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PERSPECTIVE

US power plant carbon standards and clean air and health co-benefits

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Carbon dioxide emissions standards for US power plants will influence the fuels and technologies used to generate electricity, alter emissions of pollutants such as sulphur dioxide and nitrogen oxide, and influence ambient air quality and public health. We present an analysis of how three alternative scenarios for US power plant carbon standards could change fine particulate matter and ozone concentrations in ambient air, and the resulting public health co-benefits. The results underscore that carbon standards to curb global climate change can also provide immediate local and regional health co-benefits, but the magnitude depends on the design of the standards. A stringent but flexible policy that counts demand-side energy efficiency towards compliance yields the greatest health benefits of the three scenarios analysed.

On 2 June 2014, the US Environmental Protection Agency (EPA) proposed CO_2 emissions standards for existing power plants in the Clean Power Plan[1]. When finalized in summer 2015, affected states will use the federal standards to develop state implementation plans for decreasing CO_2 emissions from the power sector. As an abundant greenhouse gas, CO_2 is a major contributor to climate change. Power plants in the USA fired by fossil fuels emitted 2 billion tonnes of CO_2 in 2012[2], representing 39% of total national emissions — more than any other single source. Standards to reduce CO_2 emissions for existing US power plants can result in near-term public health benefits locally and regionally by decreasing emissions of co-pollutants, including sulphur dioxide (SO_2), nitrogen oxides (NO_x), mercury (Hg) and fine particulate matter ($PM_{2.5}$).

We linked power sector model results with air quality and epidemiological models to quantify the air quality and public health benefits of changes in emissions of co-pollutants under different scenarios for power plant carbon standards. The analysis is based on emissions estimates for each of the 2,417 fossil-fuel-fired power plants in the USA, from the Integrated Planning Model (IPM), for a reference case and three policy scenarios (http://www.icfi.com/insights/products-and-tools/ipm; Supplementary Information: Emissions modelling). These emissions estimates were used as inputs for the spatially explicit Community Multiscale Air Quality Model (CMAQ v. 4.7.1) to project resulting changes in air quality at a 12 × 12 km resolution for the continental USA (http://www.epa.gov/AMD/Research/RIA/cmaq.html; Supplementary Information: Air quality modelling). The CMAQ results for ozone (O_3) and $PM_{2.5}$ were used as inputs for the Environmental Benefits Mapping and Analysis Program-Community Edition (BenMAP-CE v. 1.08) to estimate public health co-benefits for each scenario compared to the 2020 reference case (http://www.epa.gov/airquality/benmap/ce.html; Supplementary Information: Health co-benefits modelling). We isolate the co-benefits attributable to the carbon standards by comparing changes in air quality and health co-benefits in the year 2020 for each scenario with a reference case that includes all existing and planned air quality policies for the power sector. The results show that, for two of the three policy scenarios, carbon standards for existing power plants can substantially decrease emissions of harmful co-pollutants, and improve air quality and public health beyond what would occur under existing air quality policies.

Scenarios for power plant carbon standards

To facilitate comparison with the goals of the Clean Power Plan, we report estimated changes in CO_2 emissions to 2005 levels, the baseline year used in the plan. The Bipartisan Policy Center (BPC) and the Natural Resources Defense Council (NRDC) developed the reference case that was used for our analysis. We selected two policy scenarios that were generated by BPC (scenarios 1 and 3) and one that was developed by NRDC (scenario 2). As we were interested in a wide range of policy approaches, researchable scenarios were selected that incorporate contrasting policy assumptions. The policy differences in the scenarios include different approaches to CO_2 emissions reductions, investments in end-user energy efficiency, and inclusion of options for compliance such as co-firing, fuel-switching and cross-state trading.

The reference case uses the energy demand projections in the Annual Energy Outlook for 2013[3] as the benchmark. Current EPA clean air policies are fully implemented under this scenario, including the Mercury and Air Toxics Standard (MATS) and the Clean Air Interstate Rule. Moreover, existing state-level requirements for power sector emissions reductions and renewable energy portfolio standards are implemented under this scenario. By 2020, minor changes in energy generation sources under the reference case result in an estimated decrease in annual CO_2 emissions of 15.2% compared with 2005 levels (Table 1).

