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Abstract

We studied the contribution of coal-fired power plant (CPP) emissions (SO_2 and NOx) to air pollution levels and annual excess mortality by cardiovascular and respiratory diseases in Europe, based on fine particulate matter (PM2.5) concentrations computed with a regional atmospheric chemistry-transport model. The health burden of European CPP emission-induced PM2.5, estimated with the Global Exposure Mortality Model, amounts to at least 16 800 (CI95 14 800–18 700) excess deaths per year over the European domain. We identified an underestimation of the emissions magnitude and correcting for it doubles CPP-attributed annual excess mortality to 33 900 (CI95 33 000–37 600) per year. Due to the non-linearity of exposure-responses, especially at relatively low concentrations, these estimates represent lower limits of possible health benefits for the EU-28 states. CPP emission phase-out would avoid 18 400 (CI95 16 000–20 500) excess deaths annually assuming background PM2.5 levels of 10 μg m^{-3}, 25 500 (CI95 22 600–28 200) per year if pollution levels from other sources are reduced by 50% in parallel, and 105 900 (CI95 89 900–121 700) deaths by drastically reducing anthropogenic pollution from other sources to 2.4 μg m^{-3} that represents the threshold for health impacts. Depending on the emission scenario, large health gains can be achieved from the phase-out of CPP emissions, which calls for coordinated air pollution control strategies at the European level.

1. Introduction

Electricity generation using fossil fuels remains a large contributor to the emissions of aerosol particles and their precursors into the atmosphere. The world electricity generation fuel share of coal power plants was 40.4% in 2012 (IEA 2014). In the European Union (EU-28) almost half (49.8%) of the network electricity came from power stations using combustible fuels (biomass, natural gas, coal and oil) in 2013 (BAT 2016). The share of primary and secondary aerosols from the energy sector in the EU is 60.8% for SOx, 20.8% of NOx and 4.6% for PM2.5 (EEA 2017). External cost estimates of electricity generation from coal suggest a 95% contribution through adverse public health effects (Rabl and Spadaro 2006, ATSE 2009, Mojtaba *et al* 2018).

EU emissions from combustion plants are reported by the member states since 2004, in accordance with Directive 2001/80/EC. Predominant emissions from fossil fuel combustion are SO_2, NOx, CO, particulate matter (dust and fly ash) and greenhouse gases such as CO_2. Emissions of SO_2 originate from organic and mostly inorganic sulphur in the fuel in the form of pyrite, sulphur salts and elemental sulphur. NOx emissions originate both from the oxidation of fuel nitrogen and reactions of atmospheric N_2 and O_2 in the hot exhaust. The amount of particulate matter varies strongly with the type of combustion. Coal related fly ash is considered a strong radioactive component of coal power plant (CPP) emissions, e.g. including uranium and thorium (Tadmor 1986). The composition of PM2.5 is dominated by the sulphates and nitrates formed from SO_2 and NOx, resulting in

a significant contribution of CPPs to ambient PM2.5 levels.

A growing number of epidemiological studies is addressing the short- and long-term adverse health impacts from the exposure to PM2.5, e.g. cardiovascular and respiratory illnesses that can cause premature deaths (Sunyer 2001, Pope *et al* 2002, 2004, Pope and Dockery 2006, Krewski *et al* 2009, Young *et al* 2009, Beelen *et al* 2014, Bloemsma *et al* 2016). In a report evaluating over 40 studies on the health effects of exposure to PM2.5, the U.S. Environmental Protection Agency concluded that PM2.5 causes respiratory symptoms, development of asthma and decrements in lung function in children (US EPA 2009). In addition to respiratory illnesses, long-term exposure to PM2.5 has been causally linked to the development of lung cancer (LC), ischaemic heart disease (IHD) and cerebrovascular disease (CEV) that lead to heart attacks and strokes. In particular coal combustion emissions cause oxidative stress and inflammation leading to damage of the respiratory, cardiovascular and nervous systems, contributing to four of the top five leading causes of death in the U.S (Lockwood *et al* 2009, Casteleden *et al* 2011, Lockwood 2012). Children are particularly vulnerable to coal-related substances due to differential exposure (increased rate of inhaled air mass to body weight, more outdoor time) and pronounced susceptibility (immaturity of their immune and enzyme systems). Air pollutants adversely affect lung development in children which often precedes the development of chronic pulmonary diseases, increasing the risk of asthma and reducing the maximum lung function level in adulthood (Gauderman *et al* 2005, 2015, Khreis *et al* 2017, Orellano *et al* 2017).

