Health Co-benefits of Carbon Standards for Existing Power Plants

Part 2 of the Co-Benefits of Carbon Standards Study

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HARVARD SCHOOL OF PUBLIC HEALTH | Center for Health and the Global Environment

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Executive Summary – Part 2: Health Co-Benefits of Carbon Standards

Background

The U.S. Environmental Protection Agency (EPA) released the nation's first-ever carbon pollution standards for existing power plants on June 2, 2014. The EPA-proposed Clean Power Plan would achieve a 30% reduction in carbon emissions from U.S. power plants below 2005 levels by 2030 (USEPA 2014a). Carbon dioxide (CO_2) is an important greenhouse gas and a major driver of human-induced global climate change. Fossil-fuel-fired power plants are the single largest source of anthropogenic CO_2 emissions in the U.S. They emitted 2.2 billion tons of CO_2 in 2012 (AOE 2014) and currently account for 39 percent of total U.S. CO_2 emissions (USEPA 2014b).

Standards to address global climate change by reducing CO_2 emissions from power plants can spur significant improvements to public health and the environment by also curbing other emissions from this source such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM) and mercury (Hg). SO_2 and NO_x emissions contribute to the formation of fine particulate matter ($PM_{2.5}$) sometimes referred to as "soot". NO_x emissions are also a major precursor to ground-level ozone (O_3), sometimes referred to as "smog". For human health, these pollutants increase the risk of premature death, heart attacks, severity of asthma, and other health effects. For ecosystems, these pollutants contribute to acid rain, the over-fertilization of surface waters and many types of ecosystems, ozone damage to trees and crops, and the accumulation of toxic mercury in fish.

The Co-Benefits of Carbon Standards Study

Scientists from Syracuse, Harvard, and Boston Universities launched a three-part[1] co-benefits study in 2013 to quantify the: (1) air quality, (2) public health, and (3) environmental co-benefits of three different carbon policy scenarios based on projected changes in power plant emissions of SO_2, NO_x, and PM. The term "co-benefits" refers to the added improvements that occur from implementing a policy, beyond those associated with the primary target. In this case, the primary target is the reduction of CO_2 emissions and the co-benefits are the improvements associated with ancillary decreases in the other emissions. Since this study is strictly an analysis of co-benefits, it does not quantify the direct health benefits of mitigating climate change, such as anticipated decreases in future heat-related illness.

The three policy scenarios for power plant carbon standards assessed in this study are described on the following page and on pages 7 and 8. The three scenarios represent differing CO_2 emissions reduction stringencies, flexibility in compliance options, and investments in demand-side energy efficiency. These

[1] The Part 1 air quality results were released in May 2014 (see Driscoll et al. 2014). The Part 3 environmental co-benefits results are expected in late 2014.

scenarios were designed prior to the release of the Clean Power Plan, and capture a broad range of alternatives that can inform the final rule. The analysis isolates the co-benefits that are solely attributable to the carbon standards by comparing power plant emissions under the policy scenarios to the emissions that would have occurred under a business-as-usual reference case in the year 2020. The reference case includes the implementation of existing air pollution control policies.

Scenario 1: Power Plant Improvements (low stringency, low flexibility/no user efficiency)
This scenario focuses on heat rate upgrades and other improvements in the operating efficiency of existing power plants. It represents what is commonly referred to as an “inside the fence line” approach favored by some industry groups and states. It does not include new end-user energy efficiency.

Scenario 2: Electricity Sector Improvements (moderate stringency, high flexibility/high user efficiency)
This scenario includes state-based CO_2 emission targets, flexible compliance options, and significant program investments in new end-user energy efficiency. This scenario is most similar to the EPA-proposed Clean Power Plan.

Scenario 3: Cost of Carbon Improvements (high stringency, moderate flexibility/no user efficiency)
This scenario compels power plants to implement all upgrades and CO_2 pollution controls up to a cost of $43 per ton of CO_2 reduced. This scenario allows some shift to renewables but does not include new investments in end-user energy efficiency.