Scenario 1 uses the potential estimated heat-rate improvements at individual coal-fired units to set unit-specific emissions rate standards. The stringency of the resulting CO_2 emissions standards under this scenario is low and the requirements for compliance are limited to operational changes 'inside the fence line' of existing affected power plants. The new-source performance standard

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Table 1 | Distribution of energy generation for 2005, for the reference case and three scenarios, and EPA estimates for the proposed standards in 2020 and 2030, and associated emissions.

		2005	Reference case 2020	Scenario 1 2020	Scenario 2 2020	Scenario 3 2020	EPA Clean Power Plan 2020 scenario*	EPA Clean Power Plan 2030 scenario*
Energy generation (TWh)	Total	4,055	4,213	4,212	4,227[†]	4,166	4,235[†]	4,565[†]
	Total fossil generation	2,909	2,770	2,770	2,362	2,614	2,681	2,630
	Combined cycle (gas)	761	1,030	1,001	1,013	1,297	1,281	1,313
	Combustion turbine (gas)	–	75	72	75	84	33	32
	Coal (no CCS)	2,013	1,639	1,671	1,217	764	1,335	1,246
	Coal (CCS)	0	7	7	38	443	2	2
	Nuclear	782	804	804	788	855	817	796
	Hydro	270	307	307	308	301	282	281
	Wind	18	227	228	230	284	233	259
	Biomass	39	39	40	39	46	27	27
	New energy efficiency	N/A	0	0	437	0	133	502
	Other non-renewables[‡]	135	19	19	19	26	30	37
	Other renewables[§]	37	66	63	63	66	62	70
Annual power sector emission (t)	CO_2 (million)	2,410	2,045	1,998	1,562	1,229	1,794	1,715
	SO_2 (thousand)	9,563	1,584	1,628	1,152	1,143	1,076	1,005
	NOx (thousand)	3,592	1,210	1,174	938	1,011	1,103	1,028
	Hg	47	5	5	3	4	6	6

*Based on IPM emissions estimates for EPA's option 1: regional illustrative compliance scenario in 2020. Full implementation occurs in 2030[3]. [†]New demand-side energy efficiency included in total generation. EPA estimate based on projected 3% decline in total energy demand in 2020 and 11% decline in 2030 from demand-side energy savings[3]. [‡]Other non-renewables include generation from petroleum and other gases. [§]Other renewables includes generation from waste products, geothermal and solar/photovoltaic.

applies, but there are no new coal plants built under scenario 1. The national average CO_2 emissions rate for coal-fired power plants decreases modestly under this scenario to 907 kg MWh^{-1}. A 4% increase in fleet-wide average heat rate occurs for coal-fired power plants.

By 2020, energy generation from coal-fired power plants increases under scenario 1, but most other sources of generation remain similar to the reference case (Table 1). Scenario 1 results in an estimated decrease in annual CO_2 emissions of 2.2% from the 2020 reference case (17.1% from 2005), an annual SO_2 emissions increase of 3%, and a decrease in annual NO_x and Hg emissions of 3% (Table 1).

Scenario 2 allows numerous options for compliance and promotes large programme investments in demand-side energy efficiency. Scenario 2 uses emissions rate targets of 680 kg MWh^{-1} for coal and 453 kg MWh^{-1} for gas and the current generation mix to establish emissions rate performance standards and CO_2 emissions reductions for each state. The stringency of the CO_2 emissions standards under this scenario is moderate. Implementation of scenario 2 makes renewable energy and demand-side energy efficiency available for compliance. This scenario also allows the averaging and trading of emissions among all new existing and new fossil units in a state and between states.