Markandya and Wilkinson (2007) estimated the health burden of generating electricity from coal in Europe at 24.5 excess deaths, 225 serious illnesses including hospital admissions, congestive heart failure and chronic bronchitis, and 13 288 minor illnesses for every Terrawatt-hour (TWh) of electricity produced from coal. When lignite, the most polluting type of coal, is used, each TWh of electricity produced may result in 32.6 excess deaths, 298 serious illnesses, and 17 676 minor illnesses. In view of the relatively large contribution of CPP emissions to air pollution in Europe (300 plants produce 25% of all the electricity generated in the EU; responsible for more than 70% and 40% of the SO_2 and NO*x* emissions from the power sector, respectively) and the poorly documented CPP related health impacts, additional research is needed.

Until recently health impact studies were mainly based on epidemiological data through integrated exposure-response functions, e.g. used for the global burden of disease (GBD) (Cohen *et al* 2017). In this study we re-evaluated the relative contribution of European CPP emissions on particulate matter levels and consequently on mortality estimates in the EU-28 member states for the year 2015, based on updated epidemiological data. We used a regional atmospheric chemistry transport model to estimate exposure to fine particulate matter (PM2.5, particles with a diameter of less than 2.5 μm) combined with the new Global Exposure Mortality Model (GEMM) of Burnett *et al* (2018). GEMM provides hazard functions based on 41 cohort studies in 16 countries. The use of this comprehensive dataset reduces the associated uncertainty due to its volume and wider geographical coverage, including also regions with relatively low as well as very high PM2.5 concentrations, exposure to which was previously related to secondhand smoking and not to actual atmospheric conditions. The following disease categories are analysed: lower respiratory disease (LRI), chronic obstructive pulmonary disease (COPD), LC, IHD, CEV, all previously addressed in GBD assessments, and a new one referred to as 'other non-communicable diseases' (oNCD). We perform base case and sensitivity simulations (with and without emissions of gaseous precursor of aerosols, SO_2 and NO*x*) from 297 CPPs in Europe. Our study, to the best of our knowledge the first for Europe, aims to provide up-to-date information on the health burden of energy generation based on coal use in Europe and estimates the relative benefits in terms of avoided excess deaths associated with shifting from coal to clean fuels. We elaborate on the importance of phasing out coal-fired power production in Europe, estimating the health burden through present PM2.5 levels, and at reduced concentrations that might result from simultaneously controlling other pollution sources.

2. Materials and methods

The Weather Research and Forecast model coupled with Chemistry (WRF-Chem) version 3.9.1 was used to simulate air pollution over Europe (Grell *et al* 2005, Fast *et al* 2006). A recent study by Kushta *et al* (2018) showed that the model captures well the variation of PM2.5 over Europe with more than 95% of the mean annual modelled and observed PM2.5 data pairs within a factor of two for both coarse (100 km) and fine (20 km) configurations. They concluded that the uncertainties regarding model resolution as well as relative risk size-bin are much lower than the statistical uncertainty associated with the epidemiological data. For this work we have simulated atmospheric and chemical processes for the year 2015 over Europe with 50 km grid spacing. The meteorological initial and boundary conditions were provided by the National Center for Environmental Prediction Global Forecast System at a resolution of $0.5° \times 0.5°$, and the initial and lateral forcings for the chemical species were from global simulations with Model for Ozone and Related chemical Tracers version 4 model (Emmons *et al* 2010). Emissions are based on the global inventory EDGAR-HTAP

v2 (Janssens-Maenhout *et al* 2015) at a resolution of 0.1° × 0.1° for NO_x, SO_x, non-methane volatile organic compounds, CO, NH_3, $PM_{2.5}$ and PM_{10}.