Summary of Results

In Part 1 of the study, changes in air quality in the U.S. were evaluated in response to expected changes in power plant emissions for each policy scenario in the year 2020 (Driscoll et al. 2014). The top-performing option for *air quality* was Scenario 2: Electricity Sector Improvements. It results in an estimated 24% decrease in U.S. power plant carbon emissions from the 2020 reference case (Driscoll et al. 2014). This is equivalent to a 35% decrease from 2005 levels, the baseline year used by EPA in the Clean Power Plan. For the other pollutants, Scenario 2 results in an estimated decrease in power plant emissions from the 2020 reference case of 27% for SO_2, 22% for NO_x, and 27% for Hg. The decrease in emissions in Scenario 2 results in widespread air quality improvements of up to 1.35 micro-grams per cubic meter ($\mu g/m^3$) for annual average $PM_{2.5}$ and up to 3.6 parts per billion (ppb) for the 8-hour maximum summertime ozone by 2020.

In Part 2 of the study, we analyzed the health co-benefits of the air quality changes under each of the three scenarios. The results are summarized here and presented in detail in the sections that follow.

1. Power plant carbon standards can improve air quality and provide substantial health co-benefits. The carbon standard that is moderately stringent has the greatest health co-benefits of the three analyzed (Scenario 2). The high compliance flexibility and high end-user energy efficiency in Scenario 2 results in the greatest number of premature deaths avoided overall and per ton of CO_2 reduced. This scenario is most similar to the EPA-proposed Clean Power Plan in its design and resulting CO_2

emissions. It yields the following estimated health co-benefits in the U.S. in 2020 compared to the business-as-usual reference case:

- 3,500 premature deaths avoided each year (that is equivalent to 9 premature deaths avoided every day).
- 1,000 hospital admissions avoided from heart and lung disease each year.
- 220 heart attacks prevented each year.

It would also lead to additional health benefits not quantified here, including reduced asthma symptoms and other health benefits for children, the elderly, and vulnerable adults.

2. <u>The geographic distribution of health co-benefits in the top-performing scenario (Scenario 2) is widespread with all lower 48 states receiving some benefit.</u> The 12 states with the greatest estimated number of premature deaths avoided are those where there are a large number of exposed people and air quality improves the most. They are (in order): PA, OH, TX, IL, MI, NY, NC, GA, MO, VA, TN, and IN. The 12 states with the greatest estimated percent increase in premature deaths avoided are (in order): PA, OH, WV, MO, MI, KY, MD, DC, IL, DE, IN, and AR.

3. <u>The carbon standard with the lowest stringency has the lowest health co-benefits (Scenario 1).</u> Its low flexibility and focus on improving power plant heat rates and operating efficiency results in little to no benefit with a slight *increase* in estimated premature deaths and heart attacks per year in the U.S. from the 2020 reference case.

4. <u>The carbon standard with the highest stringency (Scenario 3) has high health co-benefits but they are lower than Scenario 2.</u> It results in fewer estimated premature deaths avoided per year in the U.S. from the 2020 reference case and nearly half as many avoided per ton of CO_2 reduced as Scenario 2.

5. <u>Overall, the study shows that the health co-benefits of power plant carbon standards can be large but the magnitude depends on critical policy choices.</u> The carbon standard scenario that combines moderately stringent carbon targets with highly flexible compliance options and more end-user energy efficiency (Scenario 2) has the greatest estimated health co-benefits.

The results of this study indicate that carbon standards for existing power plants that are aimed at addressing the long-term issue of global climate change can bring substantial near-term state and local health co-benefits. They also demonstrate that the specific policy design choices for power plant carbon standards have a critical influence on the magnitude and distribution of the health co-benefits that occur. The improvements in air quality that accompany a carbon standard can result in nearly immediate benefits to human health. Extended implementation timelines would delay the accrual of these benefits. For the U.S. and other nations with significant greenhouse gas emissions and air quality challenges, local health co-benefits could be an important additional motivator for taking action on climate change.