By 2020, energy generation under scenario 2 results in markedly less power from existing coal plants and modest increases in generation from new coal plants with carbon capture and storage (CCS). Demand-side energy efficiency is greater under this scenario than the others considered (Table 1). Under scenario 2, annual estimated CO_2 emissions decrease by 23.6% from the 2020 reference case (a 35.5% decrease from 2005 levels), annual estimated SO_2 and Hg emissions decline by 27%, and annual estimated NO_x emissions decrease by 22% (Table 1).

Scenario 3 applies the social cost of carbon of US$43 t^{-1} to drive supply-side power sector emissions reductions in 2020. The scenario mimics a national tax on CO_2, requiring all existing and new power plants to implement pollution reduction measures that are less than or equal to the social cost of carbon[3]. This strategy results in high stringency of the CO_2 emissions standards under this scenario. Such a market-based approach also allows for a wide range of compliance options including heat-rate improvements, substituting or co-firing with lower emitting fuels (for example, natural gas, biomass), or increasing generation from lower-emitting sources such as new coal plants with CCS. Scenario 3 does not promote new policy-driven investments in demand-side energy efficiency. However, increases in electricity prices reduce demand and generation. Average national CO_2 emissions rates of 544 kg MWh^{-1} for coal-fired power plants and 385 kg MWh^{-1} for gas are achieved under scenario 3.

By 2020, generation from coal-fired power plants with CCS and natural gas increased markedly under the carbon tax approach used in scenario 3 (Table 1). Under scenario 3, annual estimated CO_2 emissions decrease by 39.8% from the reference case (a 49.2% decrease from 2005 levels), annual estimated SO_2 and Hg emissions decline by 27%, and annual estimated NO_x emissions decrease by 16% (Table 1). The outcome by 2020 may seem implausible, even if a carbon tax was introduced, in part because of lingering uncertainty about CCS technology and the ability to implement it on a large scale by 2020. However, this scenario reflects changes that occur five years after adoption of new standards and provides a useful bookend representing system response to a high stringency alternative, with insights that could apply beyond 2020.

While not intended to represent the EPA proposal, scenario 2 is most similar to the Clean Power Plan in terms of stringency of the CO_2 emissions targets, flexibility of the policy structure, policy-driven incentives for energy efficiency, and outcomes for future co-pollutant emissions. Specifically, the Clean Power Plan calls for a 30% reduction in CO_2 emissions from 2005 levels by 2030, compared with 35.5% by 2020 in scenario 2[1,4] (Fig. 1). Like scenario 2, the Clean Power Plan provides states with a flexible array of options across the power sector to achieve state-specific CO_2 standards. Compliance options include: (1) improved power plant efficiency (that is, heat-rate improvements); (2) replacing coal or oil with fuels that are less CO_2 intensive (for example, natural gas); (3) switching from fossil to renewable power (for example, solar or wind); and (4) adopting new demand-side energy efficiency measures[4]. EPA estimates that the standards will result in a 25% cut in emissions of SO_2 and NO_x from their reference case by 2030, compared with 27% and 22%, respectively, in scenario 2. The decrease in co-pollutant emissions of 704,000 t in scenario 2 (432,000 t SO_2, 272,000 t NO_x) from the reference case in 2020 is well within the range EPA estimates for the proposed standards compared to EPA's 2020 reference case based on their analysis of different implementation options (637,000 t in 2020 to 816,000 t in 2030)[4]. There are moderate differences in stringency between scenario 2 and the Clean Power Plan, but our results for scenario 2 show that policies with stringency, flexibility and programmatic support for energy efficiency can result in large changes in co-pollutant emissions. This is especially evident in contrast with scenario 3, which has greater stringency but a different structure and yields lower co-benefits (Fig. 1).

Changes in air quality

Detailed boiler unit-level IPM emissions were used for the reference case and the three scenarios as input to CMAQ to estimate anticipated changes in air quality associated with changing power plant emissions. We used CMAQ output to determine spatial patterns of expected changes in ground-level O_3 and $PM_{2.5}$ for 2020. These pollutants have well-understood health and environmental consequences that are documented extensively in the peer-reviewed literature[5,6].