Information on the CPPs in Europe has been derived from the European Pollutant Release and Transfer Register (E-PRTR), which records all pollutant emissions from industrial facilities. Only CPPs that generate >50 MW are taken into account. We performed a standard simulation with the original emission dataset (PRESENT) and an additional one where the emission fluxes of SO_2 and NO*x* have been subtracted from the total emission fluxes at the grid points of the location of the CPPs (PRESENTnoCPP). To estimate disease-related mortality attributable to PM2.5, we applied recent hazard ratio functions from the GEMM (Burnett *et al* 2018). GEMM hazard functions complement those of the GBD for 2015, yielding age-dependent excess mortality rates from five disease categories considered in GBD (LRI, COPD, IHD, CEV, and LC), and an additional (oNCD) including disorders such as diabetes and hypertension that were previously not accounted for (Lelieveld *et al* 2019). Uncertainty ranges, expressed as the 95% confidence intervals (95% CIs), are adopted from Burnett *et al* (2018).

3. Results

From comparing the annual mean $PM_{2.5}$ concentrations from the two simulations we find that the contribution of CPPs peaks at 1.7 μg m^{-3}, centred on the major emitters in Germany and Poland (figure 1(a)). The difference in total $PM_{2.5}$ results from the formation of secondary aerosol components. Photochemical oxidation of NO*x* (primary CPP pollutant) leads to nitric acid formation that in turn react with the neutralizing specie ammonia (NH_3) to form ammonium nitrate (NH_4NO_3) aerosols. The production of NH_4NO_3 competes with the formation of the more thermodynamically stable ammonium sulphate $(NH_4)_2SO_4$, in which ammonia gas neutralizes the sulfuric acid aerosols in the atmosphere. NH_4NO_3 can volatilize when the temperature increases during transport from the source regions of NO and NH_3 and therefore is predicted to contribute to PM2.5 and aerosol optical depth mostly over highly emitting regions (Park *et al* 2014). As seen in figure 1(b), excluding the CPP emissions mostly influences nitrate levels in the vicinity of the emission sources while the impact of CPPs on the sulphate aerosols is more uniform downwind of major emitters over Eastern and South-eastern Europe (figure 1(c)). The CPP influence on the distribution of emission fluxes of the gaseous pollutants SO_2 and NO*x*, and their aerosol products, subsequently affects the distribution of the ammonium aerosols with the largest changes following those in the nitrate component (figure 1(d)).

Next, we calculated total excess mortality rates for six diseases (LRI, COPD, IHD, CEV, LC and oNCD) for the whole domain and each EU-28 member states for PRESENT and PRESENTnocpp simulations, hereafter Scenario 1 (S1) of phasing out CPPs. Due to the non-linearity of the exposure-response functions especially at lower concentrations, our estimates represent lower limits of avoided excess mortality attributable to PM2.5, as CPPs are unlikely to be phased out solely without other air quality mitigation efforts. The estimates increase significantly when additional reductions are applied to other sectors such as traffic, industry, agriculture and residential energy use. To illustrate the consequences of concurrent reductions, as a possible result of coordinated control strategies, we calculated the excess mortality due to the CPPs for three additional scenarios:

(a) S2: assuming that PM2.5 concentrations from other sectors are reduced by 50% relative to current levels (hereafter 50% and 50%nocpp),
(b) S3: assuming that in all locations where the WHO guideline of 10 μg m^{-3} is exceeded, the concentrations are reduced to this value (hereafter WHO10 and WHO10nocpp), and
(c) S4: assuming that background concentration levels over the entire domain are 2.4 μg m^{-3} (hereafter BASELINE and BASELINEnocpp), being the lower limit at which health effects of PM2.5 are expected (Burnett *et al* 2018).

As shown in figure 2, under present conditions, total annual excess mortality due to air pollution (with CPP emissions) over the whole domain of study reaches 63 074 (CI95 50 834–74 767) for LC; 77 147 (CI95 59 903–92 727) for ALRI; 47 636 (CI95 35 580–59 146) for COPD; 98 280 (CI95 73 375–122 421) for CEV; 454 173 (CI95 434 591–473 599) for IHD and 17 813 (CI95 16 229–19 405) for oNCD. In total, all disease categories currently cause 758 104 (CI95 670 323–843 278) excess deaths annually attributed to air pollution from all sources. Between the two pollution reduction scenarios S2 and S3, total excess mortality would be reduced much more strongly if all regions would bring current levels of pollution down by 50% (S2) than if regions that exceed the WHO guideline of 10 μg m^{-3} would bring levels down to that value (S3).