Power Plant Pollution: Emissions, Air Quality, and Health

Power plants are the single largest source of CO_2 (39%), SO_2 (71%), and Hg (53%) emissions in the U.S. (NEI 2011, USEPA 2014b). They are also the second largest source of NO_x emissions (14%) (NEI 2011). Carbon pollution standards for existing power plants would not only help address the challenge of global climate change, they would also confer substantial near-term state and local health co-benefits by reducing power plant emissions of SO_2, NO_x, Hg, and directly emitted particulate matter (PM). Emissions of SO_2 and NO_x contribute to the formation of fine particulate matter ($PM_{2.5}$) and tropospheric ozone (O_3; referred to here as "ozone"). Each pollutant and its effects are briefly described below.

$PM_{2.5}$ is particulate matter comprised of particles less than 2.5 micrometers in diameter. It is a major component of what is commonly referred to as "soot". It can occur as primary PM emitted directly from a source or as secondary PM formed in the atmosphere. Secondary PM is by far the largest fraction of PM in the air in the U.S., and is derived from precursor emissions such as SO_2, NO_x, volatile organic compounds (VOCs), and ammonia (NH_3). Secondary formation occurs through gas-phase photochemical reactions or through liquid phase reactions in clouds and fog droplets in the atmosphere, generally downwind of a source. Fine particle pollution forms the major component of haze in cities and in iconic landscapes such as national parks.

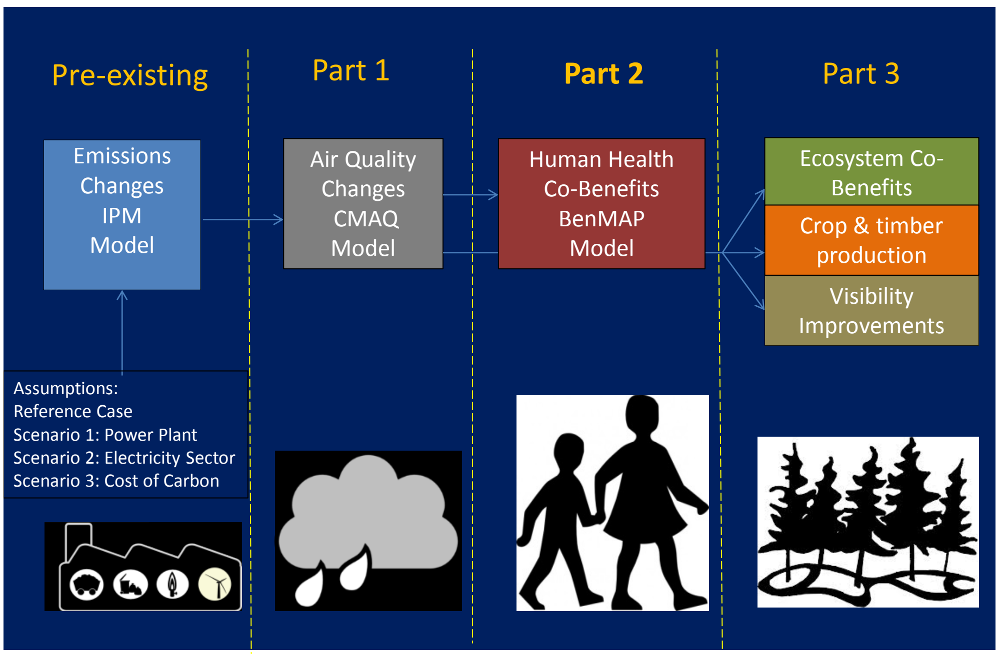
Tropospheric ozone is ground-level ozone, a major component of what is commonly referred to as "smog". Ground-level ozone is formed in the atmosphere when anthropogenic emissions of NO_x combine with VOCs and react in the presence of sunlight. Peak ozone concentrations generally occur in summer when higher temperatures and increased sunlight enhance ozone formation (Knowlton et al. 2004). Elevated ground-level ozone is not merely a concern in urban and suburban areas. Ozone and the ozone precursors (NO_x and VOCs) can also be transported long distances by wind, causing high ozone levels in rural areas. As a greenhouse gas, measures that simultaneously reduce tropospheric ozone also help mitigate climate change.

