O) and air pollutants ($PM_{2.5}$, SO_2, and NO_x) from energy consumption using the following equation:

$$Emissions_{source_i\,,\,pollutant_j\,,country_k} = Energy\ Use_{source_i\,,\,country_k} \times EF_{source_i\,,\,pollutant_j\,,\,country_k} \tag{1}$$

where $Emissions_{source_i\,,\,pollutant_j\,,\,country_k}$ is the emissions of pollutant j from energy source i in country k, $Energy\ Use_{source_i\,,\,country_k}$ is the energy consumption from energy source i in country k, and $EF_{source_i\,,\,pollutant_j\,,\,country_k}$ (emission factor) is the emissions of pollutant j per unit of energy use from source i in country k. For example, the energy use of buildings is mainly attributed to electricity consumption and on-site fuel combustion. To estimate pollutant EFs for grid electricity consumption, we first retrieved the EFs of CO_2 equivalent (CO_2e) for grid electricity production in all EU countries from the European Environment Agency (EEA) [11]. Using the grid EFs of CO_2e, the grid EFs of pollutants (CO_2, CH_4, N_2O, $PM_{2.5}$, SO_2, and NO_x) were estimated using the following equation [12]:

$$EF_{grid,\ \ pollutant\ j,\,country_k} = \frac{Emissions_{grid,\ \ pollutant\ j,\,country_k} \times \ \ EF_{grid,\,CO_2e,\,country_k}}{Emissions_{grid,\ \ CO_2e,\,country_k}} \tag{2}$$

where $Emissions_{grid,\ \ pollutant\ j,\,country_k}$ and $Emissions_{grid,\ \ CO_2e,\,country_k}$ are the annual emissions of pollutant j and CO_2e from electricity generation in country k, which were collected from the Emissions Database for Global Atmospheric Research (EDGAR) [13]. Note that the EF and emission data from EEA and EDGAR are both for year 2018 (the latest year that the air pollutant data are available in EDGAR). Next, we adjusted the EFs for electricity production to those for consumption using the country-specific data of power transmission and distribution losses provided by International Energy Agency (IEA) [14]. The calculation results of EFs for electricity consumption are summarized in Table S1.

For on-site fuel combustion, we retrieved the EFs of GHGs and air pollutants from IPCC Guidelines for National Greenhouse Gas Inventories [15] and EMEP/EEA Air Pollutant Emission Inventory Guidebook [16], respectively. As summarized in Tables S2 and S3, these EFs consider different fuel and building types, which are key factors influencing combustion emissions. Note that this dataset assumes typical combustion and emission control technologies, thus we applied it to all EU countries. The calculations of country-specific EFs require precise data on the efficiency and population of various combustion technologies across Europe, which are currently limited and need further research [16].

2.2 Assessing climate impacts of GHG emissions

We used the Social Cost of Carbon (SCC) to estimate the potential monetary impacts of climate change attributed to GHG emissions [17]:

$$Climate\ Impacts_{source_i\,,\,pollutant_j\,,country_k} = Emissions_{source_i\,,\,pollutant_j\,,country_k} \times SCC_{pollutant_j} \tag{3}$$

SCC is a widely used measure of damage caused by GHG emissions in a given year, including the impacts on agricultural productivity, climate-related public health, property damage, and energy system costs. The SCC values of CO_2, CH_4, and N_2O used in this study were estimated for 2018 (consistent with the year of emission data) at a 3 % discount rate, the central value of discount rates recommended by the U.S. Interagency Working Group on the Social Cost of Greenhouse Gases (IWG) [18,19]. For uncertainty analysis, the SCC values at discount rates of 2.5 % and 5 % were adopted for high and low estimates of climate impacts, respectively [18,20]. We then adjusted the SCC values to 2018 Euro considering inflation factor [21] and currency exchange rate [22]. Table S4 summarizes the SCC values used in this study.

2.3 Assessing health impacts of air pollutant emissions

We evaluated the health impacts of emissions of air pollutants ($PM_{2.5}$, SO_2, and NO_x) by considering premature mortality related to air pollution exposure as follows:

$$\begin{aligned} &Health\ Impact_{source_i\,,\,pollutant_j\,,country_k} \\ &= Emissions_{source_i\,,\,pollutant_j\,,country_k} \times \\ &\text{Deaths-per-ton of emissions}_{pollutant_j,country_k} \times \text{Value of Statistical Life} \end{aligned} \tag{4}$$

where $\text{Deaths-per-ton of emissions}_{pollutant_j,country_k}$ is the number of premature deaths associated with a metric ton of pollutant j emitted in country k. Country-specific data for this parameter in Europe are limited. Therefore, we estimated the *Deaths-per-ton of emissions* for EU countries based on the data provided in Zhang et al. [23]. Zhang et al. [23] calculated the annual worldwide premature deaths attributed to ambient $PM_{2.5}$ exposure resulting from primary $PM_{2.5}$ and the $PM_{2.5}$ precursors (e.g., SO_2 and NO_x) emitted in different countries. Their calculations were based on the chemical transport model GEOS-Chem [24], the Global Burden of Disease (GBD) Study [25], and the Integrated Exposure-Response (IER) model [26], with consideration of atmospheric pollutant transport, chemistry, meteorology, population distribution downwind, and local concentration-response functions. Next, we apportioned the relative contributions of air pollutant emissions examined in this study ($PM_{2.5}$, SO_2, and NO_x) to ambient $PM_{2.5}$ exposure according to Shindell [27]. Note that the data of Zhang et al. [23] are for the entire region of Western Europe and Eastern Europe, thus we applied the data to each EU country according to its region classification used in Zhang et al. [23]. Table S5 provides the estimates of *Deaths-per-ton of emissions* and Table S6 presents the region classification of EU countries. The uncertainty ranges shown in Table S5 were calculated based on 95 % confidence intervals of data provided in Zhang et al. [23]. The *Value of Statistical Life* (VSL) in Equation 4 is a commonly used metric to estimate the monetary benefits of mortality risk reductions for analysis of regulatory impact and public health policy [28]. We used a VSL of 9.75 million (in 2018 Euro) based on previous studies [20,28,29].