To illustrate the significance of background pollution levels related to the non-linearity of the relation between health risk and PM2.5 concentrations, we analyse how the health burden of CPPs varies among the four background scenarios (figure 3). By phasing out coal related pollution, annual excess mortality under present air pollution conditions (S1) drops to 61 484 (CI95 49 530–72 918) for LC; 75 155 (CI95 58 278–90 448) for ALRI; 46 511 (CI95 34 721–57 778) for COPD; 95 272 (CI95 71 098–118 713) for CEV; 454 173 (CI95 434 591–473 599)

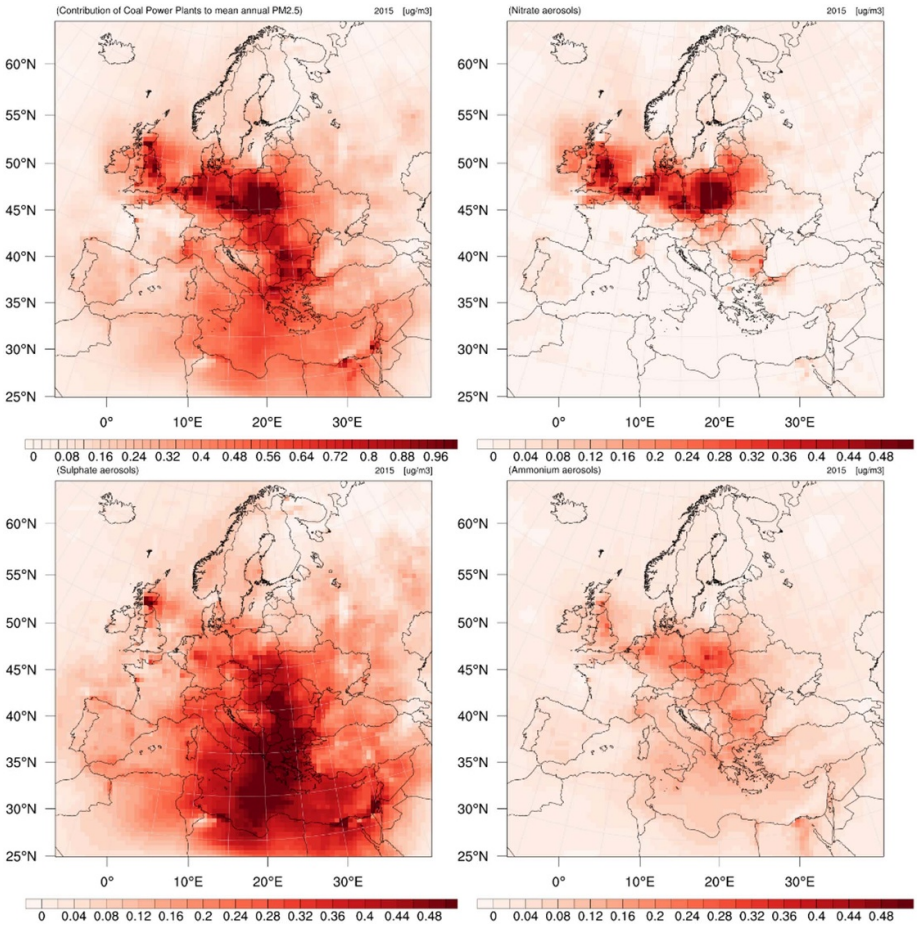

Figure 1. Concentration differences due to CPP emissions for the year 2015 of (a) total PM2.5, (b) NO_3^-, (c) SO_4^{-2} and (d) NH_4^+ in $\mu g\ m^{-3}$ expressed as the difference in the respective concentrations of the aerosol components between the PRESENT minus PRESENTnocoal simulations. Note that the colour bar for total PM2.5 is twofold that of the particulate sub-species.

