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Quantifying the reductions in mortality from air-pollution by cancelling new coal power plants

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Abstract

Deep decarbonization paths to the 1.5°C or 2°C temperature stabilization futures require a rapid reduction in coal-fired power plants, but many countries are continuing to build new ones. Coal-fired plants are also a major contributor to air pollution related health impacts. Here, we couple an integrated human-earth system model (GCAM) with an air quality model (TM5-FASST) to examine regional health co-benefits from cancelling new coal-fired plants worldwide. Our analysis considers the evolution of pollutants control based on coal plants vintage and regional policies. We find that cancelling all new proposed projects would decrease air pollution related premature mortality between 101,388-213,205 deaths (2-5%) in 2030, and 213,414-373,054 (5-8%) in 2050, globally, but heavily concentrated in developing Asia. These health co-benefits are comparable in magnitude to the values obtained by implementing the Nationally Determined Contributions (NDCs). Furthermore, we estimate that strengthening the climate target from 2°C to 1.5°C would avoid 326,351 additional mortalities in 2030, of which 251,011 (75%) are attributable to the incremental coal plant shutdown.

1 Introduction

Coal-fired electric power generation plants are one of the largest contributors of global greenhouse gas (GHG) emissions. At global level, in 2010 they represented around 25-30% of total carbon dioxide (CO_2) emissions [1], and this fraction is even larger in some regions such as China or India. Limiting warming to 1.5°C or 2°C would require all conventional coal-fired power plants to be phased out roughly within the next 30 years [2–4]. Furthermore, none of the existing plans for installation of new coal capacity is consistent with meeting the temperature stabilization targets defined in the Paris Agreement [5–8]. Even implementing projects which have already started would greatly increase the risk of stranding assets [7].

Apart from the GHG mitigation potential, phasing out coal-fired plants would directly reduce air pollution related health impacts, which has been a major driver for historical and ongoing transition from coal power [9,10]. Coal-fired plants are a major source of local air pollutants, particularly sulphur dioxide (SO_2). At the global level, coal-fired power plants were responsible for 30-45% of total SO_2 emissions in 2010 [11–13], although the share has been decreasing since 2005 (SI, Figure S2). SO_2 is one of the main contributors to the formation of secondary fine particulate matter ($PM_{2.5}$) [14,15], and $PM_{2.5}$ is the most hazardous pollutant in terms of human health [16–19] especially in regions such as China [20–22] and India [23,24], due to their high population density.

Existing literature has extensively analysed the importance of incorporating potential health co-benefits in policy design. Several studies have demonstrated that, at a global level, these co-benefits would outweigh the policy cost of mitigation [25–29]. While they show that largest co-benefits would be located in developing Asia, other studies demonstrate that health co-benefits would also play a significant role in developed regions [30,31]. Furthermore, recent studies have analysed sectorial contributions to $PM_{2.5}$ and the associated health impacts [32–34]. Reduction of fossil fuel consumption [35] , the penetration of cleaner technologies in the power sector [36–38] or the electrification of the vehicle fleet [39] have been proved as effective measures for improving air quality. Moreover, few studies have analysed the air pollution effect in human health specifically contributed from coal-fired power generation [40–43].

However, to our knowledge, this is the first study that shows the benefits of simply cancelling all the new existing projects based on a unit-level database of newly proposed coal-fired power plants worldwide. Specifically, we are asking the following questions: *How large are the health co-benefits from new project cancellation? How large are they compared to the co-benefits obtained from the implementation of the Nationally Determined Contributions (NDCs)? What is the additional impact on* *premature mortality attributable to increased coal-fired power plant retirement in a 1.5°C decarbonization scenario, compared to a 2°C scenario?*

Another innovative aspect of this study is that it combines a global dataset of existing and proposed coal plants [7] with a modelling framework that couples an integrated human-earth system model (Global Change Analysis Model, GCAM [44]) with an air quality source-receptor model (Fast Scenario Screening Tool, TM5-FASST [45]). We use GCAM to specify different coal trajectories based on the bottom-up data and quantify the GHG emission impacts from coal power plants. We use TM5-FASST to evaluate air pollutants, the concentrations of particulate matter in the atmosphere and the associated premature mortality.

In this framework, we assess health impacts associated to air pollution for five different scenarios (see section 2.2): first, a baseline scenario where all proposed coal-fired power plants are built and operate through the lifetime of 50 years (*ContinuedGrowth*); second, a coal cancellation scenario, where no new coal plants are constructed beyond 2020 (*NoNewCoal*); third, a scenario with the implementation of the NDCs (*NDC*); fourth, a cost-effective 2°C mitigation scenario where there is an implicit accelerated coal retirement (*2°C*); and fifth, a cost-effective 1.5°C mitigation scenario where the coal phase-out is even faster (*1.5°C*). We find that cancelling new proposed coal-fired power plants generates significant air pollution related health co-benefits. This is comparable in magnitude to the co-benefits obtained by implementing the NDCs, with regional divergences. Moreover, moving from the 2°C to the 1.5°C decarbonization scenario would generate extra health co-benefits related to faster retirement of coal-fired plants, mostly in the medium term (2030).