2.4 Inter-model comparisons

To facilitate comparisons across studies, we estimated the *Deaths-per-ton of emissions* for the US using the aforementioned method, and compared the results against three reduced complexity models (RCMs) that estimate the mortality attributed to air pollutant emissions in the US based on chemistry, fate, and transport mechanisms: (1) Estimating Air pollution Social Impact Using Regression (EASIUR), (2) Air Pollution Emission Experiments and Policy (AP2), and (3) Intervention Model for Air Pollution (InMAP) [10, 30-32]. As shown in Table S7, the estimates of our approach are within the uncertainty ranges predicted by RCMs. Furthermore, we applied our model to estimate the climate and health benefits of building energy savings due to green building movement in Germany and compared the results to a previous study [12]. The averages of our estimates, \$10.1 (3.0-15.2) million of climate benefits and \$22.4 (14.3-33.8) million of health benefits, are within the uncertainty ranges from the previous study [12] – \$5.3-26.4 million for climate and \$8.3-75.4 million for health. The maximums of our estimates are lower than that study likely because we used grid EFs for 2018, while they used the data for 2010. This is consistent with the EFs decreasing from 2010 to 2018 in Germany [11]. Additionally, the previous study [12] adopted a global-averaged *Deaths-per-ton of emissions*, while we used the data specifically for Western Europe.

3. Results and Discussion

Figure 1 presents the climate and health impacts per MWh of electricity consumption (€/MWh) in EU countries in 2018. The climate impacts varied from 0.5 to 32.4 €/MWh across the EU (Figure 1a). Estonia (32.4 €/MWh), Poland (28.4 €/MWh), Cyprus (23.9 €/MWh), and Greece (23.8 €/MWh) had the highest climate impacts. Sweden (0.5 €/MWh), France (2.0 €/MWh), Lithuania (2.3 €/MWh), and Luxembourg (2.5 €/MWh) had the lowest impacts. This notable regional variation was mainly attributed to the difference in energy source mix for electricity production among countries. Table S8 provides the energy mix for electricity generation in EU countries in 2018, which were collected from the Eurostat Energy Statistics [33]. The countries with high climate impacts generally have solid and/or liquid fossil fuels as dominant energy sources for power. For instance, in 2018, solid fossil fuels accounted for 76.2 % and 76.8 % of electricity production in Estonia and Poland, and liquid fossil fuels accounted for 90 % in Cyprus. By contrast, the countries with low climate impacts generally have significant shares of renewables and/or nuclear for power generation. In 2018, the combined contribution of renewables and nuclear to electricity generation was 97.8 %, 91.6 %, and 83.3 % in Sweden, France, and Lithuania, respectively.

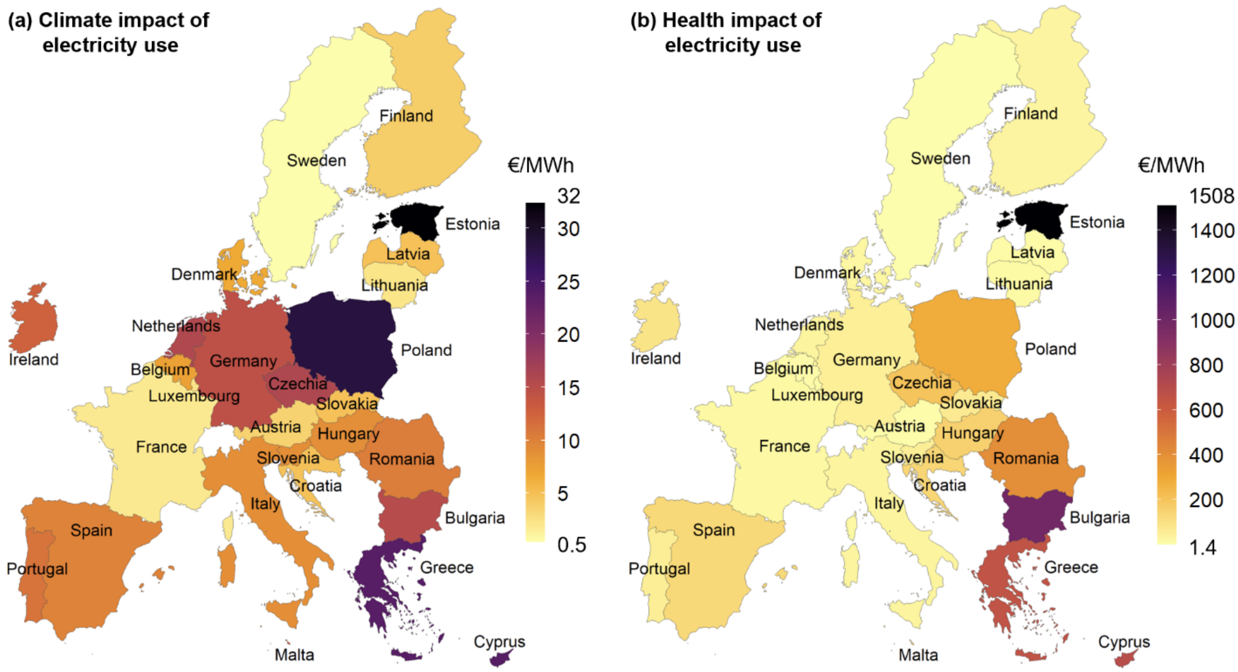

Figure 1. Climate and health impacts per MWh of electricity consumption across the EU in 2018.

The health impacts of electricity consumption varied from 1.4 to 1508 €/MWh across the EU (Figure 1b). Estonia (1508 €/MWh), Bulgaria (995 €/MWh), Cyprus (690 €/MWh), and Greece (654 €/MWh) had the highest health impacts. Sweden (1.4 €/MWh), Austria (7.2 €/MWh), and Belgium (10.5 €/MWh) had the lowest impacts. Table S9 provides a full dataset of climate and health impacts in EU countries with uncertainty ranges. The health impacts were generally higher than climate impacts among EU countries, with ratios of health to climate from 1.4 to 65. In countries where coal or oil dominated power supply such as Bulgaria, Estonia, and Greece, the health impacts were larger than climate impacts by a factor greater than 10. Moreover, the regional variation in health impacts was more dramatic than that in climate impacts. One of the main reasons is that for different energy sources, the variations in emission factors (EFs) of air pollutants are generally larger than those of GHGs [15,16]. For instance, natural gas has an EF of CO_2 about 50 % lower than coal, while its SO_2 EF can be two orders of magnitude lower. Also, hard coal and brown coal have comparable CO_2 EFs, whereas the SO_2 EFs of brown coal can be twice those of hard coal. Previous studies focused on the US also reported greater regional variations in health impacts of energy production than in climate impacts [10,29].