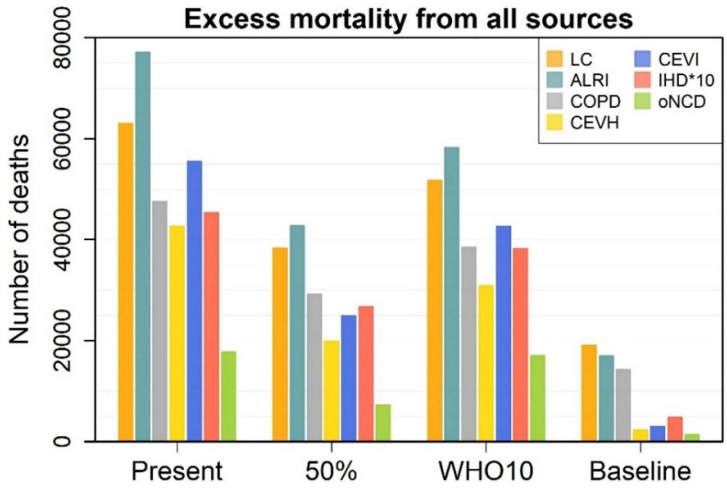

Figure 2. Annual excess mortality for each disease category for each scenario with emissions from CPPs. Note that IHD excess mortality values should be multiplied by 10 for the actual value.

for IHD and 17 531 (CI95 15 968–19 098) for other NCDs. Over the whole domain and for all diseases, removing the contribution of CPPs would reduce excess mortality attributed to air pollution by 16 802 (CI95 14 827–18 686). In S2, where all background pollution is reduced by 50% the same measures would lead to a reduction in excess mortality by 25 436 (CI95 22 557–28 215) per year. In S3, where background pollution is assumed to not exceed the WHO guideline of 10 $\mu g\ m^{-3}$, the health benefit of phasing

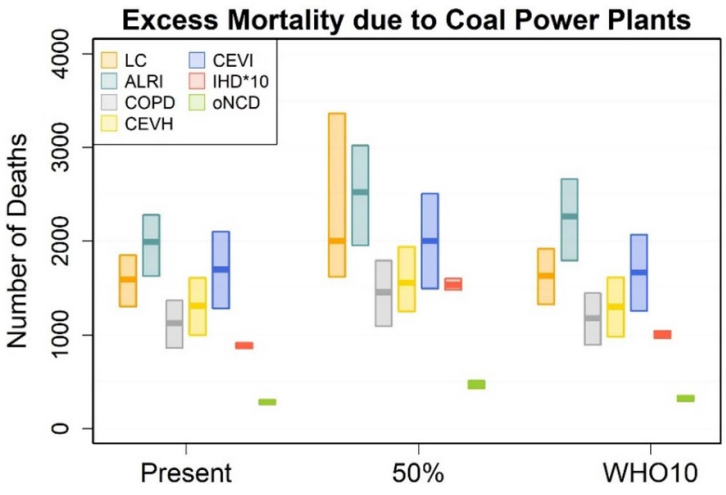

Figure 3. Annual excess mortality per scenario and disease category calculated as MS_i–MS_inoCPP where *i* is the respective scenario. Note that IHD excess mortality values should be multiplied by 10 for the actual value.