2 Methods

2.1 Methodology

Our assessments are based on a unit-level database of worldwide newly proposed coal-fired power plants in different development stages – under construction, permitted, in the permitting process, and in planning. Data on existing plants are primarily taken from the Global Coal Plant Tracker by Global Energy Monitor [46]. Information about proposed projects is gathered from various data sources, such as national and local energy development plans, public notices of project permitting processes (f.e. environmental impact assessments), coal industry status reports, power company websites, and a variety of news channels. This aggregated data is validated against other sources and modified at the national level as needed. All information is updated as of September 2018. More information can be found in Cui et al (2019) [7].

This coal data is fed into an integrated human-earth system model – the Global Change Analysis Model (GCAM) – to estimate the local air pollutant emissions under alternative coal power scenarios. GCAM is an integrated human-earth system model developed by the Joint Global Change Research Institute (JGCRI) that represents the interconnections of energy, land-use, economy, water and climate systems (https://github.com/JGCRI/gcam-doc). GCAM is divided into 32 geo-political regions and 384 land subregions and runs in 5-year time steps until the end of the century. As a relevant feature for this study, the GCAM emissions module tracks the main GHGs and air pollutants, namely carbon dioxide (CO_2), methane (CH_4), nitrogen dioxide (N_2O), black carbon (BC), organic carbon (OC), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and hydrofluorocarbons (HFCs). We use GCAM 5.1 [44,47] in this study. More information can be found in the SI.

The implementation of the coal data into GCAM is detailed in Cui et al (2019) [7]. First, the generation trajectory for each plant in the database is determined. A coal unit built in a given year is assumed to continue to operate until the end of an exogenously specified lifetime at a region-specific, constant capacity factor. Then, unit-level trajectories are aggregated to obtain coal generation pathways for GCAM-specific regions and model periods. These trajectories are implemented as constraints on the model's output and are used to quantify the committed emissions.

In order to estimate pollutant concentrations, population-weighted exposure, and premature mortality, we translate the system-wide GHG and air pollutant emissions (estimated from GCAM) to the TM5-Fast Scenario Screening Tool air quality source-receptor model (TM5-FASST) [45]. TM5-FASST is an air quality source-receptor model developed by the European Commission's Joint Research Centre (JRC) in Ispra, Italy. The model is a global reduced form representation of the TM5 full chemistry model, estimating $PM_{2.5}$ and O_3 concentration levels and their impacts in terms of health, agriculture or global warming. The model uses underlying meteorological and atmospheric information drawn from more complex chemical transport models to estimate concentrations of $PM_{2.5}$ and O_3 in each receptor-region driven by the emissions of different precursors in different sources (regions). This structure can capture cross-border health impacts associated with emission reductions in neighbouring regions.

For health impacts, TM5-FASST estimates premature mortalities attributable to particulate matter ($PM_{2.5}$) and ozone (O_3) based on the exposure-response functions (ERFs) from Burnett et al (2014) [48] and Jerret et al (2009) [49], respectively (see SI for more details). The model differentiates between different causes of death, which are ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), stroke, lung cancer (LC) and acute lower respiratory airways infections (ALRI).

For each cause, variations in mortalities would be determined as a product of the baseline mortality rates, which are taken from the World Health Organization [50], the exposed population and the attributable fraction, which is function of the relative risk (RR) of death [51]. For population exposure, we use SSP2 population data, in order to maintain consistency across the models applied in this study. In addition, some of the causes of death apply only to adults (>30 years) (IHD, stroke, COPD, LC) and ALRI applies only to infants (<5 years). To estimate the adult-infant proportions we make use of the historical shares from the United Nations population prospects [52]. For the estimation of future health impacts (as we do in this study), the used version TM5-FASST does not include any temporal change of population structure, so we do not capture the effects of population aging over time.

Van Dingenen et al (2018) [45] provides a complete documentation of the model, demonstrating that the simplifications applied (compared to full chemistry models such as TM5), do not compromise the validity of the output. That study shows that although the outputs would depend on the linearity assumption for the main exposure metrics, it is a validated tool for analysing differences across predesigned scenarios. The model is increasingly being used and has been applied in several studies [53–55]. Note that the combined use of the models allows us to capture the health impacts of both primary and secondary $PM_{2.5}$ [25]. This is essential, particularly for this study, since we need to consider the damages from the set of pollutants emitted by coal fired power plants (specially SO_2).

2.2 Scenarios

In this study we have modelled five scenarios for estimating the air pollution driven health co-benefits of coal plant cancellation through different mitigation strategies. The *ContinuedGrowth* is the baseline scenario, where all coal power projects under development will be completed by 2030, and coal power plant capacity will continue to grow at the same rate through 2050. The *NoNewCoal* is a coal peaking scenario, where no new coal plants are built after 2020. We assume that coal electricity generation will be substituted by generation from non-emitting technologies. The assumed lifetime of the installed coal plants is 50 years, so they will be gradually phased-out. The scenario does not include any carbon price. In the *NDC* scenario there is a climate policy where all of the regions apply the Nationally Determined contributions based on Fawcett et al (2015) [57]. After 2030 in the *NDC* scenario, a conservative approach is assumed ("Paris Continued ambition" in the aforementioned paper), leading to an increase in global mean temperature of around 3°C in 2100 that is still increasing. Moreover, the probability of limiting warming to 2°C in this scenario accounts for 8%. For the implementation of the NDCs we establish 32 carbon markets (for the 32 GCAM regions) and the mitigation will follow a "least-cost" approach. The *2°C* and *1.5°C* scenarios are implemented by limiting end-of-century radiative forcing to 2.6 Wm^{-2} and 1.9 Wm^{-2}.