Furthermore, the climate impacts of energy consumption in a country do not necessarily scale with its health impacts. For example, Estonia and Poland had comparable levels of climate impacts (32.4 and 28.4 €/MWh, respectively) due to their similar shares of solid fossil fuels (76.2 % and 76.8 %) and renewable energy (16.1 % and 13.0 %) for electricity generation. Nevertheless, the health impacts in Estonia (1508 €/MWh) were five times that in Poland (284 €/MWh). One of the key reasons is due to their distinct disaggregated energy mix: 1) the major renewable energy used in Estonia was biofuels (65.7 % of renewable energy), which are considered carbon neutral but have considerable emissions of air pollutants, whereas the main renewable energy in Poland was wind (58.1 % of renewable energy) (see Table S10 that summarizes the shares of various renewable energy sources), and 2) the dominant solid fuel in Estonia was oil shale, which has an SO_2 EF twice that of hard coal, the dominant fuel in Poland [33]. Figure S1 depicts the emissions of various air pollutants per electricity consumption across the EU. There were much higher emissions of SO_2 and NO_x in Estonia than Poland, despite their comparable CO_2 emissions. Similarly, in Hungary the climate impacts were relatively low (9.0 €/MWh) due to its 60 % share of nuclear and renewable energy for power supply. However, their health impacts were much higher (155.6 €/MWh) largely due to their use of biomass (61.0 % of renewable energy) (see Table S10).

Figure 2 depicts the relative contributions of SO_2, $PM_{2.5}$, and NO_x to the health impacts across the EU in 2018. Unlike climate impacts (contributions of CO_2 were >94 % for all EU countries), health impacts were dominated by different air pollutants across countries. SO_2 was dominant for most EU countries (24 out of 27). Bulgaria, Greece, Hungary, Cyprus, Estonia, and Czechia had high SO_2 contributions above 80 %. These countries had brown coal or fuel oil as dominant fossil fuels for power generation [33]. Luxembourg and Latvia had NO_x as the dominant driver for health impacts, mainly due to their large shares of natural gas in fossil fuel usage [33]. The health impacts in Belgium were dominated by $PM_{2.5}$. It was likely attributed to their minimal usage of solid and liquid fossil fuels and relatively more use of biofuels [33]. These results are consistent with a previous study in the US, which reported that SO_2 drives the health impacts in regions where coal dominates the power generation, while NO_x drives where natural gas dominates [10].

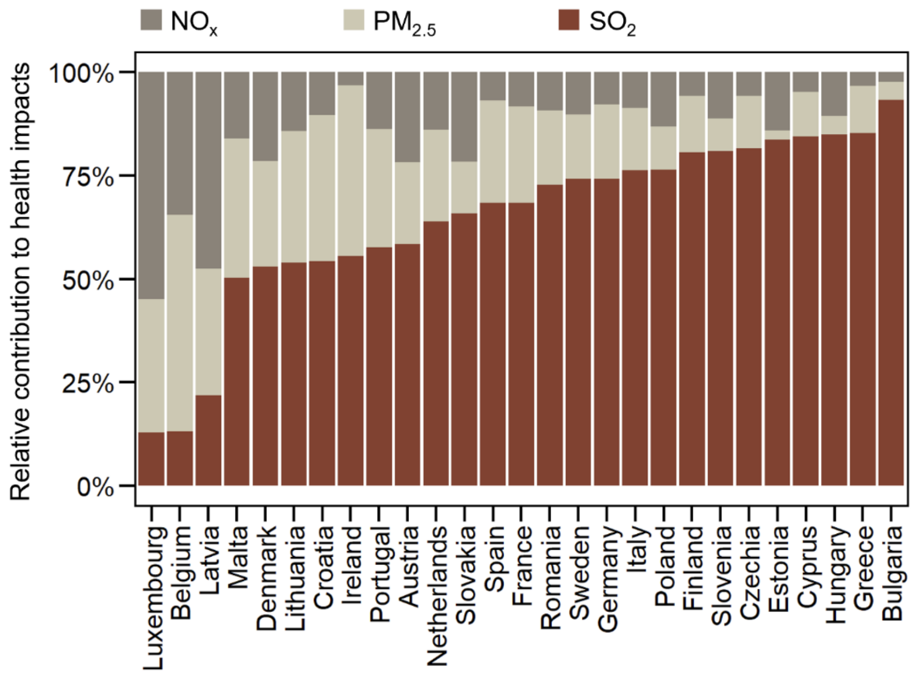

Figure 2. Relative contributions of SO_2, $PM_{2.5}$, and NO_x to the health impacts of electricity consumption across the EU in 2018.

In general, our results imply the necessity of incorporating health impacts when assessing energy efficiency and carbon reduction strategies. Detailed information of disaggregated energy sources is essential to predict the full impacts of energy consumption. Energy reports with biofuels lumped into renewables may overlook the potential health burden of combusting biofuels. Note that our discussion above was focused primarily on the effects of energy source mix on the health and climate impacts. There may be other factors such as the performance of pollutant control technologies in power plants [34]. For example, coal-fired power plants with different technologies can yield larger variations in emissions of air pollutants than in emissions of CO_2 [35], potentially contributing to a larger regional variation in health impacts than in climate impacts. However, the data of efficiency and population of power technologies across the EU are relatively limited. More surveys and research are warranted to explore this factor. Moreover, our estimates of health impacts were based on premature mortality associated with air pollution, yet morbidity outcomes were not included. Although previous studies in the U.S. found that mortality generally makes up more than 99 % of the monetized impacts of air pollution [36,37], our results of health impacts should be considered conservative. In addition, the emission data adopted in this study were for 2018 and should be regularly updated when more recent data become available. Also, our model is currently focused on the EU member states since there are relatively well-documented data for grid emission factors. We will extend our data libraries and include the estimates for non-EU countries in future work.