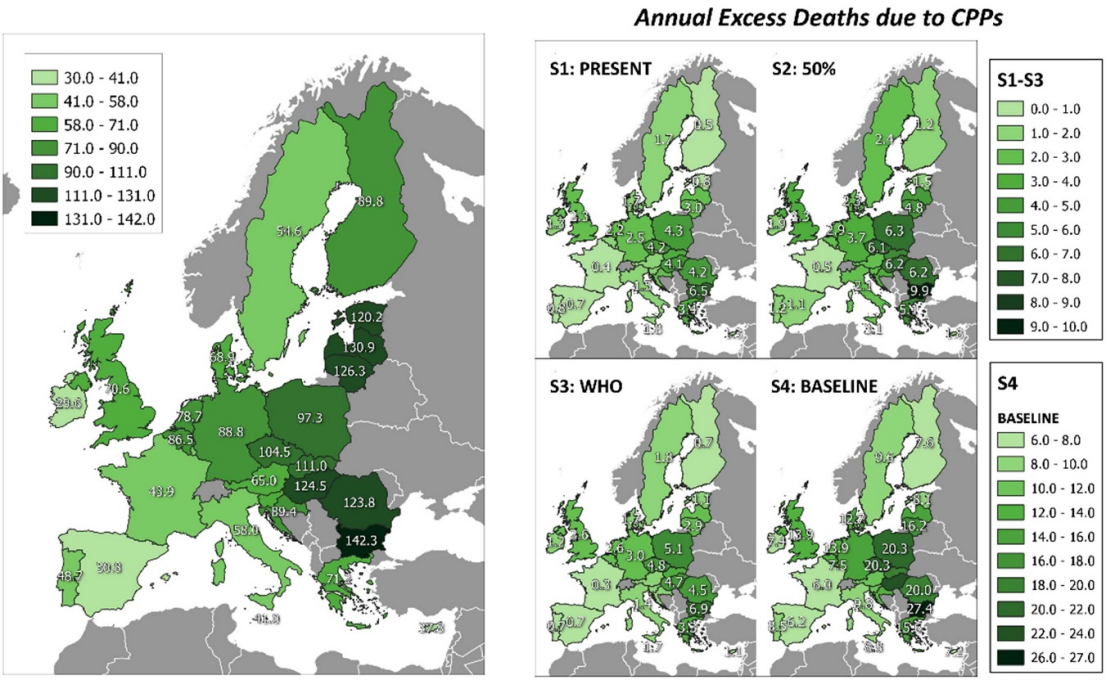

Figure 4. Annual excess mortality for EU-28 member states (left) and the difference in the annual total excess mortality for each background pollution scenario (S1–S4), with and without CPPs, normalized to 100 000 inhabitants (right) (right).

out coal power plants would reach 18 421 less excess deaths (CI95 16 083–20 519) per year. And in S4, in which background pollution equals the health impact threshold of 2.4 μg m^{-3}, the health benefit from CPP phase-out would be as high as 105 896 excess deaths (CI95 89 903–121 702) per year. Between the three first scenarios, the health benefits in terms of avoided excess mortality due to coal-related pollution would be stronger if the background pollution is reduced everywhere to 50% of the current values (S2). The health benefits remain high if the areas with PM2.5 concentrations above 10 μg m^{-3} are targeted specifically (S3) while the lowest gain in absolute terms is under current conditions, highlighting the importance of strategically aiming at a coordinated approach regarding air pollution reduction measures.

At country level under present conditions, we find that several Eastern European countries located downwind of areas with strong emissions (Bulgaria, Lithuania, Romania, Hungary, Latvia, Slovakia, Czech Republic and Croatia), have significant excess death rates (>100 deaths per 100 000 inhabitants per year) varying from 104.5 (CI95 93.2–115.3) in the Czech Republic to 142.3 (CI95 126.2–157.9) per year in Bulgaria, as depicted in figure 4(a). This follows from the collocation of dense population

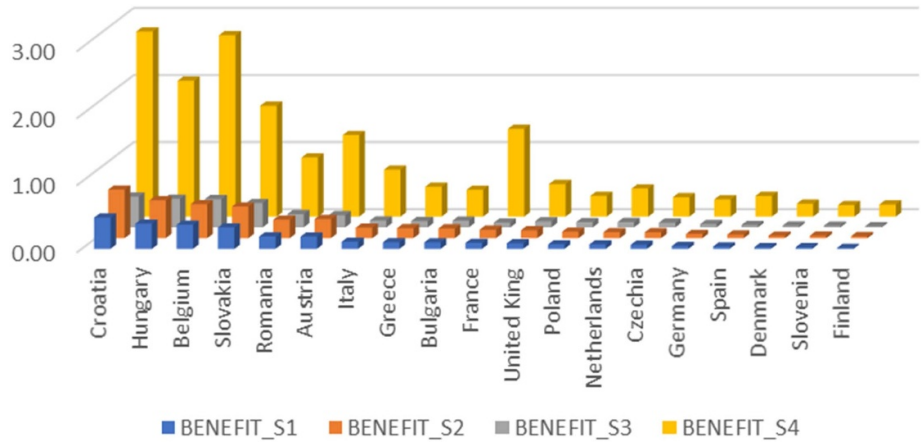

Figure 5. BI calculated as potentially avoided excess mortality due to CPPs, normalized by the net electrical capacity of the CPPs, calculated by excluding CPPs from the emission inventory per country.

and areas with significantly enhanced PM2.5 levels either due to domestic pollution or transported pollution. Countries with relatively low excess death rates include several Mediterranean states (Cyprus, Malta and Spain with 37.8, 41 and 30.8 deaths per 100 000 inhabitants/year, respectively) and northwestern European countries such as Ireland (29.6, CI95 25.5–33.6).