Starting in 2025, emissions reductions are pursued cost-effectively across regions via a single global carbon price on energy-related emissions. This is different from the regionally differentiated approach in the *NDC* scenario. Cumulative emissions in the 2°C scenario peak at 900 $GtCO_2$ in 2070 and decline to 600 $GtCO_2$ in 2100. The 1.5°C scenario peaks at 420 in 2050 and declines below zero by 2100. These limits correspond to cumulative CO_2 emissions that are below the budgets suggested by the IPCC [58].

In addition, trajectories of coal plants' future emission factors will directly affect the health co-benefit calculation. These emissions factors represent the emissions per unit of activity, so they implicitly capture the potential implementation of air pollution policies and/or the installation of end-of-pipe technologies. For one set of the scenarios, we apply region, year, fuel, and sector specific emission factors from the SSP2 (Shared Socioeconomic Pathways) narrative (f.e. *ContinuedGrowth-SSP2*). The SSP2 sectoral specification [53] provides a gradual reduction in emission factors over time due to future technological developments (i.e. desulphurization) and the implementation of stricter air pollution regional policies. For the regional evolution of these emission factors, it is assumed that high- and middle-income countries will implement near-term (2030) pollution control policies, being gradually more stringent up to 2050. The increase in ambition combined with technological improvement, reduces emission factors by 2100. In low-income regions, emission factors equal to the application of near-term policies in high- and middle-income regions, would be delayed until 2050. Thereafter, emission factors would continuously decline until 2100.

However, this approach lacks the differentiation between coal plants by vintage with specific emission factors. For example, historical experience to date, particularly for sulphur dioxide emissions, shows that countries generally set stringent emission limits for new power plants at some point in time. Additionally, national policies and standards often require existing plants to lower emissions over their lifetime. SO_2 emissions in particular can potentially drop dramatically over sub-decadal timescales, as seen historically in Japan [59] and recently in China [60]. Furthermore, the emission factors for new power plants can be substantially different from the average emission factor of existing plants due to different regulations. Therefore, we also implement an alternative approach to modelling SO_2 emissions and calculate the potential health co-benefits. This approach, labelled as "*VintageControl*" (*e.g., ContinuedGrowth-VintageControl*), takes advantage of the electric power generation's vintage representation in GCAM and better matches historical practice (see SI for detailed description). For the implementation of this approach, we specify a time at which any new coal-fired electric power plants in must meet a specified standard, which is going to differ across each region (see SI, Table S4). This entails that the SO_2 emissions per unit of electricity will be reduced, but with substantial different across regions and periods (see SI, Figure S13 and Figure S14). This has significant implications for SO_2 emissions. At a global level, SO_2 emissions from coal power plants in the baseline scenario account for 20 and 12 Tg in 2030 and 2050 using SSP2 emission factors (31% and 26% of total SO_2 emissions). The implementation of the *VintageControl* approach reduces those values to 12 Tg (-42%) and 6 Tg (-51%) in the same periods. Across regions, India shows by far the largest difference between the two approaches. In 2030, India accounts for around 65% of the total SO_2 emission difference (-5.54 of -8.57 Tg), and, in 2050, this proportion increases to 85% (-5.15 of -6 Tg).

3 Results

3.1 Proximity of coal plants from densely populated regions

Coal power plants are one of the major sources for SO_2 emissions (SI, Figure S2) so we have observed that there is a direct relation between SO_2 emissions from the power sector and the location of coal-fired power plants. This relation is shown in the SI, as gridded SO_2 emissions and, for each cell in the grid map, SO_2 emissions and the Euclidean distance to a plant (SI, Figures S3 and S4). The distance of the emission sources (coal-fired power plants) to cities is a key factor for the estimation of health impacts. The location of the power plants and the transport of the pollutants emitted (largely dependent on prevailing winds) have direct impacts on total $PM_{2.5}$ exposure, which is the most hazardous pollutant for human health [18,61]. Therefore, we have assessed to which extent existing coal-fired plants are relatively close (less than 50 km) to high populated/dense nodes (Figure 1). The objective of this assessment is to verify that the base-year SO_2 emissions patterns used in TM5-FASST are sufficiently robust with respect to the spatial distributions of existing power plants. Moreover, to verify that plants are relatively close to populated nodes reduces the inherent uncertainty of the air pollution model (TM5-FASST) in terms of atmospheric and meteorological assumptions.

