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LETTER

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

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Abstract

Greenhouse gas emissions from burning fossil fuels are routinely counted in energy and climate policies, yet the immediate health burden of air pollution emissions from combusting these fuels is rarely quantified alongside. Particularly, the European Union (EU) comprises countries with diverse energy mixes, emission characteristics, reduction technologies, and policy frameworks, leading to large variations in the impacts of energy consumption on climate, air quality, and public health. Understanding these country-level variations is critical to optimize regional energy policies and reduce climate and health disparities in the EU. This study quantifies the regional variations in both climate and health impacts of energy consumption across EU countries. In countries where coal or oil dominates power supply, the health impacts of electricity consumption can be larger than climate impacts by more than ten times (e.g. Bulgaria, Romania, and Greece), highlighting the necessity of incorporating health impacts into climate and energy policies. We found a significant variability in health impacts per electricity usage (1.4–1508 € MWh^{-1}) among EU countries, largely driven by their energy source mix. The health benefits of sustainable energy strategies can be notably higher in Eastern Europe countries than those in Western or Northern Europe. For instance, saving the same amount of electricity in Estonia could achieve health benefits 1043 times greater than in Sweden. Furthermore, our results suggest that energy policies and reports with biomass lumped into renewables can overlook its potential health burden. The dataset of climate and health impact factors produced in this study can be useful for future research, practice, and policymaking to quantify the burdens of energy consumption or assess the benefits of energy efficiency measures in the EU.

1. Introduction

Combusting fossil fuels for energy generation emits greenhouse gases (GHGs) that are the major driver of global climate change. In response, 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 PM_{10}, 58% of $PM_{2.5}$, 37% of black carbon, 46% of CO, 17% of SO_2, and 9% of NO_x emissions 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 each year [3].

Therefore, developing energy efficiency strategies and policies across sectors such as buildings, transportation, and industry is a key step to combat pressing energy, climate, and environmental challenges in the EU. To meet the EU's 2030 climate goal, the EU published the Energy Efficiency Directive in 2012 and revised the directive a few times through 2012–2023 [4]. The latest directive requires EU countries to collectively achieve an additional 11.7% reduction in energy consumption by 2030, compared to the projected reference scenario in 2020. EU countries must achieve an average annual energy savings rate of 1.49% from 2024 to 2030. As a result, overall EU energy consumption in 2030 should not exceed 992.5 Mtoe for primary energy and 763 Mtoe for final energy [4]. In addition, the EU released guidelines focused on different critical sectors such as the Energy Performance of Buildings Directive [5] and Sustainable and Smart Mobility Strategy [6]. Achieving these goals will help the EU protect the environment, mitigate climate change, enhance energy security and affordability, and support the sustainable growth of economy [4].

While the Energy Efficiency Directive sets the EU-level guidelines and targets, it allows each member state to devise its own strategies and measures to meet these goals [4]. EU Member States have diverse energy mixes, emission source characteristics, emission reduction technologies, meteorological conditions, socioeconomic conditions, and policy frameworks. For example, the share of energy from renewable sources ranged from 14.4% to 66.4% across EU countries in 2023 [7]. The GHG emission intensity of electricity production varied significantly from 8–690 gCO_2e/kWh among EU countries in 2023 [8]. Knoop and Lechtenböhmer [9] reviewed studies on energy efficiency potentials in the EU and found large variations by country. Thonipara *et al* [10] reported that the impacts of regulatory standards of building energy performance may vary significantly in different EU countries. These data and findings suggest potential regional variations in the implications of energy consumption and energy efficiency measures on climate, air quality, and public health across the EU. It is imperative to capture these variations to optimize the benefits of regional energy policies and reduce climate and health disparities in the EU.

Furthermore, GHG emissions are routinely counted in energy and climate policies in the EU, yet the health burden of air pollution emissions is rarely quantified alongside [5, 11, 12]. This could lead to policy decisions that inadvertently overlook the health impacts of energy consumption, such as the transition to energy sources with low carbon footprints but high air pollutant emissions (e.g. biofuels) [13]. Therefore, it is critical to consider both climate and health impacts when assessing energy policies and practices. However, limited information is available on the regional variations in climate and health impacts of energy consumption among EU countries that could be used for guiding policy making and sustainability development. Given this background, the aim of this study is to provide a holistic assessment of climate and public health impacts of energy consumption across EU countries and characterize the country-level variability. The study results can be used to evaluate the climate and health burdens of energy consumption or to predict the co-benefits of energy efficiency strategies and policies in the EU with the consideration of disparities across 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:

$$\begin{aligned}\text{Emissions}_{\text{source}_i,\ \text{pollutant}_j,\text{country}_k} &= \text{Energy Use}_{\text{source}_i,\text{country}_k}\\ &\quad\times \text{EF}_{\text{source}_i,\ \text{pollutant}_j,\ \text{country}_k}\end{aligned} \tag{1}$$

where $\text{Emissions}_{\text{source}_i,\ \text{pollutant}_j,\ \text{country}_k}$ is the emissions of pollutant j from energy source i in country k, $\text{Energy Use}_{\text{source}_i,\text{country}_k}$ is the energy consumption from source i in country k, and $\text{EF}_{\text{source}_i,\ \text{pollutant}_j,\ \text{country}_k}$ emission factor (EF) is the emissions of pollutant j per unit of energy use from source i in country k. Grid electricity consumption is one of the most critical sources of energy use. To estimate EFs for electricity consumption at different EU countries, 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) [14]. We then collected emission data of CO_2e as well as pollutants (CO_2, CH_4, N_2O, $PM_{2.5}$, SO_2, and NO_x) from the Emissions Database for Global Atmospheric Research (EDGAR) [15]. Using these data, the EF of pollutant j for grid electricity generation in country k ($\text{EF}_{\text{grid, pollutant}\ j,\ \text{country}_k}$) was estimated using the following equation [16]:

$$\begin{aligned}\text{EF}_{\text{grid, pollutant}\ j,\ \text{country}_k} &= \text{Emissions}_{\text{grid, pollutant}\ j,\ \text{country}_k}\\ &\quad\times \frac{\text{EF}_{\text{grid},\ CO_2e,\ \text{country}_k}}{\text{Emissions}_{\text{grid},\ CO_2e,\ \text{country}_k}}\end{aligned} \tag{2}$$

where $\text{Emissions}_{\text{grid,pollutant}j,\ \text{country}_k}$ and $\text{Emissions}_{\text{grid},CO_2e,\text{country}_k}$ are the annual emissions of pollutant j and CO_2e, respectively, from electricity generation in country k. $\frac{\text{EF}_{\text{grid},CO_2e,\ \text{country}_k}}{\text{Emissions}_{\text{grid},CO_2e,\ \text{country}_k}}$ is the reciprocal of annual electricity generation responsible for pollutant emissions. Next, we adjusted the EFs for electricity generation to EFs for electricity consumption using the country-specific data of power transmission and distribution losses provided by

International Energy Agency [17]. The calculation results of EFs for electricity consumption are summarized in table 1 and figure S1. Regarding EFs for sectors other than electricity generation, such as building on-site combustion, we retrieved the EFs of different fuels from IPCC Guidelines for National Greenhouse Gas Inventories (for GHGs) [18] and EMEP/EEA air pollutant emission inventory guidebook (for air pollutants) [19]. For instance, tables S1 and S2 summarize the EFs for building on-site combustion based on fuel and building types.

2.2. Assessing climate and health impacts of emissions

We used the social cost of carbon (SCC) to estimate the potential monetary impacts of climate change attributed to GHG emissions from energy consumption [20, 21]. A detailed description of this method is provided in supplementary text S1. We evaluated the health impacts of air pollutant emissions based on the data provided in Zhang *et al* [22]. Zhang *et al* estimated the annual worldwide premature deaths attributed to the increase in ambient $PM_{2.5}$ exposure due to the air pollution emitted in Western Europe and Eastern Europe, respectively. However, the data reported in Zhang *et al* [22] were the overall death cases attributed to the emissions of six pollutants (black carbon, organic carbon, SO_2, NO_x, NH_3, and CO), and they did not report the death cases due to the emission of each pollutant. In order to apportion the relative contributions of air pollutants examined in this study ($PM_{2.5}$, SO_2, and NO_x), we referred to the study of Shindell [23] that reported the contributions of global emissions of $PM_{2.5}$ (black carbon and organic carbon), SO_2, and NO_x to ambient $PM_{2.5}$ concentrations, which were 37.5%, 37%, and 8%, respectively. Accordingly, we estimated the worldwide death cases due to a metric ton of pollutant$_j$ emitted in region$_z$ (Western Europe or Eastern Europe), $\text{Deaths-per-ton of emissions}_{\text{pollutant}_j,\ \text{region}_z}$, as follows:

$$\text{Deaths-per-ton of emissions}_{\text{pollutant}_j,\ \text{region}_z} = \frac{\text{Total death cases due to pollution emissions}_{\text{region}_z} \times \text{Relative contribution}_{\text{pollutant}_j}}{\text{Emissions}_{\text{pollutant}_j,\ \text{region}_z}}. \quad (3)$$

The data of overall death cases due to air pollution emitted in region$_z$, $\text{Total death cases due to pollution emissions}_{\text{region}_z}$, and the emissions of pollutant j in region$_z$, $\text{Emissions}_{\text{pollutant}_j,\text{region}_z}$, were collected from Zhang *et al* [22], while the data of relative contribution of pollutant$_j$ to ambient $PM_{2.5}$ exposure, $\text{Relative contribution}_{\text{pollutant}_j}$, were culled from Shindell [23], as discussed above. Table 2 provides the estimates of Deaths-per-ton of emissions. The uncertainty ranges were calculated based on 95% confidence intervals of data provided in Zhang *et al* [22]. Table S4 and figure S2 present the EU countries classified into Western Europe or Eastern Europe according to the Global Trade Analysis Project (GTAP), as suggested in Zhang *et al* [22].

Next, we quantified the monetary health impacts of emissions of pollutant j from energy source i in country k ($\text{Health Impact}_{\text{source}_i,\ \text{pollutant}_j,\ \text{country}_k}$) as follows:

$$\begin{aligned}
&\text{Health Impact}_{\text{source}_i,\ \text{pollutant}_j,\ \text{country}_k}\\
&\quad = \text{Emissions}_{\text{source}_i,\ \text{pollutant}_j,\ \text{country}_k}\\
&\qquad \times \text{Deaths-per-ton of emissions}_{\text{pollutant}_j,\ \text{region}_z}\\
&\qquad \times \text{Value of Statistical Life} \qquad (4)
\end{aligned}$$

where $\text{Emissions}_{\text{source}_i,\ \text{pollutant}j,\ \text{country}_k}$ are the annual emissions of pollutant *j* from energy source *i* in country *k*. The Value of Statistical Life (VSL) is a commonly used metric to estimate the monetary benefits of mortality risk reductions for analysis of regulatory impact and public health policy [24]. We used a VSL of 9.75 million (in 2018 Euro) based on previous studies [21, 25, 26].