Scenario 1 results in a modest increase in average annual $PM_{2.5}$ (Fig. 2a) and peak ground-level O_3 concentrations (Fig. 3a) compared with the reference scenario. This pattern of 'emissions rebound' at several coal-fired power plants occurs when facilities that exhibit high emissions are made more efficient and therefore run more frequently and for longer periods than in the reference case[7].

Scenario 2 results in lower average annual $PM_{2.5}$ (Fig. 2b) and peak ground-level O_3 concentrations (Fig. 3b) in all the lower 48 US states compared with the reference case. The largest decreases in pollution occur in the eastern USA, particularly in states in and around the Ohio River Valley. The stringent carbon emissions rate standard is flexible enough to allow fuel substitution, and yields a substitution away from coal to natural gas. The scenario also promotes a shift towards demand-side energy reductions.

Air quality patterns for scenario 3 are similar to scenario 2, despite greater CO_2 emissions reductions (Supplementary Fig. 1a,b). Fewer tonnes of SO_2 and NO_x are controlled per tonne of CO_2 controlled for scenario 3 than for scenario 2 and for the EPA proposed standards (Fig. 1). This pattern is due to continued reliance on fossil fuel sources, expansion of coal with CCS and the lack of new demand-side energy efficiency investments under this scenario.

Health co-benefits analysis

We used the $PM_{2.5}$ and O_3 concentrations from the CMAQ air quality simulations for the continental USA and compared them with the 2020 reference case to estimate and map the health co-benefits for each of the policy scenarios. These estimates do not include the direct health benefits resulting from mitigating climate change (for example, reduced heat-related illness). Concentration–response functions were derived for six health co-benefit outcomes, on the basis of extensive published literature on the health effects of air pollution. The six outcomes are: $PM_{2.5}$-related changes in premature deaths; myocardial infarctions (heart attacks); cardiovascular hospital admissions (excluding myocardial infarctions); respiratory hospital admissions; O_3-related changes in premature deaths; and hospital admissions associated with respiratory illness.