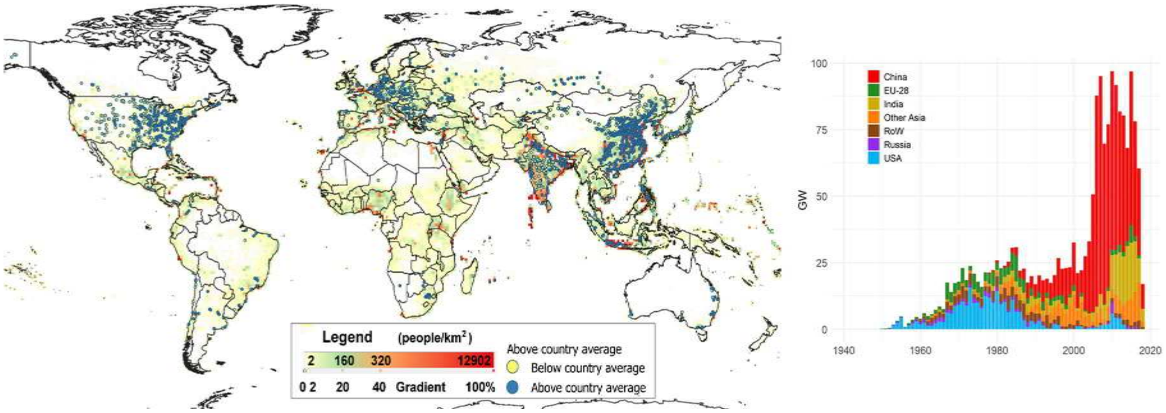

Figure 1: Geolocation of the world coal power plants. Comparison of the distance of coal-fired power plants to high-populated nodes. The green to red gradient shows the gridded population density. The blue and yellow dots represent if the plant is above or below the country average density, respectively. Location of the plants is taken from World Resource Institute (http://datasets.wri.org/). Population data from CIESIN 2017 [62]. The panel in the right shows the global coal capacity by vintage year (GW). Data form Cui et al (2019)[7].

In China, 80% of the plants, i.e. 645, are situated (with the 50km radius) in an area where population density is above the national average (150 person/km2), while the remaining 20% are located in an area with a below-average population density. In the USA, 55%, around 235 plants, are situated in an area of higher density than the average of the country (36.5 person/km2), while 191 plants are situated in an area of lower density than the average. In India, on the other hand, only 37% of the plants, i.e. 91 of them, are situated in an area of higher density than the average of the country (401 person/km2), while 155 plants are situated in an area of lower density than the country average. However, given that India's population density is significantly higher the world average population density (57 person/km2), more than 99% of coal plants in India would be located relatively close to areas where the population density is above the world average. In the rest of the world, the percentage of the plants close to relatively dense population grids varies significantly, ranging from 97% in Poland to 43% in Japan. Additionally, we have compared the plant distance to high and low population density areas (25th and 75th percentiles, see the SI, Table S1). Around 53% of the plants are located relatively close to high-populated nodes at a global level (75th percentile), while only the 13% of the plants are close to low density areas (percentile 25th).

3.2 Health impacts from cancelling new projects

In the last decade, SO_2 emissions associated to coal plants have been a major contributor to the formation of $PM_{2.5}$. This has generated significant health impacts. Between 2010 and 2020, we estimate that SO_2 emissions from power plants have caused 275,000-305,000 premature mortalities each year at a global level, which represents around 6-8% of total premature deaths attributable to air pollution. These premature mortalities would be heavily concentrated in India (100,000-150,000) and China (60,000-80,000) (SI, Table S2).

We find that cancelling all new projects that are currently under development would decrease $PM_{2.5}$ globally due to the replacement of coal by clean energy sources in electricity generation (comparing the results of "*ContinuedGrowth*" vs "*NoNewCoal*" scenarios). The largest reductions will occur in South and East Asia, mostly China and India (Figure 2). In each country, $PM_{2.5}$ concentration will decrease up to 4%, and 13%, respectively in 2030, and to 3%, and 24% in 2050. In addition, the large emissions reductions in these regions make that some contiguous countries (e.g. Pakistan) would present significant cross-border reductions in $PM_{2.5}$ concentration levels (12-15%).