To facilitate comparisons across studies, we applied our model to estimate the climate and health benefits of electricity savings due to the green building movement in Germany and compared the results to a previous study of MacNaughton *et al* [16]. As reported in MacNaughton *et al*, the total electricity savings from the green building movement in Germany was estimated as 0.51 billion kWh. By using our model, the climate benefit of this energy saving was estimated as \$10.1 (3.0–15.2) million, and the health benefit was \$22.4 (14.3–33.8) million. These estimates are within the uncertainty ranges reported by MacNaughton *et al* [16] that are \$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 grid EFs decreasing from 2010 to 2018 in Germany [14]. Additionally, the

Table 1. Pollutant emission factors (g kWh^{-1}) for electricity consumption in European Union (EU) countries.

Country	CO_2e	CO_2	CH_4	N_2O	$PM_{2.5}$	SO_2	NO_x
Mean of EU	323.0	321.1	0.0098	0.0056	0.0174	1.3629	0.6360
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	11.153	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 2. Worldwide death cases due to a metric ton of pollutants emitted in Western Europe and Eastern Europe (deaths/ton). The country classification is according to the Global Trade Analysis Project (GTAP). CI: confidence intervals.

	$PM_{2.5}$		SO_2		NO_x	
	Mean	95% CI	Mean	95% CI	Mean	95% CI
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

previous study [16] adopted a global-averaged value of 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^{-1}), i.e. impact factors, across EU countries in 2018. There were notable regional variations in both climate and health impact factors. The climate impact factors varied from 0.5 to 32.4 € MWh^{-1} across the EU (figure 1(a)). Estonia (32.4 € MWh^{-1}), Poland (28.4 € MWh^{-1}), Cyprus (23.9 € MWh^{-1}), and Greece (23.8 € MWh^{-1}) had the highest climate impact factors. Sweden (0.5 € MWh^{-1}), France (2.0 € MWh^{-1}), Lithuania (2.3 € MWh^{-1}), and Luxembourg (2.5 € MWh^{-1}) had the lowest impact factors. The health impacts per electricity consumption varied from 1.4 to 1508 € MWh^{-1} (figure 1(b)). Estonia (1508 € MWh^{-1}), Bulgaria (995 € MWh^{-1}), Cyprus (690 € MWh^{-1}), and Greece (654 € MWh^{-1}) had the highest health impact factors, while Sweden (1.4 € MWh^{-1}), Austria (7.2 € MWh^{-1}), and Belgium (10.5 € MWh^{-1}) had the lowest impact factors. One of the main drivers behind these large variations was the difference in energy source mix for electricity production among countries. Figure S3 and table S5 provide the energy mix for electricity generation in EU countries in 2018 [7]. The countries with high climate and health impact factors generally had 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 impact factors generally had significant shares of renewables and/or nuclear for power generation. For example, in 2018, the combined contribution of renewables and nuclear to electricity generation was 97.8%, 91.6%, 83.3%, and 78% in Sweden, France, Lithuania, and Austria, respectively.

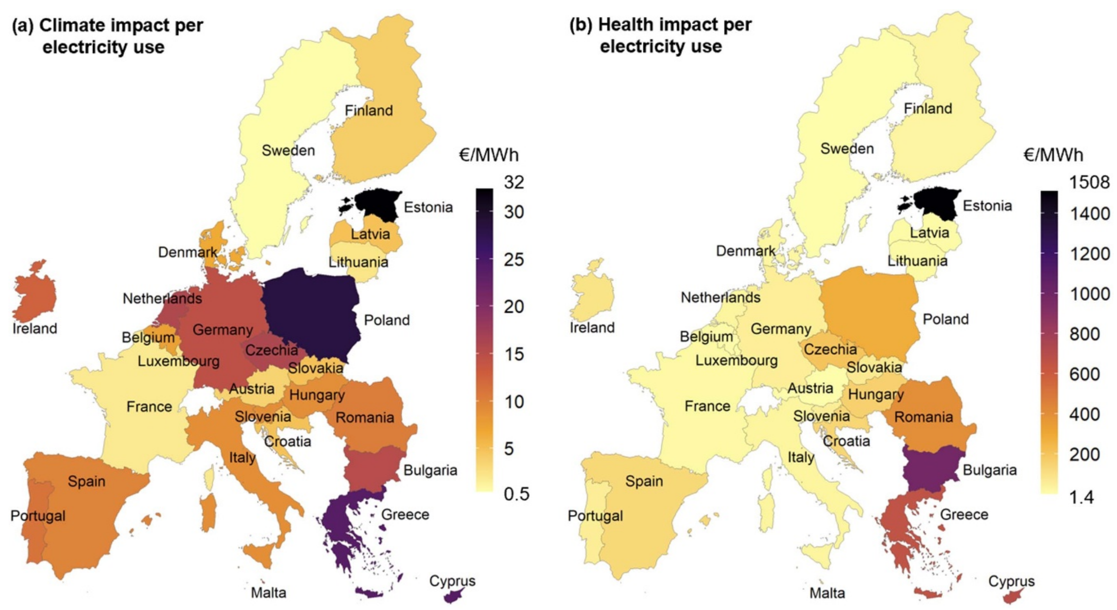

Figure 1. Climate and health impacts per MWh of electricity consumption across the EU in 2018. Note that non-EU countries in 2018 such as Switzerland, Norway, and the United Kingdom are not included.

Moreover, the health impact factor in a country can be significantly higher than its climate impact factor, with ratios of health to climate from 1.4 to 65 (table 3 provides a full dataset of climate and health impact factors in EU countries). In countries where coal or oil dominated power supply such as Bulgaria (health/climate ratio = 65), Estonia (health/climate = 47), Romania (health/climate = 39), Cyprus (health/climate = 29), Greece (health/climate = 27), and Czechia (health/climate = 13), the health impact factor can be larger than climate impact factor by a factor greater than 10.