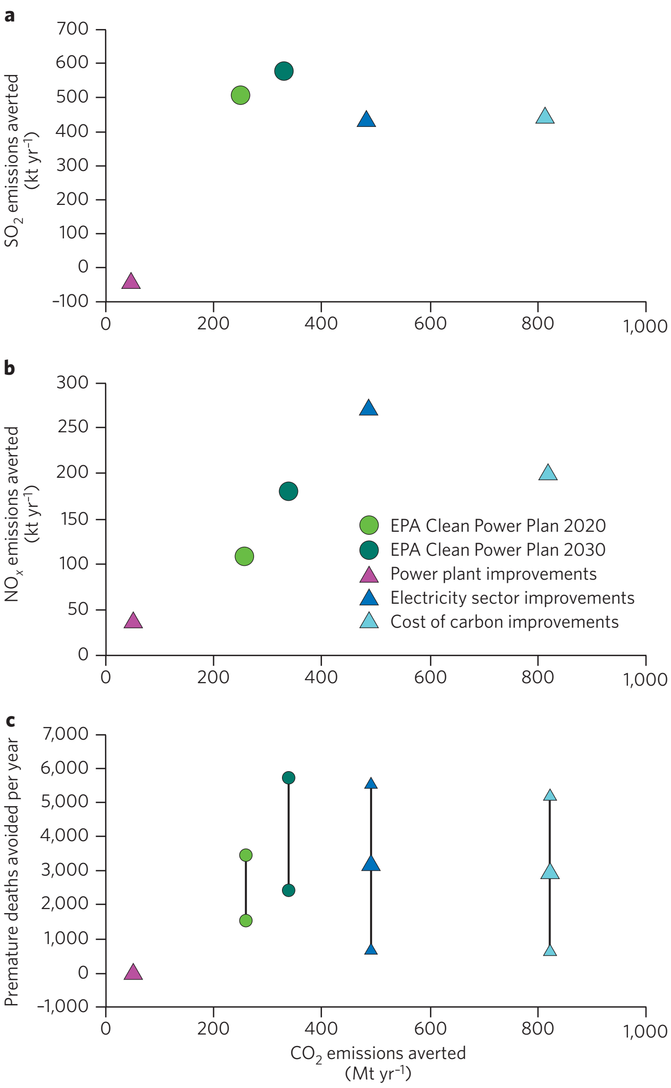

Figure 1 | Comparison of each scenario and the proposed US EPA Clean Power Plan by SO_2 and NO_x averted, and premature deaths avoided, per tonne of CO_2 averted. **a**, SO_2 averted; **b**, NO_x averted; and **c**, premature deaths avoided per tonne of CO_2 averted. Smaller symbols indicate uncertainty bounds and larger symbols indicate central estimates, where available, for premature deaths avoided.

We selected this subset of health outcomes from the numerous effects associated with $PM_{2.5}$ and O_3 because they are supported by concentration–response functions derived from investigations that examined populations from multiple cities simultaneously under different conditions across the USA, large cohort studies of residents from different locations, or meta-analyses of studies that have taken place in many different locations. These health outcomes contribute to most of the monetized benefits accompanying air quality management[4,8–11].

In BenMAP-CE, we linked data on population, age structure, baseline prevalence and incidence rates of the health co-benefit outcomes of interest to estimate changes in outcomes at the county and state levels for the continental USA for each of the three carbon standard scenarios, compared with the 2020 reference case. We report the central estimate and 95% confidence intervals for each health outcome, based on only concentration–response function uncertainties, given a lack of quantitative information on other model uncertainties. Population data are from Woods & Poole[12]; baseline hospitalization and myocardial

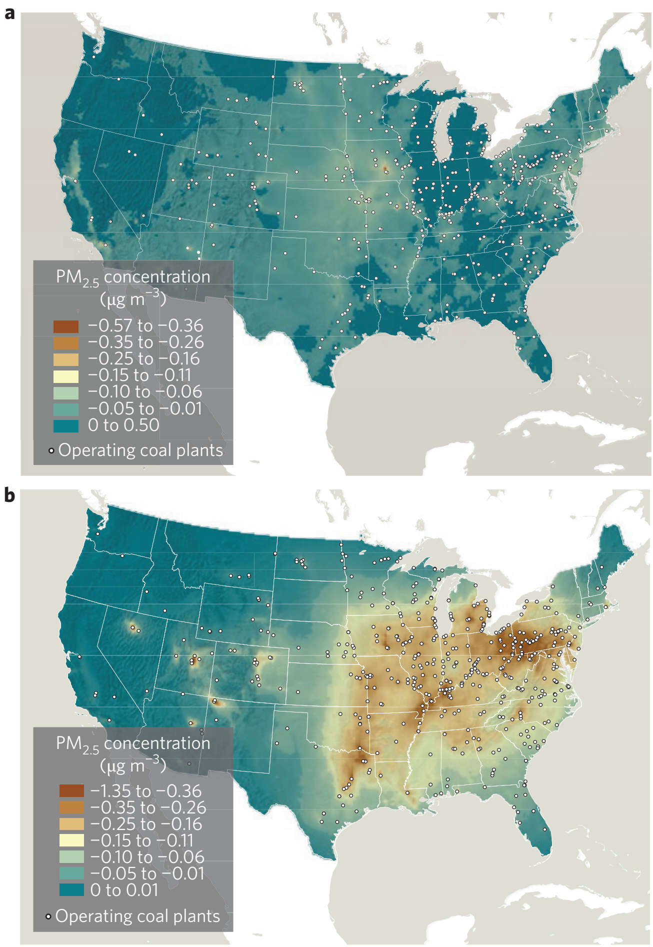

Figure 2 | Maps for the continental USA of difference in annual average concentrations of $PM_{2.5}$ in 2020 for scenarios 1 and 2, less the reference scenario. a, Scenario 1; and **b**, scenario 2.