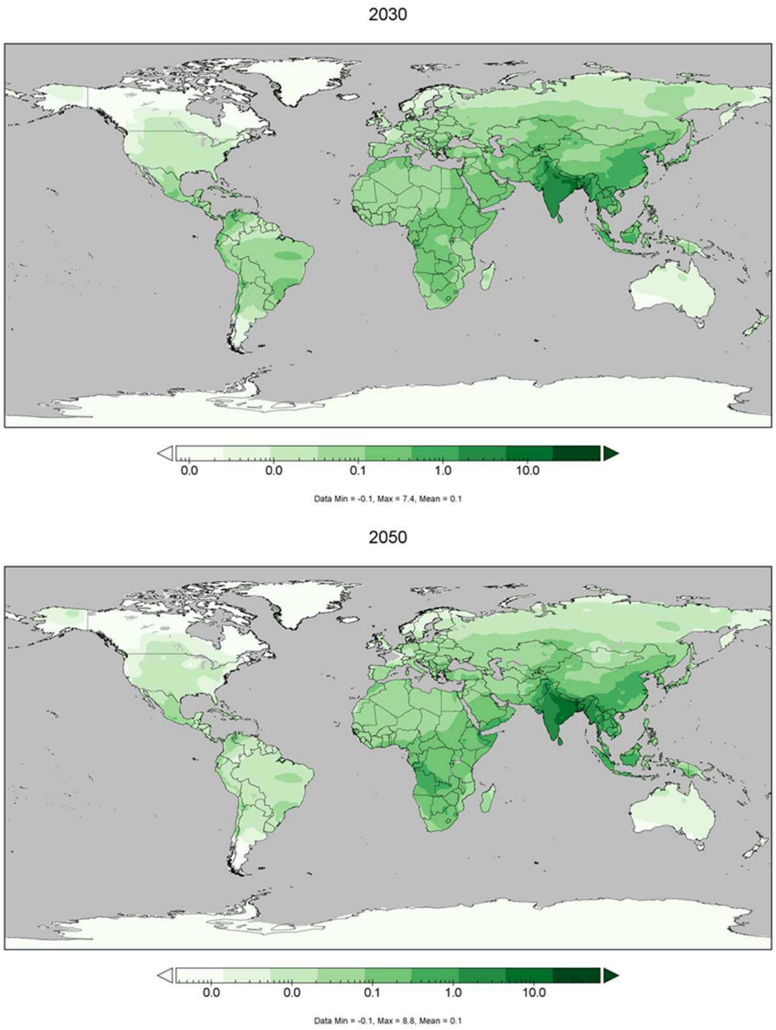

Figure 2: Change in anthropogenic $PM_{2.5}$ concentrations in 2030 and 2050 (log(µg/m3)) between "*ContinuedGrowth*" and "*NoNewCoal*" scenarios, using SSP2 emission factors**.** $PM_{2.5}$ estimations are obtained by feeding GCAM emissions of $PM_{2.5}$ precursors into TM5-FASST. These pollutants are sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), black carbon (BC) and organic carbon (OC).

These $PM_{2.5}$ reductions would decrease premature mortality attributable to air pollution by 213,205 (5%) and 373,054 (8%) at a global level, in 2030 and 2050, respectively, based on emission factor trajectories from the SSP2 narrative. Alternatively, when using the vintage approach to modelling SO_2 emissions (*VintageControl*), we have estimated that these values would be reduced to 101,388 (2%) and 213,414 (5%). By assuming improved control technologies for newer plants, the avoided mortality remains significant; on the other hand, if they are not successfully implemented moving forward, the health co-benefits from new plants cancellation could be even larger.

While air quality improves in many regions across the world, health benefits from cancelling new coal projects are concentrated in India, China and Southeast Asia due to their high population densities and the existing coal fleet (Figure 3A). Using SSP2 emission factors, premature mortality will decrease between 3% and 8% in 2030 and around 3% and 17% in 2050, in China and India, respectively. The implementation of the *VintageControl* approach in the baseline scenario reduces those values, particularly in India, where they would decrease to 2% and 8% for 2030 and 2050.

Moreover, the avoided premature mortality of cancelling new coal-fired power plants in China and India are comparable to the health benefits obtained by implementing the NDCs. Specifically, premature mortality associated with air pollution would decrease around 5% and 7% in 2030, and around 8% and 11% in 2050, in China and India, respectively, if they achieve their NDC targets (see detailed description of the estimated premature mortalities by region and scenario in SI, Figure S6). The co-benefits obtained from the implementation of the NDCs are in line with previous studies [25,26], by taking into account projected population growth by 9% and 26% by 2030 and 2050, respectively.

Globally, the no new coal strategy and the economy-wide emission reduction (NDCs) are also comparable in terms of the resulted air pollution driven health co-benefits. However, the relative effects between the two tend to vary across regions (Figure 3B). On the one hand, cancellation of coal-fired power plants would be more effective than the application of the NDCs in India, Indonesia, rest of Southeast Asia or Eastern Europe. In Indonesia, for example, premature mortality from cancelling coal-fired plants would decline by 8% in 2030 and 11% in 2050 using SSP2 emission factors; while the application of the NDCs would only reduce the premature mortality by 3% in 2030 and 2% in 2050. On the other hand, China (and several other regions, mostly Europe) would obtain larger health co-benefits from the NDCs than no new coal. This does not imply a choice would need to be made between one strategy or the other, but that regions can experience differing relative benefits depending on the pathway.