Furthermore, figure 1 reveals that the regional variation in health impact factor was more dramatic than that in climate impact factor (1.4–1508 vs 0.5–32.4 € MWh^{-1}). One of the main reasons is that for different fuels, the variations in EFs of air pollutants are generally larger than those of GHGs [18, 19]. 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 [18, 19]. Besides energy source mix, the performance of pollutant control technologies in power plants is another key factor [27]. For example, coal-fired power plants with different technologies yield larger variations in emissions of air pollutants than in emissions of CO_2, since emissions of NO_x, SO_2, and $PM_{2.5}$ are driven in large part by the quality and chemical makeup of the coal, efficiency of combustion, and use of pollution control devices [28]. This factor was incorporated in our model by applying country-specific grid EFs. Moreover, the fact that GHGs have their impacts mixed globally while air pollutants have impacts regionally also contributes to a larger regional variation in health impacts than in climate impacts [26]. This factor was accounted for in our model by using global SCC of GHG emissions while region-specific values of deaths/ton of air pollutant emissions. Previous studies also reported greater regional variations in health impacts of energy production than in climate impacts in the US [25, 26] and worldwide [29]. Overall, these results demonstrate the necessity of incorporating the immediate health burden of air pollution emissions when developing energy and climate policies to understand their full impacts. The policies should be formulated to minimize both carbon and air pollution emissions.

Figure 2 displays the climate and health impacts per electricity consumption in the EU, with the countries grouped into four sub-regions (Eastern, Northern, Southern, and Western Europe) based on their geographical locations [30]. Note that this country classification is different from that in our calculations of Deaths-per-ton of emissions (table 2), which classified all EU countries into Western and Eastern Europe based on the GTAP [22]. The figure shows clear geographic patterns in climate and health impact factors of electricity use in the EU. In comparison with other regions, there were more countries in Eastern Europe that had markedly high health and climate impact factors, including Estonia, Bulgaria, Romania, Poland, and Czechia. The countries in Southern Europe exhibited two distinct patterns: the Southeastern countries (Greece and Cyprus) had noticeably high impact factors, while others (e.g. Italy and Portugal) had relatively low impact factors. The countries in Northern Europe (Sweden, Finland, and Denmark) had low climate and health impact factors due to their development of renewable and nuclear

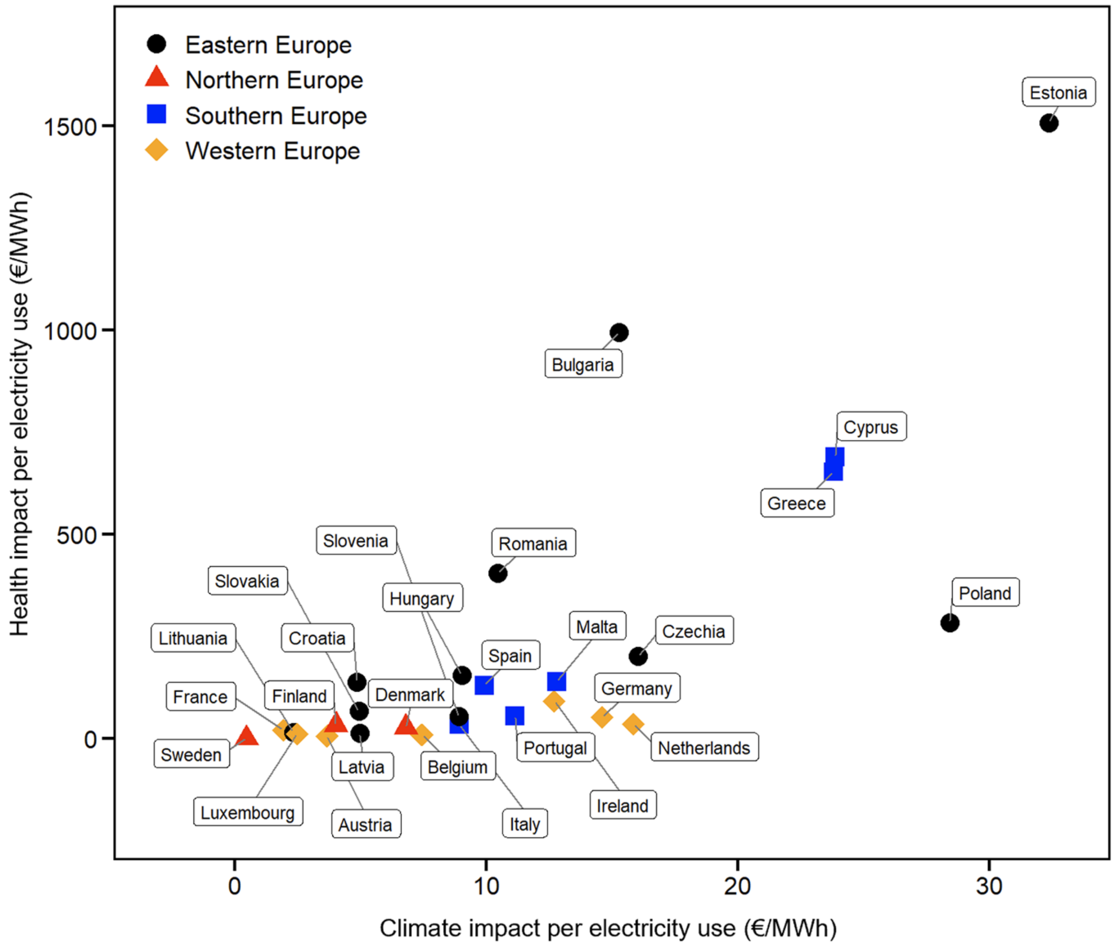

Figure 2. Climate impact vs. health impact per MWh of electricity consumption in EU countries in 2018. The countries are grouped into four sub-regions according to [30].