4. Implications

Our results show that both climate and health impacts of energy consumption exhibit notable variations among EU countries depending on their energy source mix. In countries relying on coal or oil for energy supply, the health impacts can be higher than climate impacts by a factor greater than 10 (e.g., Greece had 23.8 €/MWh in climate impacts and 654 €/MWh in health impacts). We also found that using fuel sources that can be "carbon neutral", such as biofuels, can lead to considerable health burden. For example, Estonia and Poland had comparable levels of climate impacts (32.4 and 28.4 €/MWh, respectively) due to their similar shares of solid fossil fuels and renewable energy for power supply. However, the health impacts in Estonia (1508 €/MWh) were five times that in Poland (284 €/MWh), and one of the key reasons is the use of biomass in Estonia. These results demonstrate the health impacts as a critical component of the assessment of energy efficiency and carbon reduction strategies and policies. Energy and climate plans should be formulated to minimize both carbon and air pollution emissions.

Acknowledgements

This work was supported by Login5 Foundation. We would like to acknowledge Anna Makido and Danielle von Rechenberg-Paulsson for their work on project coordination and communication.

References

1. European Union. (2021). European Climate Law. Accessed December 6, 2023, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119

2. European Environment Agency (EEA). (2022). Sources and emissions of air pollutants in Europe. Accessed December 6, 2023, https://www.eea.europa.eu/publications/air-quality-in-europe-2022/sources-and-emissions-of-air

3. European Commission. (2022). Directive of the European Parliament and of the Council on ambient air quality and cleaner air for Europe. Accessed December 6, 2023, https://eur-

lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A542%3AFIN

4. European Commission. (2022). REPowerEU at a glance. Accessed December 6, 2023, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en#saving-energy

5. European Commission. (2022). Nearly zero-energy buildings. Accessed December 6, 2023, https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-buildings_en

6. Maduta, C., Melica, G., D'Agostino, D., & Bertoldi, P. (2022). Towards a decarbonised building stock by 2050: The meaning and the role of zero emission buildings (ZEBs) in Europe. Energy Strategy Reviews, 44, 101009. https://doi.org/10.1016/j.esr.2022.101009

7. Buonocore, J. J., Salimifard, P., Michanowicz, D. R., & Allen, J. G. (2021). A decade of the US energy mix transitioning away from coal: historical reconstruction of the reductions in the public health burden of energy. *Environmental Research Letters*, *16*(5), 054030. https://doi.org/10.1088/1748-9326/abe74c

8. Carbon Risk Real Estate Monitor. Accessed December 6, 2023, https://www.crrem.eu/about-crrem/

9. Co-Benefits of the Built Environment (CoBE) tool. (2023). Accessed December 6, 2023, https://cobe.forhealth.org/

10. Salimifard, P., Rainbolt, M., Buonocore, J., Lahvis, M., Sousa, B., & Allen, J. G. (2023). A novel method for calculating the projected health and climate co-benefits of energy savings through 2050. *Building and Environment*, 110618. https://doi.org/10.1016/j.buildenv.2023.110618

11. European Environment Agency (EEA). (2021). Greenhouse gas emission intensity of electricity generation in Europe. Accessed December 6, 2023, https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment

12. MacNaughton, P., Cao, X., Buonocore, J., Cedeno-Laurent, J., Spengler, J., Bernstein, A., & Allen, J. (2018). Energy savings, emission reductions, and health co-benefits of the green building movement. *J. Expo. Sci. Environ. Epidemiol*, *28*(4), 307-318. https://doi.org/10.1038/s41370-017-0014-9

13. Emissions Database for Global Atmospheric Research (EDGAR). (2022). Accessed December 6, 2023, https://edgar.jrc.ec.europa.eu/emissions_data_and_maps

14. International Energy Agency (IEA). (2018). Electric power transmission and distribution losses. Accessed December 6, 2023, https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=EU&most_recent_year_desc=false

15. Intergovernmental Panel on Climate Change (IPCC). (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

16. European Environment Agency (EEA). (2019). EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019.

17. U.S. Environmental Protection Agency (EPA). (2016). The Social Cost of Carbon: Estimating the Benefits of Reducing Greenhouse Gas Emissions. Accessed December 6, 2023, https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html

18. Interagency Working Group on Social Cost of Greenhouse Gases (2016). Technical support document: technical update of the social cost of carbon for regulatory impact analysis under executive order 12866.

19. Interagency Working Group on Social Cost of Greenhouse Gases (2016). Addendum to Technical Support Document on Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866: Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide.

20. Salimifard, P., Buonocore, J. J., Konschnik, K., Azimi, P., VanRy, M., Laurent, J. G. C., ... & Allen, J. G. (2022). Climate policy impacts on building energy use, emissions, and health: New York City local law 97. *Energy*, *238*, 121879. https://doi.org/10.1016/j.energy.2021.121879

21. Inflation Calculator (2023). Accessed December 6, 2023, https://www.inflationtool.com/

22. Yearly average rates (2023). Accessed December 6, 2023, https://www.ofx.com/en-us/forex-news/historical-exchange-rates/yearly-average-rates/

23. Zhang, Q., Jiang, X., Tong, D., Davis, S. J., Zhao, H., Geng, G., ... & Guan, D. (2017). Transboundary health impacts of transported global air pollution and international trade. *Nature*, *543*(7647), 705-709. https://doi.org/10.1038/nature21712

24. Bey, I., Jacob, D. J., Yantosca, R. M., Logan, J. A., Field, B. D., Fiore, A. M., ... & Schultz, M. G. (2001). Global modeling of tropospheric chemistry with assimilated meteorology: Model description and evaluation. *Journal of Geophysical Research: Atmospheres*, *106*(D19), 23073-23095. https://doi.org/10.1029/2001JD000807

25. Lim, S. S., Vos, T., Flaxman, A. D., Danaei, G., Shibuya, K., Adair-Rohani, H., ... & Pelizzari, P. M. (2012). A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *The lancet*, *380*(9859), 2224-2260. https://doi.org/10.1016/S0140-6736(12)61766-8

26. Burnett, R. T., Pope III, C. A., Ezzati, M., Olives, C., Lim, S. S., Mehta, S., ... & Cohen, A. (2014). An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environmental health perspectives*, *122*(4), 397-403. https://doi.org/10.1289/ehp.1307049