Fine particulate matter and ground-level ozone have demonstrated and well-understood human health consequences which have been extensively documented in the peer-reviewed literature. The populations in the U.S. who are most vulnerable and at-risk for these effects include the elderly, children, people suffering from other respiratory or cardiovascular diseases, and highly exposed individuals living in areas with poor ambient air quality. Despite improvements in U.S. air quality in recent decades, current emissions and air pollution levels still pose considerable health risks. A U.S. EPA study estimated that in 2005, $PM_{2.5}$ was associated with approximately 180,000 non-fatal heart attacks, 200,000 hospital admissions and emergency room visits, 2.5 million asthma exacerbations, 18 million lost days of work, and other public health effects in the U.S. (Fann et al. 2012). Depending on the choice of the study, the authors estimated that either 130,000 or 320,000 premature deaths in 2005 were attributable to $PM_{2.5.}$ Similarly, ground-level ozone was associated with approximately an additional 77,000 hospital admissions and emergency room visits, and 11 million school absence days in 2005 in the U.S., along with 4,700 or 19,000 premature deaths depending on the study chosen (Fann et al. 2012).

Study Approach

Scientists from Harvard, Syracuse, and Boston Universities initiated the first integrated, spatially explicit study for the entire lower 48 U.S. states of the health and environmental co-benefits associated with different policy scenarios for carbon pollution standards for existing power plants in the U.S. The study answers three questions: (1) Are there health co-benefits associated with carbon standards for existing power plants in the U.S.? (2) If so, how much and where? (3) How do different options for the power plant carbon standards influence the magnitude and geographic distribution of the co-benefits? The study has three major parts (see Figure 1).

Figure 1: The Co-Benefits of Carbon Standards Study



Part 1 of the study uses estimates of power plant emissions in the year 2020 for a reference case and three scenarios to simulate changes in air quality (ozone and $PM_{2.5}$). To quantify and map future air quality, we used parsed unit-level emissions output from the Integrated Planning Model (IPM) produced by the consulting firm ICF International as input to the Community Multi-scale Air Quality (CMAQ) Model.

Simulations using CMAQ produce gridded air quality concentrations and air pollution deposition rates for the entire lower 48 states of the U.S. at a 12 kilometer grid-size resolution. The simulations do not include an evaluation of feedbacks between climate change and air quality, such as the influence of increasing temperatures on the formation of ozone and $PM_{2.5}$. *See Part 1 report by Driscoll et al. 2014 for details and results.*

Part 2 of the study uses the spatially explicit air quality results from CMAQ to quantify and map the health co-benefits for each of the three policy scenarios using the Benefits Mapping and Analysis Program (BenMAP). We used BenMAP CE v1.0.8, published by the U.S. EPA (USEPA, Office of Air and Radiation, n.d.). Each policy scenario was compared to the reference case, and the health co-benefits specifically attributable to each scenario were calculated using the difference in air quality between the policy scenario and the reference case.

BenMAP CE is a Geographic Information System (GIS)-based software tool designed for calculating the health co-benefits of air quality management scenarios. BenMAP contains data on population, demographics, and incidence and prevalence rates of health outcomes. We used BenMAP, with 2020 population and baseline health incidence and prevalence rates in conjunction with concentration-response functions we developed and the CMAQ results to estimate the health co-benefits of the three policy scenarios. As a result, the co-benefits reported here are additional benefits associated with the carbon standard beyond the benefits that are anticipated to occur with the continued implementation of existing air policies.