energy. The countries in Western Europe also had relatively low health impact factors, whereas a few of them (Netherlands, Germany, Ireland) had relatively high climate impact factors. This was primarily due to their reliance on coal and natural gas for power production (figure S3). These results imply that deploying sustainable energy strategies in regions with more fossil fuel usage (e.g. Eastern Europe and Southeastern Europe) could yield higher health and climate benefits than in areas that already had high levels of renewables (e.g. Western Europe and Northern Europe). For example, saving the same amount of electricity in Estonia could achieve 1043 times more health benefits and 67 times more climate benefits than in Sweden.

Furthermore, figure 2 indicates that the health impact factor of electricity consumption in a country does not necessarily scale with its climate impact factor. For example, Estonia and Poland had comparable levels of climate impact factors (32.4 and 28.4 € MWh^{-1}, 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 impact factor in Estonia (1508 € MWh^{-1}) was five times that in Poland (284 € MWh^{-1}). One of the key reasons was the use of biofuels in Estonia. Figure S4 and table S6 summarize the shares of different renewable energy sources for power production in the EU countries. 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 and associated health impacts [13], whereas the main renewable energy in Poland was wind (58.1% of renewable energy). Another reason is that 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, despite their comparable CO_2 EFs [7]. Similarly, in Hungary the climate impact factor was relatively low (9.0 € MWh^{-1}) due to its 60% share of nuclear and renewable energy for power supply. However, its health impact factor was much higher (155.6 € MWh^{-1}), largely due to its use of biomass (accounting for 61.0% of renewable energy). These results suggest that detailed information on disaggregated energy sources is essential to understand the full impacts of energy consumption. Energy reports with biofuels lumped into renewables may overlook the potential health burden of air pollution from combusting biofuels.

The climate and health impact factors described in figures 1 and 2 (and summarized in table 3) are useful to quantify the climate and health burdens of electricity consumption or to predict the benefits of energy saving methods in EU countries. As a demonstration, we calculated the total climate and health impacts (in billion €) due to electricity usage in EU countries in 2018, as presented in figure 3. It shows that the health burden of electricity usage in EU countries could be significantly higher than the climate impact. Poland, Germany, Greece, Spain, and Bulgaria had the largest impacts of electricity use. These countries had either large climate and health impact factors (e.g. Greece and Bulgaria), high levels of electricity usage (e.g. Germany and Spain), or both (e.g. Poland). For example, electricity usage in Germany (521.8 TWh) was one order of magnitude higher than that in Greece (51.1 TWh). However, Greece and Germany had similar levels of total burden of electricity use (34.63 vs. 35.06 billion €) since Greece had a health impact factor (654 € MWh^{-1}) that was one order of magnitude larger than that in Germany (52.6 € MWh^{-1}). Therefore, EU policies should be developed considering the regional variations in both total energy consumption and impact factors. Table 3 summarizes electricity usage and related climate and health burdens in EU countries in 2018.

Figure 4 displays 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). There were two main reasons. Firstly, in most EU countries, SO_2 EFs of electricity consumption were one to two orders of magnitude larger than $PM_{2.5}$ EFs, as shown in table 1. The average ratio of SO_2 EF to $PM_{2.5}$ EF across all countries was 78. In countries with SO_2 contributions above 80% such as Bulgaria, Estonia, and Hungary, the ratio of SO_2 EF to $PM_{2.5}$ EF can be larger than 200. Secondly, although the differences between SO_2 EFs and NO_x EFs were less dramatic (average ratio of SO_2 EF to NO_x EF = 2.14), the Deaths-per-ton of emissions value of SO_2 was 10 and 3 times higher than that of NO_x in Western and Eastern Europe, respectively. Consequently, SO_2 dominated health impacts in most EU countries. 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 [7]. 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 [7]. 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 [26]. Overall, this pattern of dominant air pollutants should be considered to develop effective air pollution reduction plans in the EU.

There are a few limitations of this study. Firstly, our estimates of health impacts were based on premature mortality associated with air pollution, yet morbidity outcomes, such as asthma, stroke, heart attack, and hospitalizations 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 [31, 32], our results of health impacts should be considered conservative. In addition, we only considered the $PM_{2.5}$-related impacts of SO_2, $PM_{2.5}$, and NO_x emissions from energy production. Ozone-related health outcomes and other air pollutant emissions, such as volatile organic compounds, NH_3, and CO, were not included due to lack of related data, which may lead to underestimation of the health impacts [33]. Secondly, our model is currently focused on the EU member states since there are relatively well-documented data for grid EFs. We will extend our data libraries and include the estimates for non-EU countries in future work. Thirdly, the EF data from EEA and the emission data from EDGAR are both for year 2018 (the latest year that the air pollutant data are available in EDGAR). The results should be updated when more recent data become available. Fourthly, we did not include the impact of international trade of electricity when calculating EFs of electricity consumption. In practice, imported electricity of a country was included in the country's electricity consumption but its related emissions were not included in the country's emission profiles. Emissions associated with the exported electricity of a country, on the other hand, were allocated to the emissions of the country, although the exported electricity was not included in the country's electricity consumption. Therefore, countries with net electricity exports were likely to have overestimated EFs of electricity consumption, while those with net imports might have underestimated EFs [34]. However, accurately incorporating this factor would require detailed information about electricity trade among countries around the world and EF inventories of GHGs and air pollutants for all countries involved, which is currently limited. Future work is warranted to include this factor and better understand its influence. Fifth, we adopted data in two separate studies [22, 23] with different years and inputs to calculate Deaths-per-ton of emissions due to unavailability of more consistent data. Particularly, Shindell [23] reported global-average values of relative contributions of different air pollutants to ambient $PM_{2.5}$ concentrations. However, the relative contributions of pollutants may vary by region because of local meteorological conditions, geographical and