27. Shindell, D. T. (2015). The social cost of atmospheric release. *Climatic Change*, *130*, 313-326. https://doi.org/10.1007/s10584-015-1343-0

28. Dockins, C., Maguire, K., Simon, N., & Sullivan, M. (2004). Value of statistical life analysis and environmental policy: A white paper. *US Environmental Protection Agency, National*

Center for Environmental Economics. https://doi.org/10.1017/CBO9781107415324.004

29. Buonocore, J. J., Hughes, E. J., Michanowicz, D. R., Heo, J., Allen, J. G., & Williams, A. (2019). Climate and health benefits of increasing renewable energy deployment in the United States. *Environmental Research Letters*, *14*(11), 114010. https://doi.org/10.1088/1748-9326/ab49bc

30. Gilmore, E. A., Heo, J., Muller, N. Z., Tessum, C. W., Hill, J. D., Marshall, J. D., & Adams, P. J. (2019). An inter-comparison of the social costs of air quality from reduced-complexity models. *Environmental Research Letters*, *14*(7), 074016. https://doi.org/10.1088/1748-9326/ab1ab5

31. Heo, J., Adams, P. J., & Gao, H. O. (2016). Reduced-form modeling of public health impacts of inorganic PM2. 5 and precursor emissions. *Atmospheric Environment*, *137*, 80-89. https://doi.org/10.1016/j.atmosenv.2016.04.026

32. Heo, J., Adams, P. J., & Gao, H. O. (2016). Public health costs of primary PM2. 5 and inorganic PM2. 5 precursor emissions in the United States. *Environmental science & technology*, *50*(11), 6061-6070. https://doi.org/10.1021/acs.est.5b06125

33. Eurostat Energy Statistics. (2022). Accessed December 6, 2023, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Primary_energy_production

34. Buonocore, J. J., Luckow, P., Norris, G., Spengler, J. D., Biewald, B., Fisher, J., & Levy, J. I. (2016). Health and climate benefits of different energy-efficiency and renewable energy choices. *Nature Climate Change*, *6*(1), 100-105. https://doi.org/10.1038/nclimate2771

35. International Energy Agency (IEA). (2012). Technology Roadmap-High-Efficiency, Low Emissions Coal-Fired Power Generation.

36. Buonocore, J. J., Reka, S., Yang, D., Chang, C., Roy, A., Thompson, T., ... & Arunachalam, S. (2023). Air pollution and health impacts of oil & gas production in the United States. *Environmental Research: Health*, *1*(2), 021006. https://dx.doi.org/10.1088/2752-5309/acc886

37. Buonocore, J. J., Lambert, K. F., Burtraw, D., Sekar, S., & Driscoll, C. T. (2016). An analysis of costs and health co-benefits for a US power plant carbon standard. *PloS one*, *11*(6), e0156308. https://doi.org/10.1371/journal.pone.0156308

Supporting Information

Table S1. Pollutant emission factors (g/kWh) for electricity consumption in the European Union (EU) countries.

Country	CO_2e	CO_2	CH_4	N_2O	$PM_{2.5}$	SO_2	NO_x
Austria	107.4	107.0	0.0060	0.0008	0.0011	0.0251	0.0889
Belgium	217.9	217.1	0.0150	0.0014	0.0043	0.0083	0.2061
Bulgaria	447.4	445.5	0.0049	0.0057	0.0307	8.2076	0.5882
Croatia	142.1	141.6	0.0058	0.0011	0.0355	0.6659	0.3527
Cyprus	698.9	697.7	0.0110	0.0034	0.0590	3.4907	1.8886
Czechia	468.4	461.5	0.0069	0.0226	0.0202	0.9861	0.6614
Denmark	198.9	197.7	0.0124	0.0033	0.0057	0.0892	0.3422
Estonia	947.4	944.9	0.0296	0.0056	0.0248	11.1532	5.1904
Finland	116.8	111.0	0.0043	0.0192	0.0037	0.1620	0.1089
France	56.8	56.5	0.0038	0.0008	0.0039	0.0871	0.0995
Germany	427.4	424.9	0.0115	0.0072	0.0075	0.2342	0.2322
Greece	696.8	694.3	0.0181	0.0071	0.0595	3.3439	1.2149
Hungary	264.2	263.3	0.0091	0.0022	0.0051	1.1674	0.4020
Ireland	371.6	370.3	0.0152	0.0030	0.0302	0.3070	0.1639
Italy	261.1	259.7	0.0117	0.0037	0.0042	0.1626	0.1754
Latvia	145.3	145.1	0.0040	0.0003	0.0029	0.0252	0.1515
Lithuania	68.4	68.2	0.0042	0.0005	0.0038	0.0782	0.0568
Luxembourg	72.6	72.0	0.0096	0.0012	0.0032	0.0097	0.3928
Malta	374.7	373.9	0.0262	0.0007	0.0376	0.4228	1.2823
Netherlands	464.2	462.5	0.0185	0.0042	0.0063	0.1386	0.2872
Poland	830.5	819.8	0.0100	0.0351	0.0218	1.9165	0.9049
Portugal	326.3	325.1	0.0081	0.0033	0.0127	0.1930	0.4373
Romania	306.3	305.3	0.0039	0.0030	0.0526	2.6061	0.9204
Slovakia	144.2	141.4	0.0026	0.0093	0.0061	0.3906	0.3539
Slovenia	261.1	259.9	0.0040	0.0035	0.0031	0.3879	0.1480
Spain	290.5	289.5	0.0074	0.0030	0.0254	0.5339	0.5132
Sweden	13.7	13.4	0.0017	0.0008	0.0002	0.0064	0.0084

Table S2. Pollutant emission factors (g/GJ) for on-site combustion in <u>residential buildings</u>.