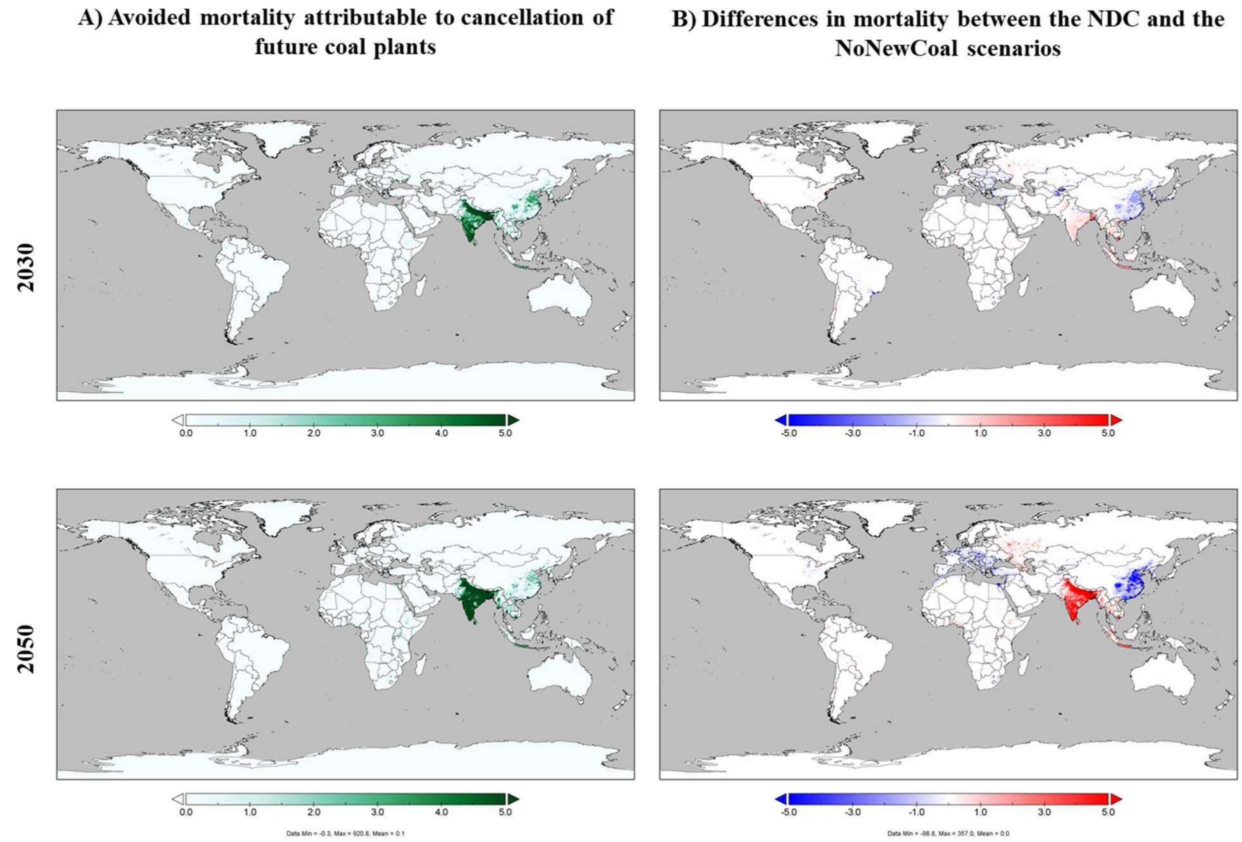

Figure 3: Avoided premature mortality of cancelling future coal plants (*NoNewCoal*) and implementing the NDCs, using SSP2 emission factors**.** A) Comparison of the avoided premature mortality between *NoNewCoal* and *ContinuedGrowth-SSP2* scenarios for 2030 (top) and 2050 (down). B) Comparison of the avoided premature mortality between *NoNewCoal* and *NDC* scenarios (*NDC-NoNewCoal*) for 2030 (top) and 2050 (down). Red indicates that co-benefits are higher by cancelling all new power plant projects and blue that they would be higher by applying NDCs.

3.3 Health co-benefits in a context of decarbonization

As demonstrated above, cancelling new coal-fired power plants can effectively reduce the impacts of air pollution. Next, we quantify the co-benefits generated by the accelerated coal retirement under deep decarbonization scenarios, where different coal retirement pathways are taken (see SI, Figures S7-S10). Specifically, we compare air pollution related regional premature mortality of two stringent decarbonization scenarios, which are the 2°C and 1.5°C temperature stabilization targets. Then, we examine which share of those mortalities corresponds to the rapid phaseout of coal power plants in these scenarios.

Strengthening the climate target from the 2°C to the 1.5°C would reduce a significant amount of premature mortality. Globally, the reduction of premature mortality driven by reinforcing the temperature objective from 2°C to 1.5°C accounts for 326,351 fewer deaths in 2030, of which 251,011 (75%) would be driven by faster retirement of coal-fired power plants in the 1.5°C decarbonization scenario (Table 1). However, the additional reduction in mortality driven by faster coal shutdown will disappear in 2050 (SI, Table S3), because a large majority of coal power generation without carbon capture and storage (CCS) would be phased out by 2050 under both scenarios [3,5,6] (coal plants with CCS will not emit significant SO_2 emissions).