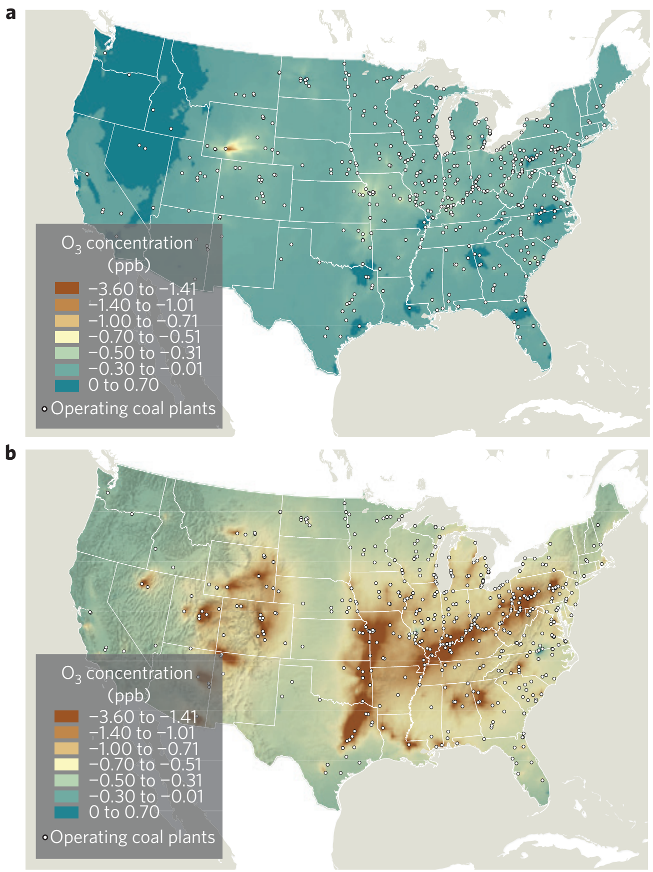

Figure 3 | Maps for the continental USA of difference in annual average concentrations of peak summertime O_3 in 2020 for scenarios 1 and 2, less the reference scenario. a, Scenario 1; and **b**, scenario 2.

infarction data are from the Healthcare Utilization and Cost Program[13]; and mortality rate projections for 2020 are from the US Centers for Disease Control and Prevention WONDER database (http://wonder.cdc.gov/natality-current.html).

The concentration–response functions we derived relate changes in air quality to changes in the rate of an adverse health outcome (Supplementary Information: Concentration–response functions). The functions are based on published epidemiological literature (Supplementary Table 1) and are expressed as a change in the risk of each outcome per unit concentration change of a given pollutant over a given time period. Unless indicated otherwise, we based all values shown here on central estimates.

Comparison of health co-benefits for the USA

Our results show that scenario 1 has the lowest health co-benefits in the continental USA of the three scenarios considered (Table 2). Under this scenario, estimated decreases in hospitalizations were modest and there was a slight increase in premature deaths and heart attacks from the 2020 reference case. This represents a negative co-benefit of 10 additional premature deaths per year (Table 2), which corresponds to −0.2 premature deaths avoided per million tonne decrease in CO_2 (Fig. 1). This pattern is likely to be due to the increase in SO_2 emissions and resulting $PM_{2.5}$ concentrations that are projected for this scenario.

The greatest health co-benefits occur under scenario 2, which results in 3,500 estimated premature deaths avoided annually by 2020 (Table 2). This corresponds to approximately 7.3 premature deaths averted per million tonne decrease in CO_2 emissions (Fig. 1). The national health co-benefits under scenario 3 are lower than those for scenario 2, although the spatial distribution is similar. We estimate a decrease of 3,200 premature deaths each year under scenario 3, corresponding to 4.0 premature deaths avoided per million tonne decrease in CO_2 emissions (Fig. 1).

To put the results in context, the health co-benefits estimated here can be compared to the health co-benefits estimated for the US EPA's MATS rule[11]. MATS results in greater co-pollutant emissions reductions and is estimated to decrease annual average $PM_{2.5}$ by 0.36 μg m^{-3} and annual average eight-hour O_3 concentrations by 0.2 ppb. It results in an estimated 7,600 avoided premature deaths per year (2.17 times the premature deaths avoided under scenario 2), 4,700 avoided non-fatal heart attacks, and other health co-benefits. Although a comparison of the monetized value of these health co-benefits to compliance costs is beyond the scope of this paper, we expect the value to be similar to that of the direct climate-related benefits valued at the social cost of carbon, which alone exceeds the expected cost of compliance[4,7].