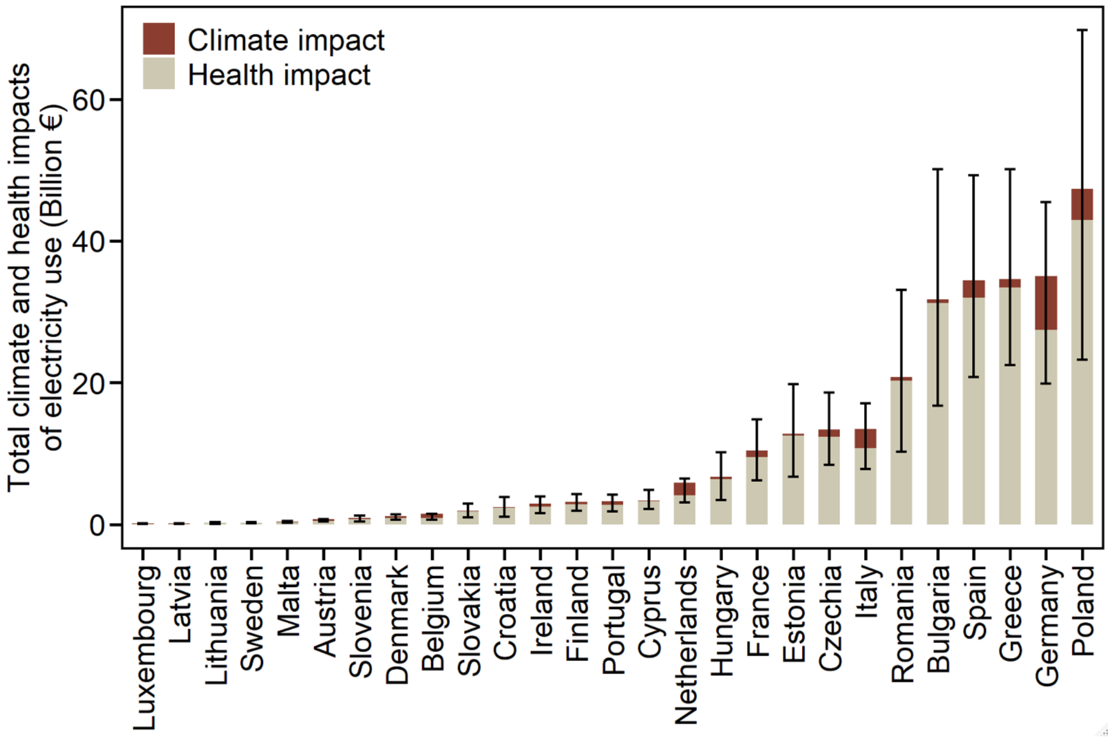

Figure 3. Total climate and health impacts (in billion €) of electricity consumption in EU countries in 2018. The error bars are calculated based on the uncertainty ranges of climate and health impact factors.

Table 3. Summary of climate and health impact factors of electricity consumption (in 2018 € MWh^{-1}), total electricity consumption (collected from the Eurostat Energy Statistics [7]), and total climate and health impacts due to electricity use in EU countries in 2018. For the climate impact factor, the reported values are at a 3% discount rate and the uncertainty ranges are based on discount rates from 2.5% to 5%. For the health impact factor, the reported values are means and the uncertainty ranges are 95% confidence intervals.

Country	Climate impact factor (€ MWh^{-1})	Health impact factor (€ MWh^{-1})	Electricity use (TWh)	Climate impact (Billion €)	Health impact (Billion €)
Mean of EU	11.0 (3.32–16.6)	216 (123–339)	96.0	0.98	9.71
Austria	3.67 (1.10–5.50)	7.15 (4.48–11.0)	65.9	0.24	0.47
Belgium	7.45 (2.24–11.2)	10.5 (5.66–16.6)	84.2	0.63	0.88
Bulgaria	15.3 (4.59–23.0)	994 (529–1594)	31.4	0.48	31.23
Croatia	4.86 (1.46–7.29)	139 (63.4–232)	16.6	0.08	2.31
Cyprus	23.9 (7.17–35.8)	690 (456–1034)	4.7	0.11	3.22
Czechia	16.0 (4.82–24.1)	202 (132–303)	61.3	0.98	12.36
Denmark	6.80 (2.04–10.2)	28.0 (17.2–43.0)	31.9	0.22	0.90
Estonia	32.4 (9.72–48.6)	1508 (797–2389)	8.3	0.27	12.51
Finland	4.03 (1.21–6.04)	33.5 (21.9–50.4)	84.0	0.34	2.82
France	1.94 (0.58–2.91)	21.2 (13.3–32.2)	448.6	0.87	9.51
Germany	14.6 (4.39–22.0)	52.6 (33.7–79.5)	521.8	7.62	27.44
Greece	23.8 (7.15–35.7)	654 (432–980)	51.1	1.22	33.41
Hungary	9.03 (2.71–13.6)	156 (81.8–248)	40.9	0.37	6.36
Ireland	12.7 (3.81–19.1)	92.1 (54.4–141)	27.6	0.35	2.54
Italy	8.93 (2.68–13.4)	35.5 (23.0–53.6)	303.4	2.71	10.78
Latvia	4.96 (1.49–7.44)	13.1 (5.78–21.1)	6.7	0.03	0.09
Lithuania	2.34 (0.70–3.51)	16.4 (7.58–27.3)	11.3	0.03	0.19
Luxembourg	2.48 (0.75–3.73)	12.6 (7.17–19.7)	6.5	0.02	0.08
Malta	12.8 (3.85–19.2)	140 (84.0–216)	2.4	0.03	0.34
Netherlands	15.9 (4.76–23.8)	36.2 (22.7–55.0)	113.5	1.80	4.10
Poland	28.4 (8.54–42.7)	284 (145–456)	151.4	4.31	42.98
Portugal	11.2 (3.35–16.7)	55.9 (34.2–85.6)	48.9	0.55	2.73
Romania	10.5 (3.14–15.7)	405 (201–661)	50.0	0.52	20.25
Slovakia	4.94 (1.49–7.4)	67.1 (33.6–108)	26.9	0.13	1.80
Slovenia	8.93 (2.68–13.4)	54.2 (28.1–86.9)	13.8	0.12	0.75
Spain	9.93 (2.98–14.9)	130 (81.5–198)	246.1	2.44	32.02
Sweden	0.47 (0.14–0.70)	1.45 (0.93–2.18)	130.6	0.06	0.19