Fuel		CO_2e	CO_2	CH_4	N_2O	$PM_{2.5}$	SO_2	NO_x
Hard Coal	Coking Coal	102547	94600	300	1.5	398	900	110
	Other Bituminous Coal	102547	94600	300	1.5	398	900	110
	Sub-Bituminous Coal	104047	96100	300	1.5	398	900	110
	Hard Coal: Patent Fuel	105447	97500	300	1.5	398	900	110

	Coke Oven Coke and Lignite Coke	114947	107000	300	1.5	398	900	110
	Gas Coke	114947	107000	300	1.5	398	900	110
	Coal Tar	88647	80700	300	1.5	398	900	110
Brown Coal	Lignite	108947	101000	300	1.5	398	900	110
	Oil Shale and Tar Sands	114947	107000	300	1.5	398	900	110
	Peat	113917	106000	300	1.4	398	900	110
	Brown Coal: Patent Fuel	105447	97500	300	1.5	398	900	110
Gaseous fuels	Natural Gas	56255	56100	5	0.1	1.2	0.3	51
	Natural Gas Liquids	64629	64200	10	0.6	1.2	0.3	51
	Liquefied Petroleum Gases	63255	63100	5	0.1	1.2	0.3	51
	Ethane	61755	61600	5	0.1	1.2	0.3	51
	Refinery Gas	57755	57600	5	0.1	1.2	0.3	51
	Gas Works Gas	44555	44400	5	0.1	1.2	0.3	51
	Coke Oven Gas	44555	44400	5	0.1	1.2	0.3	51
	Blast Furnace Gas	260155	260000	5	0.1	1.2	0.3	51
Heavy Fuel Oil	Residual Fuel Oil	77829	77400	10	0.6	1.9	70	51
	Orimulsion	77429	77000	10	0.6	1.9	70	51
	Crude Oil	73729	73300	10	0.6	1.9	70	51
	Bitumen	81129	80700	10	0.6	1.9	70	51
	Petroleum Coke	97929	97500	10	0.6	1.9	70	51
	Refinery Feedstocks	73729	73300	10	0.6	1.9	70	51
Light oil	Gas/Diesel Oil	74529	74100	10	0.6	1.9	70	51
	Jet Kerosene	71929	71500	10	0.6	1.9	70	51
	Other Kerosene	72329	71900	10	0.6	1.9	70	51
	Shale Oil	73729	73300	10	0.6	1.9	70	51
	Naphtha	73729	73300	10	0.6	1.9	70	51
Biomass	Wood / Wood Waste	120692	112000	300	4	740	11	50
	Charcoal	117298	112000	200	1	740	11	50

Table S3. Pollutant emission factors (g/GJ) for on-site combustion in commercial/institutional buildings.

Fuel		**CO_2e**	**CO_2**	**CH_4**	**N_2O**	**$PM_{2.5}$**	**SO_2**	**NO_x**
Hard Coal	Coking Coal	95297	94600	10	1.5	108	840	173
	Other Bituminous Coal	95297	94600	10	1.5	108	840	173
	Sub-Bituminous Coal	96797	96100	10	1.5	108	840	173
	Hard Coal: Patent Fuel	98197	97500	10	1.5	108	840	173
	Coke Oven Coke and Lignite Coke	107155	107000	5	0.1	108	840	173
	Gas Coke	107155	107000	5	0.1	108	840	173

	Coal Tar	81397	80700	10	1.5	108	840	173
Brown Coal	Lignite	101697	101000	10	1.5	108	840	173
	Oil Shale and Tar Sands	107697	107000	10	1.5	108	840	173
	Peat	106667	106000	10	1.4	108	840	173
	Brown Coal: Patent Fuel	98197	97500	10	1.5	108	840	173
Gaseous fuels	Natural Gas	56255	56100	5	0.1	0.78	0.67	74
	Natural Gas Liquids	64629	64200	10	0.6	0.78	0.67	74
	Liquefied Petroleum Gases	63255	63100	5	0.1	0.78	0.67	74
	Ethane	61755	61600	5	0.1	0.78	0.67	74
	Refinery Gas	57755	57600	5	0.1	0.78	0.67	74
	Gas Works Gas	44555	44400	5	0.1	0.78	0.67	74
	Coke Oven Gas	44555	44400	5	0.1	0.78	0.67	74
	Blast Furnace Gas	260155	260000	5	0.1	0.78	0.67	74
Heavy Fuel Oil	Residual Fuel Oil	77829	77400	10	0.6	18	94	306
	Orimulsion	77429	77000	10	0.6	18	94	306
	Crude Oil	73729	73300	10	0.6	18	94	306
	Bitumen	81129	80700	10	0.6	18	94	306
	Petroleum Coke	97929	97500	10	0.6	18	94	306
	Refinery Feedstocks	73729	73300	10	0.6	18	94	306
Light oil	Gas/Diesel Oil	74529	74100	10	0.6	18	94	306
	Jet Kerosene	71929	71500	10	0.6	18	94	306
	Other Kerosene	72329	71900	10	0.6	18	94	306
	Shale Oil	73729	73300	10	0.6	18	94	306
	Naphtha	73729	73300	10	0.6	18	94	306
Biomass	Wood / Wood Waste	120692	112000	300	4	160	11	91
	Charcoal	117298	112000	200	1	160	11	91

Table S4. Social Cost of Carbon (SCC) estimates in 2018 Euro per metric ton of emissions.

	Discount rate		
	5 %	**3 %**	**2.5 %**
CO_2	10	34	51
CH_4	436	940	1281
N_2O	3758	11957	17936

Table S5. Worldwide deaths per ton of pollutants emitted in Western Europe and Eastern Europe.

	$PM_{2.5}$			**SO_2**			**NO_x**		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Western Europe	0.1293	0.0588	0.2100	0.0171	0.0118	0.0253	0.0018	0.0011	0.0028

Eastern Europe	0.1412	0.0450	0.2625	0.0116	0.0063	0.0185	0.0042	0.0020	0.0062

Table S6. EU country classification for regions.

Region	**Country**
Western Europe	Austria
	Belgium
	Cyprus
	Czech Republic
	Denmark
	Finland
	France
	Germany
	Greece
	Italy
	Ireland
	Luxembourg
	Malta
	Netherlands
	Portugal
	Spain
	Sweden
Eastern Europe	Estonia
	Hungary
	Latvia
	Lithuania
	Poland
	Slovakia
	Slovenia
	Bulgaria
	Romania
	Croatia

Table S7. Deaths per ton of emissions in the US calculated in this study and by three reduced complexity models (RCMs).