	2030 Premature mortality			**2030 Mortality from coal plants**		
Region	**2°C**	**1.5°C**	**Diff**	**2°C**	**1.5°C**	**Diff**
China	1,300,940	1,203,130	97,810	86,510 *(6.65%)*	17,980 *(1.49%)*	68,530
India	1,205,730	1,009,650	196,08	184,310 *(15.29%)*	49,130 *(4.87%)*	135,180
Rest of South Asia	331,767	298,811	32,956	25,021 *(7.54%)*	6,258 *(2.09%)*	18,763
Russia	199,643	218,410	-18,767	1,098 *(0.55%)*	269 *(0.12%)*	829
Western Africa	178,705	179,640	-936	496 *(0.28%)*	85 *(0.05%)*	412
Gulf States	131,146	127,914	3,232	644 *(0.49%)*	130 *(0.10%)*	513
Eastern Africa	109,310	106,288	3,022	2,253 *(2.06%)*	472 *(0.44%)*	1,781
EU-28	93,557	89,021	4,536	2,749 *(2.94%)*	466 *(0.52%)*	2,284
Vietnam	53,294	52,542	752	2,745 *(5.15%)*	468 *(0.89%)*	2,277
Indonesia	52,822	52,574	248	3,406 *(6.45%)*	851 *(1.62%)*	2,555
Egypt	52,674	50,207	2,467	483 *(0.92%)*	66 *(0.13%)*	417
Central Asia	50,433	49,110	1,323	556 *(1.10%)*	66 *(0.13%)*	490
Ukraine	45,94	44,195	1,745	1,149 *(2.50%)*	238 *(0.54%)*	910
USA	45,852	55,749	-9,897	985 *(2.15%)*	157 *(0.28%)*	828
Rest of Southeast Asia	32,174	28,794	3,380	4,252 *(13.22%)*	886 *(3.08%)*	3,366
Korea	31,119	27,602	3,516	2,146 *(6.90%)*	439 *(1.59%)*	1,707
Germany	22,346	22,428	-82	588 *(2.63%)*	96 *(0.43%)*	492
Turkey	19,463	16,721	2,742	1,084 *(5.57%)*	176 *(1.05%)*	908
Japan	17,011	17,385	-374	1,281 *(7.53%)*	252 *(1.45%)*	1,029
Total 19 selected	3,973,923	3,650,172	323,751	321,755 *(8.10%)*	78,485 *(2.15%)*	243,270
All other	199,334	196,734	2,600	9,404 *(4.72%)*	1,663 *(0.85%)*	7,741
TOTAL	**4,173,257**	**3,846,906**	**326,351**	**331,159** ***(7.94%)***	**80,148** ***(2.08%)***	**251,011**

Table 1: Total premature mortality and share of coal-fired power plants driven premature mortality per region and scenario in 2030. Results for 19 selected regions are presented, which account for the largest amount of premature mortality and are the most affected by the coal plant retirements. These regions cover more than 93% of the premature mortality, so remaining regions are gathered as "Rest of the World (RoW)". The countries included in the groups are:

Rest of South Asia: Afghanistan, Bangladesh, Bhutan, Nepal and Pakistan; *Western Africa*: Benin, Burkina Faso, Cameroon, Cape Verde, Cote d'Ivoire, Equatorial Guinea, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Republic of Congo, Saint Helena, Sao Tome and Principe, Senegal, Sierra Leone and Togo; *Gulf States*: Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates, Yemen; *Eastern Africa*: Burundi, Central African Republic, Chad, Comoros, Congo, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Seychelles, Somalia, South Sudan, Sudan, Tanzania and Uganda*; Central Asia*: Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan; *Rest of Southeast Asia*: Cambodia, Laos and Myanmar.

Across regions, China and India each account for around 30-31% and 26-29% of total premature mortality in 2030, followed by far by Rest of South Asia (7-8%) and Western Africa (4-5%). Although they have large mitigation potential, the development stage and their high population density make these two regions account for a substantial amount of the total premature mortality attributable to air pollution (SI, Figure S11). In terms of premature mortalities associated to coal-fired power plants in 2030 in the 2°C scenario, India shows the largest amount (184,310; 15%), followed by China (86,510; 7%), Rest of South Asia (25,021; 8%) and Rest of Southeast Asia (4,252; 13%). Due to the lower temperature target, these numbers would be greatly reduced in the 1.5°C scenario in 2030, but the regional trends are similar, as India (49,130; 5%), China (17,980; 1.5%), and Rest of Asia (6,258; 2%) would show the largest premature mortalities attributable to coal power plants (SI, Figure S12).

For certain regions, mortality may increase under the more ambitious 1.5°C target, mainly due to the potential expansion of biomass used with CCS. Higher biomass consumption would be associated with additional land conversion, which can result in increases in primary $PM_{2.5}$ emissions. However, this effect is relatively small and only shows in a few countries (Table 1 and SI, Table S3). On the other hand, the additional health co-benefits driven by faster coal plants shutdown is consistent across countries. In particular, China and India jointly represent 81% of the total additional reduction of premature mortality in 2030 (68,530 and 135,180 additional avoided deaths), followed by other Asian regions such as Rest of Asia, Indonesia or Rest of Southeast Asia.

4 Discussion

The combined use of integrated models applied in this study is a well-accepted methodology to analyse the whole-system interactions and implications of different policy strategies. In such a modelling framework, the socioeconomic, energy, land and environmental assumptions taken will have direct effects on the results. One of the key assumptions of the scenario analysis is the values of future emission factors, as they are a key determinant of regional and global emissions levels. Emission factors represent current and future GHG or air pollutants emissions per unit of activity (produced output or consumed resource). Thus, these include not only pollutant contents but technological improvements and implicit air quality regulation that would potentially decrease unitary emissions in the future. Therefore, estimations of future emission factors would be uncertain as noted in the literature [63,64].