Geographic distribution of health co-benefits

The estimated health co-benefits vary widely across the USA and under the three scenarios, with all states experiencing some benefit under scenario 2. For all three scenarios, areas with the highest health benefits have the greatest air quality improvements and large exposed populations.

Scenario 1 results in small changes in the number of premature deaths relative to the 2020 reference case for most counties (Supplementary Fig. 2a). At the state level, based on central

Table 2 | Central estimates and 95% confidence intervals for the change in total national health co-benefits under the three scenarios from the 2020 reference case. All results are rounded to whole numbers with two significant figures.

	Pollutant	Scenario 1 central estimate (95% CI)	Scenario 2 central estimate (95% CI)	Scenario 3 central estimate (95% CI)
Premature deaths avoided (all causes)	$PM_{2.5}$	−44 (−79 to −9)	3,200 (680 to 5,600)	3,000 (650 to 5,400)
Respiratory hospitalizations avoided	$PM_{2.5}$	−5 (−7 to −2)	280 (150 to 420)	280 (140 to 410)
Cardiovascular hospitalizations avoided (except heart attacks)	$PM_{2.5}$	−6 (−7 to −4)	330 (230 to 440)	320 (220 to 420)
Heart attacks avoided (acute non-fatal myocardial infarction)	$PM_{2.5}$	−3 (−5 to −2)	220 (130 to 310)	210 (120 to 300)
Premature deaths avoided (respiratory causes)	O_3	34 (11 to 56)	300 (100 to 500)	200 (68 to 340)
Respiratory hospitalizations avoided	O_3	25 (9 to 41)	410 (150 to 680)	260 (94 to 430)
Total premature deaths avoided	$PM_{2.5}$ and O_3	−10 (−23 to 2)	3,500 (780 to 6,100)	3,200 (720 to 5,700)
Total hospitalizations avoided (respiratory and cardiovascular)	$PM_{2.5}$ and O_3	15 (3 to 27)	1,000 (530 to 1,500)	860 (460 to 1,300)
Total heart attacks avoided (acute non-fatal myocardial infarction)	$PM_{2.5}$	−3 (−5 to −2)	220 (130 to 310)	210 (120 to 300)

estimates, the health co-benefits include 21 to −33 premature deaths eliminated annually (Fig. 4a), 5 to −10 hospitalizations averted per year and 2 to −2 heart attacks avoided each year.

Scenario 2 results in a decrease in mortality risk compared to the 2020 reference case for most of the USA, as indicated by the wide geographic extent of premature deaths avoided (Supplementary Fig. 2b). Based on state-level central estimates, this scenario prevents between 1 and 330 premature deaths (Fig. 4b), up to 71 hospitalizations and up to 19 heart attacks per year. Except for New York, which has a large population and is downwind of many emission sources, the states with high health co-benefits are also those with a large dependency on coal-fired electricity. As a result, the co-benefits coincide spatially with areas where costs of the policy are likely to be greatest.

Scenario 3 results in widespread reductions in mortality risk compared with the 2020 reference case, but they are lower than in scenario 2. Based on state-level central estimates, this scenario prevents 1 to 260 premature deaths, up to 56 hospitalizations and up to 16 heart attacks annually.