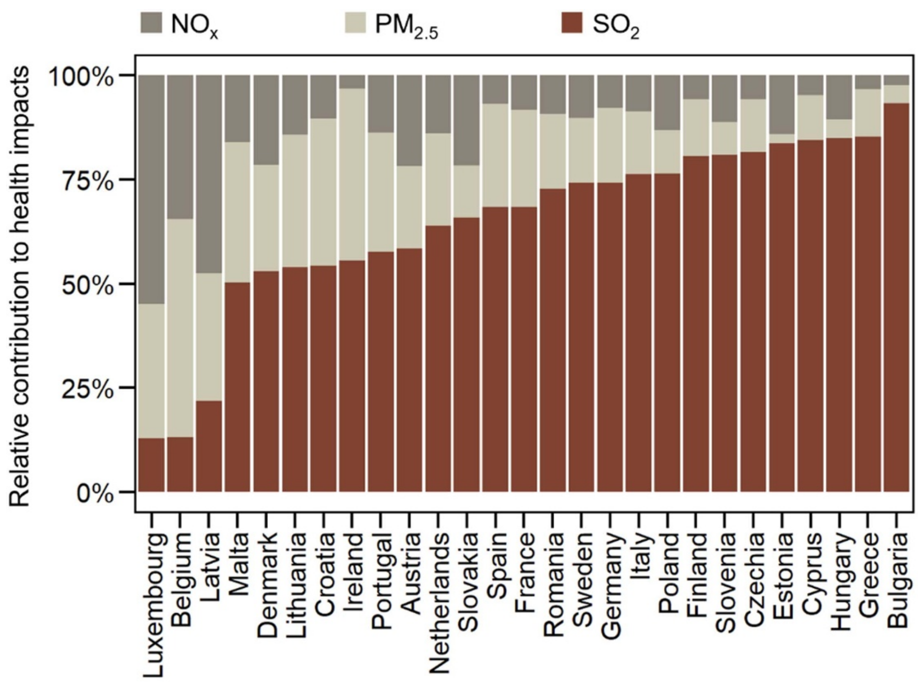

Figure 4. Relative contributions of SO_2, $PM_{2.5}$, and NO_x to the health impacts of electricity consumption across the EU in 2018.

topographical features, pre-existing pollution levels, and regional regulatory and mitigation measures. Therefore, our calculations of regional variation in health impacts should be considered conservative.

4. Conclusions

Our study provides insights into the regional variations of climate and health impacts of electricity consumption across the EU, which can inform country-level policies to approach EU climate target while considering immediate air quality-related health impacts. Our results show that the health impact of electricity use can be more than 10 times larger than its climate impact in countries where coal or oil dominates power supply, demonstrating the necessity of including health impacts into the assessment of energy and climate policies. Moreover, we found a dramatic degree of variation in health impacts of electricity use across EU countries (from 1.4 to 1508 € MWh^{-1}), which is largely driven by their energy source mix. This highlights that health benefits of renewable energy deployment, energy efficiency, and other energy interventions may be higher in countries in Eastern and Southeastern Europe than in Western or Northern Europe. The climate and health impact factors generated in this study (table 3) can be useful for future research, practice, and policymaking aimed at evaluating the environmental burden of energy consumption or predicting the benefits of energy saving measures in the EU.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare no competing interests.