In order to analyse the effects of future SO_2 emission factors on the results, we have calculated health co-benefits attributable to coal phase-out by implementing an alternative approach for SO_2 emission factors (*VintageControl*, see section 2.2). This approach, by assuming improved control technologies for newer plants, largely reduces SO_2 emissions in the baseline scenario. As the result, the avoided premature mortality associated to cancelling new coal projects would be smaller by using the *VintageControl* approach compared to SSP2 emission factors [65]. Specifically, at a global level, mortality reduction would decrease from 5% to 2% in 2030, and from 8% to 5% in 2050, when considering the evolution of emissions control cross coal plants vintages in the baseline. This difference is especially relevant in India, where estimated avoided premature mortalities decrease from 8% to 2% in 2030 and from 17% to 8% in 2050. These results demonstrate that coal vintages dynamics would directly impact the results.

Apart from the technological developments and the stringency of the proposed air quality policies, the degree to which air quality policies are effectively implemented will also be a relevant driver. For example, there exists strong evidence which demonstrates that China has substantially reduced SO_2 emissions in recent years [60,66], so it seems likely that future emission factors will continue to decrease. Zheng et al (2018) [60] demonstrate that air pollutant emissions in China have substantially decreased in recent years due to effective implementation of air quality policies, estimating that SO_2 emissions have decreased by 62% over 2010-2017. Therefore, future SO_2 emission factors in reality are likely to be significantly lower than the values assumed in the SSP2 narrative. On the other hand, we note that SO_2 emissions in India are not aligned with the targets defined in the country's air pollution policies. However, Indian Government has recently announced a plan for a large-scale installation of flue gas desulphurization (FGD) units in coal plants by 2022, that would significantly reduce SO_2 emissions [67]. Therefore, future research should focus on baseline regional emission trends for air pollutants in order to better estimate health co-benefit potential.

5 Conclusion

In this research, we quantify the health co-benefits from cancelling new coal-fired power plants in the context of deep decarbonization. We find that that this measure would result in significant reductions of $PM_{2.5}$ concentrations at a global level, with largest reductions in China and India. These regions also present the largest health co-benefits due to high population density. In China and India reductions in premature mortality related to air pollution would account for 47,470 (3%) and 114,590 (8%) in 2030 and 29,840 (3%) and 263,500 (17%) in 2050, respectively.

Moreover, strengthening the climate target from the 2°C to the 1.5°C would reduce a significant amount of premature mortality, especially during the medium-term transition period. While the reduction of premature mortality related to reinforcing the climate target accounts for 326,351 deaths in 2030, 251,011 (75%) are attributable to the additional retirement of coal-fired power plants. We find that these extra co-benefits would be heavily focused in India, followed by China and other Asian regions. However, the additional reduction in mortality driven by faster coal shutdown will disappear in the long run, because the large majority of coal plants are phased out by 2050 under both the 1.5°C and 2°C scenarios.

Phasing out conventional coal plants is necessary for meeting objectives defined in the Paris Agreement. Mitigating the effects of climate change is a complex undertaking [68], but recent studies have proved that regional health co-benefits can provide additional incentive to reduce emissions [69]. This study demonstrates that air quality related health co-benefits from coal plant cancellation are comparable at a global level to the co-benefits obtained from the implementation of the NDCs. Although end-of-pipe emission controls can also achieve air pollutant reductions in the near-term, continued air quality improvement to a higher standard requires energy system transition from fossil fuels to non-emitting resources (such as renewables) [70] . Therefore, coal plants cancellation would generate greater health benefits over the long run. Moreover, this work opens avenues for future research. First, a more detailed analysis of coal retirement, by including variables such as vintage of existing facilities or the investment needs for alternatives (i.e. costs of CCS retrofits) would allow assessing the economic impacts of such energy system transformations. Likewise, the monetization of the obtained premature mortality, as done in previous studies [25,26], would also highlight the magnitude of the potential economic benefits, even though there exists a scientific debate on the methodologies for monetizing health co-benefits [71]. Finally, implications of coal power plant cancellation and retirement may also have effects on other Sustainable

Development Goals (SDGs) (i.e. water, energy access, employment) which could be incorporated into the analysis.

Data Availability

All data used for analysis are available from publicly available sources cited or from the authors upon reasonable request. Scenarios have been modelled with GCAM, which is an open source human-earth system model that can be downloaded from a public repository: https://github.com/JGCRI/gcam-core/releases

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Author Contributions

J.S. and R.C. coordinated the research and performed the scenario analysis. J.S. led the writing of the paper. H.M., N.H. and S.J.S. contributed to the study and scenario design. L.H. and A.S. contributed to data collection and analysis. I.C. and J.S. designed the geolocation assessment and I.C performed the analysis. RVD contributed to the TM5-FASST simulations. All the authors contributed to the writing.