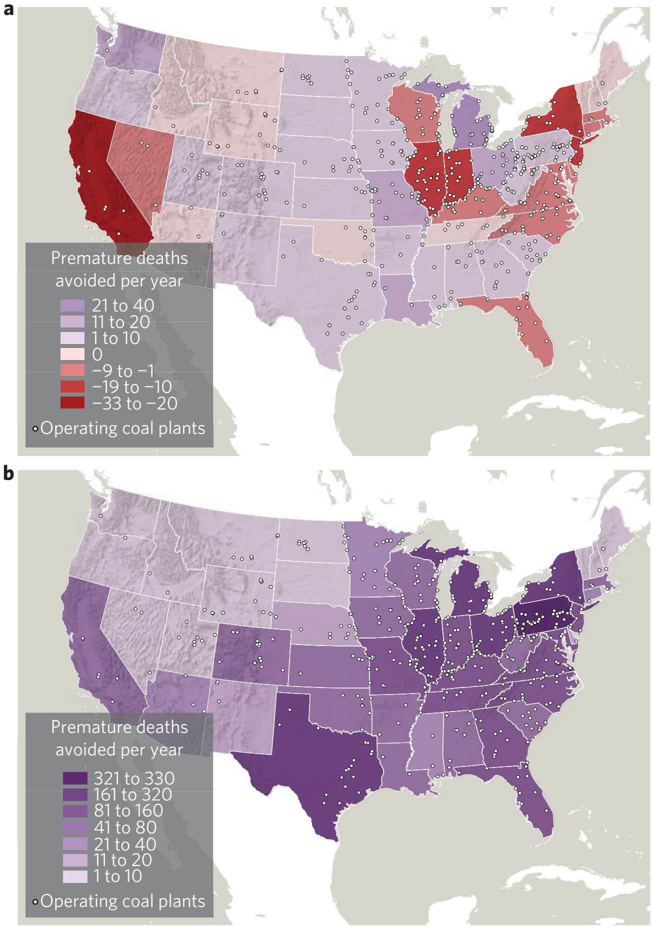

Figure 4 | Change in premature deaths avoided for states of the continental USA from the 2020 reference case for scenarios 1 and 2. **a**, Scenario 1; and **b**, scenario 2.

Policy implications

Different policy approaches to US carbon standards for power plants produce markedly different changes in $PM_{2.5}$ and O_3, and associated health co-benefits. The magnitude and direction of the changes in health co-benefits parallel the changes in annual emissions of SO_2 and NO_x for each scenario (Fig. 1). In each scenario, the geographic distribution of state-level health co-benefits is consistent with air quality changes coupled with population distribution (Figs 2–4; Supplementary Fig. 2). Our analysis shows that the design of carbon standards for US power plants can have a marked impact on air quality and associated health outcomes for local communities and states. Scenario 2 — which is the most similar of our three scenarios to the Clean Power Plan proposal of the EPA in terms of stringency, policy structure and anticipated changes in power generation — results in the greatest estimated emissions reductions, air quality improvements and health co-benefits (Fig. 1). Its top performance is due to lower total fossil fuel generation, greater substitution of natural gas for coal and more new demand-side energy efficiency. In contrast, carbon standards that largely rely on retrofitting existing power plants, as illustrated in scenario 1, could increase SO_2 emissions from the power sector, resulting in potential increases in air pollution beyond what is expected to occur in the reference case. As illustrated by scenario 3, a lower ratio of health co-benefits per tonne of CO_2 emissions controlled can occur when the standards result in carbon pollution controls that continue or increase reliance on coal generation by means of CCS, and provide no new programmatic investment in demand-side energy efficiency.

Carbon standards implemented for existing US power plants that result in improvements in air quality can lead to immediate local and regional health co-benefits. For the USA and other countries with sizeable greenhouse-gas emissions along with air pollution challenges, the link between climate policy, air quality and public health could provide a key catalyst to act on climate change.

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Author contributions

C.T.D. conceived and designed the modelling scenarios/experiments, analysed data and co-wrote the paper. J.J.B. analysed data and co-wrote paper. J.I.L. derived concentration–response functions, contributed to health impact modelling and co-wrote the paper. K.F.L. conceived and designed the modelling scenarios/experiments and co-wrote the paper. D.B. analysed data and scenarios and co-wrote paper. S.B.R. conducted atmospheric modelling. H.F. analysed data. J.S. derived concentration–response functions, contributed to health impact modelling and co-wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to C.T.D.

Competing financial interests

The authors declare no competing financial interests.