The omission of emissions from CPPs leads to a reduction in excess mortality rates under present conditions (S1) from 72.8 (CI95 63.5–81.7) to 70.6 per 100 000 inhabitants (CI95 61.6–79.3) per year averaged over all EU-28. The reduction under scenario S2 is 42.7–39.6 (CI95 37.3–48.0 and 34.5–44.5), representing an average of 8.0% excess mortality burden due to CPPs in Europe (relative to the total mortality due to all PM2.5) in S2. The reduction in S3 is from 59.4 to 57.0 deaths per 100 000 inhabitants (CI95 51.8–66.7 and 49.7–64.0) per year. The countries that would benefit most from the reduction of CPP emissions, in terms of fewer excess deaths under present conditions, are Greece (5.1% reduction compared to PM2.5 from all anthropogenic activities), Bulgaria (4.8%), Poland (4.7%) and Malta (4.6%), due to both large national CPP emissions and their unfavourable location downwind of the major EU emitters (figure 4(b)). Under scenario S2 the largest reduction rates in premature mortality are found in countries that either have enhanced domestic pollution due to national or upwind CPPs or low levels of background pollution making the benefit of phasing out coal more pronounced (due to the non-linearity of exposure-responses). Such countries include the Czech Republic, Poland, Sweden, Bulgaria, Greece, Ireland and Malta with reductions of 10.4%, 11.6%, 11.9%, 13.2%, 14.5%, 15.3% and 15.7%, respectively. In other large emitter countries (e.g. Germany and Czech Republic) excess mortality is reduced when CPP emissions are excluded in S1, varying from 2.9% to 4.2%, respectively, in the first emission reduction scenario). This results from the combination of air pollution exports (long-range transported downwind from CPPs) and lower baseline mortalities in these countries. Detailed values of excess premature mortality rates and contribution of CPPs under each scenario (normalized to 100k inhabitants and absolute values) are given in tables 1 and 2 of the supplementary material (available online at stacks.iop.org/ERL/16/045010/mmedia).

Next, we integrate the net electrical capacity of the CPPs excluded from the emission inventory in each EU-28 member states, and calculate a benefit index (BI) as the number of excess deaths due to emissions from the CPPs of that country related to the net capacity of the CPPs (figure 5). This parameter is a measure of the gain per country when clean electricity production would replace the use of coal in Europe. This number however must not merely be taken as a measure of national achievement, as the reduction in excess mortality in each country is not a result of the reduction of the respective emissions from that country alone, but rather a collective effort from all EU-28 member states. Further, it cannot be used as a 'cost-benefit' index as this ratio is strongly influenced by the non-linearity of the relationship between national CPP productivity and excess mortality due to the transboundary transport of pollution. In countries without listed CPPs, the excess deaths are only the result of emissions from upwind countries.

Croatia, Hungary, Belgium, Slovakia, Romania and Austria are expected to have the largest health benefits in terms of fewer excess deaths relative to the electricity range they derive from coal. On the other hand, large and medium size emitters such as Germany, Denmark, Czech Republic, Finland, the Netherlands, Slovenia and Spain will have smaller reductions in excess mortality relative to the total electricity potential needed to be replaced by

less polluting fuels. This occurs when either the national coal-related emissions are high, and/or when the country is not affected by large upwind CPP emitters.

4. Uncertainties

In this section we address uncertainties in our results that might derive from the representation of the CPP spatial distribution and the magnitude of emissions. Model uncertainties are addressed in Kushta *et al* (2018) who concluded that the configuration aspects of the model setup and operation do not strongly affect PM2.5-related excess mortality results (less than a few percent). Uncertainties related to the exposure and epidemiological data of the risk factors in GEMM are addressed in Burnett *et al* (2018) and represented in the confidence interval shown along average values in all estimates regarding excess mortality. We investigate further the central aspect of the current work, namely the accuracy of the emission inventories. In order to assess the contribution of a specific industry, it should be well represented in terms of spatial distribution and magnitude of emissions or else its impact will be underestimated.