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References

[1] European Union 2021 Establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (‘European Climate Law’)

(available at: https://eur-lex.europa.eu/eli/reg/2021/1119/oj/eng) (Accessed 20 March 2025)
[2] European Environment Agency n.d. Sources and emissions of air pollutants in Europe (available at: www.eea.europa.eu/publications/air-quality-in-europe-2022/sources-and-emissions-of-air) (Accessed 20 March 2025)
[3] European Commission 2022 Proposal for a Directive of the European Parliament and of the Council on ambient air quality and cleaner air for Europe (recast) (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52022PC0542) (Accessed 20 March 2025)
[4] European Commission n.d. Energy Efficiency Directive (available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en) (Accessed 6 April 2025)
[5] European Commission n.d. Nearly-zero energy and zero-emission buildings—European Commission (available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-and-zero-emission-buildings_en) (Accessed 20 March 2025)
[6] European Commission 2020 Sustainable and Smart Mobility Strategy—putting European transport on track for the future (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0789) (Accessed 20 March 2025)
[7] Eurostat n.d. Database (available at: https://ec.europa.eu/eurostat/web/main/data/database) (Accessed 20 March 2025)
[8] European Environment Agency 2024 Greenhouse gas emission intensity of electricity generation in Europe (available at: www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1) (Accessed 6 April 2025)
[9] Knoop K and Lechtenböhmer S 2017 The potential for energy efficiency in the EU Member States—a comparison of studies *Renew. Sustain. Energy Rev.* **68** 1097–105
[10] Thonipara A, Runst P, Ochsner C and Bizer K 2019 Energy efficiency of residential buildings in the European Union—an exploratory analysis of cross-country consumption patterns *Energy Policy* **129** 1156–67
[11] European Commission 2022 REPowerEU (available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en) (Accessed 20 March 2025)
[12] Maduta C, Melica G, D'Agostino D and Bertoldi P 2022 Towards a decarbonised building stock by 2050: the meaning and the role of zero emission buildings (ZEBs) in Europe *Energy Strategy Rev.* **44** 101009
[13] Buonocore J J, Salimifard P, Michanowicz D R and Allen J G 2021 A decade of the U.S. energy mix transitioning away from coal: historical reconstruction of the reductions in the public health burden of energy *Environ. Res. Lett.* **16** 054030
[14] European Environment Agency n.d. Greenhouse gas emission intensity of electricity generation in Europe—European Environment Agency (available at: www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment) (Accessed 20 March 2025)
[15] EDGAR n.d. The Emissions Database for Global Atmospheric Research (available at: https://edgar.jrc.ec.europa.eu/emissions_data_and_maps) (Accessed 20 March 2025)
[16] 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** 307–18
[17] World Bank Open Data n.d. World Bank Open Data (available at: https://data.worldbank.org) (Accessed 20 March 2025)
[18] IPCC n.d. 2006 IPCC Guidelines for National Greenhouse Gas Inventories (available at: www.ipcc-nggip.iges.or.jp/public/2006gl/) (Accessed 20 March 2025)
[19] EMEP/EEA 2019 EMEP/EEA air pollutant emission inventory guidebook 2019 (available at: www.eea.europa.eu/en/analysis/publications/emep-eea-guidebook-2019) (Accessed 20 March 2025)
[20] US EPA n.d.The social cost of carbon (available at: https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon) (Accessed 20 March 2025)
[21] Salimifard P, Buonocore J J, Konschnik K, Azimi P, VanRy M, Cedeno Laurent J G, Hernández D and Allen J G 2022 Climate policy impacts on building energy use, emissions, and health: New York City local law 97 *Energy* **238** 121879
[22] Zhang Q *et al* 2017 Transboundary health impacts of transported global air pollution and international trade *Nature* **543** 705–9
[23] Shindell D T 2015 The social cost of atmospheric release *Clim. Change* **130** 313–26
[24] US EPA 2017 Value of statistical life analysis and environmental policy: a white paper with appendices for presentation to science advisory board—Environmental Economics Advisory Committee (2004) (available at: www.epa.gov/environmental-economics/value-statistical-life-analysis-and-environmental-policy-white-paper) (Accessed 20 March 2025)
[25] Buonocore J J, Hughes E J, Michanowicz D R, Heo J, Allen J G and Williams A 2019 Climate and health benefits of increasing renewable energy deployment in the United States* *Environ. Res. Lett.* **14** 114010
[26] Salimifard P, Rainbolt M V, Buonocore J J, Lahvis M, Sousa B and Allen J G 2023 A novel method for calculating the projected health and climate co-benefits of energy savings through 2050 *Build. Environ.* **244** 110618
[27] Buonocore J J, Luckow P, Norris G, Spengler J D, Biewald B, Fisher J and Levy J I 2016 Health and climate benefits of different energy-efficiency and renewable energy choices *Nat. Clim. Change* **6** 100–5
[28] IEA – International Energy Agency 2012 Technology roadmap—high-efficiency, low-emissions coal-fired power generation—analysis *IEA* (available at: www.iea.org/reports/technology-roadmap-high-efficiency-low-emissions-coal-fired-power-generation) (Accessed 20 March 2025)
[29] Buonocore J J, Choma E, Villavicencio A H, Spengler J D, Koehler D A, Evans J S, Lelieveld J, Klop P and Sanchez-Pina R 2019 Metrics for the sustainable development goals: renewable energy and transportation *Palgrave Commun.* **5** 136
[30] Royal Berglee P World Regional Geography. University of Minnesota Libraries Publishing edition 2016 *This Edition Adapted from a Work Originally Published in 2012 by Flatworld Knowledge* (https://doi.org/10.24926/8668.2701)
[31] Buonocore J J, Reka S, Yang D, Chang C, Roy A, Thompson T, Lyon D, McVay R, Michanowicz D and Arunachalam S 2023 Air pollution and health impacts of oil & gas production in the United States *Environ. Res. Health* **1** 021006
[32] Buonocore J J, Lambert K F, Burtraw D, Sekar S, Driscoll C T and Newth D 2016 An analysis of costs and health co-benefits for a U.S. power plant carbon standard *PLoS One* **11** e0156308
[33] Markandya A and Wilkinson P 2007 Electricity generation and health *Lancet* **370** 979–90
[34] Scarlat N, Prussi M and Padella M 2022 Quantification of the carbon intensity of electricity produced and used in Europe *Appl. Energy* **305** 117901