			$PM_{2.5}$	**SO_2**	**NO_X**
This study		Mean	0.0632	0.0029	0.0004
		Max	0.1103	0.0037	0.0006
		Min	0.0341	0.0022	0.0003
RCMs (On-site Combustion)	AP2	Mean	0.0160	0.0071	0.0016
		Max	0.5296	0.1763	0.0159
		Min	0.0008	0.0011	-0.0011
	EASIUR	Mean	0.0346	0.0060	0.0024
		Max	0.4957	0.0270	0.0416

		Min	0.0018	0.0009	0.0000
	InMAP	Mean	0.0209	0.0060	0.0032
		Max	1.1813	0.0437	0.0248
		Min	0.0007	0.0002	0.0001
RCMs (Electricity)	AP2	Mean	N/A	0.0037	0.0003
		Max		0.0402	0.0007
		Min		0.0001	0.0001
	EASIUR	Mean		0.0040	0.0022
		Max		0.0411	0.0142
		Min		0.0001	0.0001
	InMAP	Mean		0.0029	0.0007
		Max		0.0291	0.0016
		Min		0.0001	0.0002

Table S8. Energy source mix for electricity production in the EU in 2018. The data were collected from the Eurostat Energy Statistics [33].

Country	Solid fossil fuels	Oil and petroleum products	Natural gas and manufactured gases	Nuclear	Renewables and biofuels	Others
Austria	2.6%	1.0%	17.1%	0.0%	78.2%	1.0%
Belgium	0.1%	0.2%	35.2%	38.4%	24.4%	1.7%
Bulgaria	39.9%	0.7%	4.3%	34.4%	20.6%	0.0%
Croatia	10.7%	0.5%	16.5%	0.0%	72.4%	0.0%
Cyprus	0.0%	90.6%	0.0%	0.0%	9.4%	0.0%
Czechia	46.9%	0.1%	7.0%	34.0%	11.9%	0.1%
Denmark	21.6%	0.9%	6.8%	0.0%	68.4%	2.3%
Estonia	76.2%	0.7%	6.2%	0.0%	16.1%	0.8%
Finland	13.2%	0.4%	7.1%	32.6%	45.9%	0.7%
France	1.4%	1.0%	5.7%	71.1%	20.5%	0.4%
Germany	35.7%	0.8%	14.8%	11.9%	35.7%	1.1%
Greece	32.3%	10.4%	26.4%	0.0%	30.3%	0.5%
Hungary	14.6%	0.3%	23.3%	49.3%	11.8%	0.7%
Ireland	13.6%	0.4%	51.4%	0.0%	33.5%	1.0%
Italy	9.8%	3.8%	45.3%	0.0%	40.2%	0.8%
Latvia	0.1%	0.0%	47.9%	0.0%	52.0%	0.0%
Lithuania	0.0%	4.0%	10.1%	0.0%	83.3%	2.6%
Luxembourg	0.0%	0.0%	8.9%	0.0%	87.6%	3.5%
Malta	0.0%	0.9%	88.9%	0.0%	10.1%	0.0%
Netherlands	24.2%	1.1%	53.2%	3.1%	16.6%	1.8%
Poland	76.8%	1.1%	8.9%	0.0%	13.0%	0.3%
Portugal	20.1%	1.9%	26.2%	0.0%	51.4%	0.4%
Romania	24.1%	0.9%	16.4%	17.5%	41.0%	0.0%

Slovakia	11.2%	1.7%	9.0%	55.3%	22.7%	0.1%
Slovenia	28.3%	0.1%	2.9%	35.4%	33.2%	0.1%
Spain	13.6%	5.3%	21.6%	20.3%	38.8%	0.4%
Sweden	0.4%	0.2%	0.7%	42.0%	55.8%	1.0%

Table S9. Climate and health impacts of electricity consumption in the EU in 2018 €/MWh (2020 $/MWh).

	Climate impacts			**Health impacts**		
	Mean	Min	Max	Mean	Min	Max
Austria	3.67 (3.20)	1.1	5.5	7.15 (6.24)	4.48	10.91
Belgium	7.45 (6.50)	2.24	11.17	10.48 (9.15)	5.66	16.57
Bulgaria	15.29 (13.35)	4.59	22.94	994.79 (868.38)	529.19	1594.83
Croatia	4.86 (4.24)	1.46	7.29	138.71 (121.08)	63.39	232.43
Cyprus	23.89 (20.85)	7.17	35.83	689.59 (601.96)	455.75	1033.55
Czechia	16.04 (14.00)	4.82	24.07	201.54 (175.93)	132.16	302.76
Denmark	6.80 (5.94)	2.04	10.2	28.04 (24.48)	17.19	42.98
Estonia	32.38 (28.27)	9.72	48.56	1508.37 (1316.69)	797.33	2389.39
Finland	4.03 (3.52)	1.21	6.04	33.53 (29.27)	21.9	50.43
France	1.94 (1.69)	0.58	2.91	21.20 (18.51)	13.33	32.21
Germany	14.61 (12.75)	4.39	21.92	52.58 (45.90)	33.74	79.48
Greece	23.82 (20.79)	7.15	35.73	653.95 (570.85)	431.93	980
Hungary	9.03 (7.88)	2.71	13.55	155.57 (135.80)	81.81	248.02
Ireland	12.70 (11.09)	3.81	19.05	92.10 (80.40)	54.38	141.98
Italy	8.93 (7.80)	2.68	13.39	35.52 (31.01)	23.01	53.56
Latvia	4.96 (4.33)	1.49	7.44	13.05 (11.39)	5.78	21.13
Lithuania	2.34 (2.04)	0.7	3.51	16.41 (14.32)	7.58	27.27
Luxembourg	2.48 (2.16)	0.75	3.73	12.56 (10.96)	7.17	19.69
Malta	12.81 (11.18)	3.85	19.21	140.42 (122.58)	83.97	216.32
Netherlands	15.87 (13.85)	4.76	23.8	36.16 (31.56)	22.67	55.04
Poland	28.44 (24.83)	8.54	42.65	283.89 (247.81)	144.96	456.29
Portugal	11.15 (9.73)	3.35	16.73	55.89 (48.79)	34.19	85.6
Romania	10.47 (9.14)	3.14	15.71	404.96 (353.50)	201.15	660.52
Slovakia	4.94 (4.31)	1.49	7.41	67.10 (58.57)	33.58	107.52
Slovenia	8.93 (7.80)	2.68	13.39	54.23 (47.34)	28.09	86.91
Spain	9.93 (8.67)	2.98	14.9	130.11 (113.58)	81.52	197.82
Sweden	0.47 (0.41)	0.14	0.7	1.45 (1.27)	0.93	2.18

Table S10. Percentage of renewable sources for entire renewable energy used for electricity production in the EU in 2018. The data were collected from the Eurostat Energy Statistics [33].