By removing the NOx and SO_2 emission fluxes of CPPs as listed on E-PRTR we derived the contribution of this source on national total emissions of the respective pollutant. The phasing out of CPP emissions produces a reduction in the total national emissions of each country that is in general below the contribution of the emissions categorized under 'thermal power stations and other combustion facilities' in the respective countries as reported on E-PRTR (for detailed information see table 3, supplementary material). We conducted a sensitivity test in which the removal of the emission fluxes for the CPPs on the E-PRTR database was performed with another approach. In the first approach, described above and used for the main analysis, the fluxes were removed based on the values given on the E-PRTR portal, while in the second case the whole flux value of the NOx and SO_2 emissions in the emission inventory (EDGAR-HTAP) was removed from the grid cell where the respective CPP was located, independent of the actual reported value. With this second, bolder approach, significantly higher benefits are found with lower excess mortalities estimates. Over the entire domain, the phasing out of all-grid CPP emissions would lead to 33 920 (CI95 33 000–37 600) less deaths compared to 16 800 (CI95 14 800–18 700) per year estimated with the removal of the E-PRTR reported flux value. This illustrates the importance of accurately representing the emission sources in assessment studies. Underestimation of the magnitude of emission strength can lead to a strong underestimation of the impacts and consequently the benefits anticipated from the CPP phase-out.

5. Conclusions

We estimated the impacts of air pollution emissions by CPPs on excess mortality in Europe. Emissions from coal combustion of gaseous pollutants that act as precursors to aerosols in the atmosphere (SO_2 and NOx) significantly contribute to mean annual near-surface PM2.5. We find that CPP emissions cause at least 9500–12 100 excess deaths each year within EU-28 member states, with 1800–2260 in Germany, 1270–1670 in the UK, 1470–1840 in Poland and 2800–3600 in Romania, Bulgaria and Greece. The CPP emissions also contribute to excess mortality outside the EU-28, i.e. both within and outside Europe adding up to 16 800 (CI95 14 800–18 700) per year. The above estimates represent lower limits due to the likely underestimation of source strengths in the emission inventory and the additional impact of co-emitted or other secondary pollutants. The scaling of emission removal factors towards the reported CPP contribution per country shows that the health benefit from removing coal-related emissions would reach a reduction of about 33 920 (CI95 33 000–37 600) excess deaths per year. These numbers could increase significantly in view of the realization of nearly 110 new CPPs currently under construction and/or planned (new or by extending existing units), of which 75 in Turkey alone. The latter could strongly deteriorate air quality in Eastern Europe and eastern Mediterranean countries.

Our results reveal a strong dependence on the emission scenario applied, and the above estimates should be considered as lower limits, being based on the assumption that emission reductions result only from the phase-out of CPPs, while emissions from other sources remain unchanged. Due to the non-linearity of the exposure-responses, assuming background PM2.5 levels of 10 μg m^{-3} (WHO guideline), a CPP emission phase-out would avoid excess mortality of about 18 400 (CI95 16 000–20 500) per year. We find that if simultaneous air pollution control strategies are applied to other sectors, leading to a PM2.5 reduction of 50%, nearly 25 500 (CI95 22 600–28 200) excess deaths could be avoided each year by phasing out CPPs in the EU-28 member states. Excess mortality rates under such a coordinated emission control scenario would drop significantly in all countries. Under an optimal European emission control strategy, the health benefits could be disproportionally greater. By assuming that all anthropogenic emissions in Europe would be reduced such that a baseline average concentration 2.4 μg m^{-3} is achieved (health damage threshold), the potentially avoided excess mortality from a CPP phase-out would be 105 900 (CI95 89 900–121 700) per year, which is about 15% of the total number of air pollution related excess deaths in Europe.

Clearly, the phase-out of CPP emissions would make a major contribution to the improvement of

public health, especially when applied simultaneously to emission reductions in other sectors. Considering the continued availability of data on the location and operational status of existing and planned CPP facilities in Europe and neighbouring regions (i.e. Western Balkans and Turkey), the assessment of their impact on excess mortality should be updated regularly, while it will be important to improve the representation of CPP emissions in international databases.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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