Country	**Biofuels**	**Hydro**	**Wind**	**Solar**	**Geothermal**	**Tide, Wave and Ocean**
Austria	9.19%	76.85%	11.24%	2.71%	0.00%	0.00%
Belgium	29.77%	7.18%	41.60%	21.45%	0.00%	0.00%

Bulgaria	16.29%	56.16%	13.65%	13.91%	0.00%	0.00%
Croatia	6.77%	78.91%	13.54%	0.76%	0.02%	0.00%
Cyprus	11.92%	0.00%	46.30%	41.78%	0.00%	0.00%
Czechia	46.09%	25.58%	5.82%	22.52%	0.00%	0.00%
Denmark	28.37%	0.07%	66.97%	4.59%	0.00%	0.00%
Estonia	65.72%	0.75%	31.98%	1.55%	0.00%	0.00%
Finland	40.17%	41.38%	18.17%	0.28%	0.00%	0.00%
France	7.04%	59.25%	24.04%	9.16%	0.11%	0.40%
Germany	22.25%	10.45%	48.17%	19.04%	0.08%	0.00%
Greece	1.94%	35.63%	38.97%	23.45%	0.00%	0.00%
Hungary	60.97%	5.89%	16.12%	16.70%	0.32%	0.00%
Ireland	8.12%	8.92%	82.74%	0.21%	0.00%	0.00%
Italy	16.49%	43.49%	15.26%	19.51%	5.26%	0.00%
Latvia	26.97%	69.50%	3.49%	0.04%	0.00%	0.00%
Lithuania	19.87%	35.11%	41.86%	3.17%	0.00%	0.00%
Luxembourg	11.27%	69.36%	13.21%	6.16%	0.00%	0.00%
Malta	4.50%	0.00%	0.03%	95.47%	0.00%	0.00%
Netherlands	24.21%	0.38%	55.80%	19.61%	0.00%	0.00%
Poland	29.72%	10.83%	58.08%	1.36%	0.00%	0.00%
Portugal	10.30%	44.48%	41.18%	3.28%	0.75%	0.00%
Romania	1.64%	67.96%	23.74%	6.65%	0.00%	0.00%
Slovakia	26.66%	63.64%	0.10%	9.60%	0.00%	0.00%
Slovenia	4.93%	90.25%	0.11%	4.70%	0.00%	0.00%
Spain	5.56%	34.60%	47.86%	11.98%	0.00%	0.00%
Sweden	13.06%	68.26%	18.23%	0.45%	0.00%	0.00%

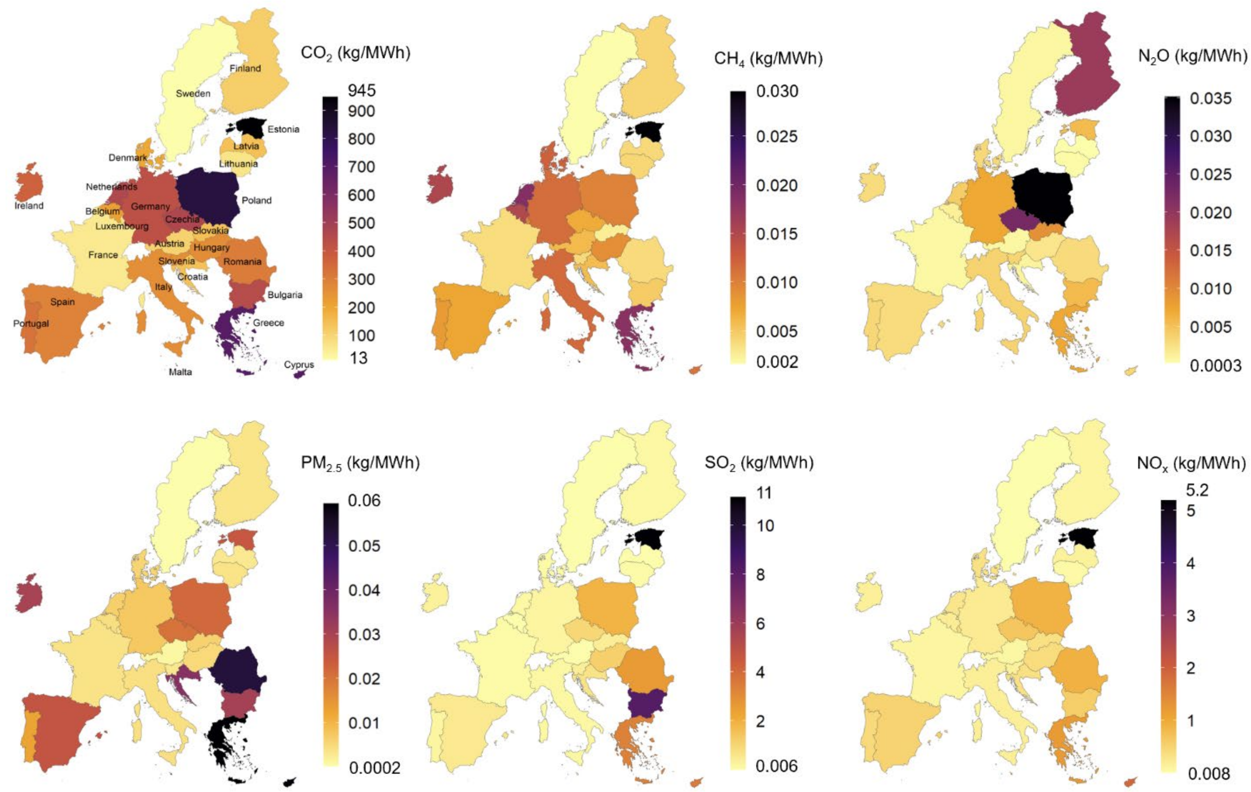

Figure S1. Emissions of various pollutants per MWh of electricity consumption across the EU in 2018.