In Part 3 of the study, the air quality and atmospheric deposition results will be used to estimate environmental benefits and changes in ecosystem services using various models. This is likely to include recovery of streams and forests from acid deposition, reduced ozone damage to crops and timber, and improved visibility in focal landscapes. *We anticipate these results and a full report on the three parts will be released in early 2015.*

Three Scenarios for Power Plant Carbon Standards

A reference case and three policy scenarios for power plant carbon standards were used for this analysis. Estimates of power plant emissions for the year 2020 for these cases were then used to simulate air quality changes and calculate health co-benefits. The reference case is a “business-as-usual” scenario that was developed jointly by the Bipartisan Policy Center (BPC) and the Natural Resources Defense Council (NRDC). The three alternative policy scenarios include two commissioned by BPC (Scenarios 1 and 3) and one commissioned by NRDC (Scenario 2).

The three scenarios represent high, moderate, and low stringencies for CO_2 emissions targets. They also encompass a range of flexibility for compliance options, investments in demand-side energy efficiency, and incorporation of state or regional trading programs. They were selected as a set of researchable options that bound a range of plausible but divergent alternatives. The scenarios were analyzed using air quality models in 2013, prior to the release of the EPA-proposed Clean Power Plan on June 2, 2014. The scenarios are summarized on pages 7 and 8. Additional details about the scenario assumptions, resulting generation mix, and associated emissions are provided in Appendices 1-3.

Reference case: Business-as-usual

The reference case is benchmarked to the energy demand in the Energy Information Administration's Annual Energy Outlook for 2013 (AEO 2013). It assumes full implementation of current clean air policies adopted by EPA including the Mercury and Air Toxics Standard and the Clean Air Interstate Rule, as well as state-based emission reduction requirements and programs such as renewable portfolio standards. By 2020, the reference case results in modest shifts in energy generation from 2005 and achieves an estimated 15.2% decrease in annual CO_2 emissions from the electricity sector (Table 1).

Scenario 1: Power Plant Improvements (low stringency, low flexibility/no user efficiency)

Scenario 1 focuses on improving the operating efficiency of existing power plants. It is referred to as the "Unit Retrofit" scenario by BPC. Scenario 1 introduces unit-specific emissions rate standards for coal-fired units based on an estimated heat rate improvement potential. It is a *low* stringency alternative with compliance options limited to changes "inside the fence line" of existing affected power plants. The scenario incorporates the New Source Performance Standard for new power plants; however no new coal plants are projected to be built in Scenario 1. This scenario results in a national average emissions rate of 2000 pounds per megawatt-hour (lbs/MWh) for coal plants, which represents a modest improvement over the current emissions rate. Under this scenario, the fleet-wide average heat rate for coal-fired power plants improves by 4%.

In 2020, Scenario 1 has similar energy generation sources as the reference case, but with increased generation from coal plants without carbon capture and storage (CCS) (Table 1). It results in an estimated annual 2.2% decrease in CO_2 emissions from the 2020 reference case (17.4% decrease from 2005 levels), an estimated annual 3% *increase* in SO_2 emissions, and a 3% decrease in NO_X and Hg emissions from the 2020 reference case (Table 1). This result is likely due to "emissions rebound" at several coal-fired power plants in the U.S. fleet. Emissions rebound refers to an increase in emissions that can occur when power plants that emit larger amounts of SO_2 per Btu (British thermal unit) of energy are made more efficient, emit less carbon, and therefore rise in the dispatch order and run more than in the reference case. This analysis did not consider whether other state or federal policies would apply under these circumstances.

Scenario 2: Electricity Sector Improvements (moderate stringency, high flexibility/high user efficiency)

Scenario 2 is a moderate stringency scenario with a wide range of compliance options and substantial investments in demand-side energy efficiency. It is referred to as the "Moderate Full-Efficiency" scenario by NRDC. Scenario 2 achieves CO_2 emissions reductions through emissions rate performance standards calculated for each state based on their current generation mix and emissions rate targets of 1500 lbs/MWh for coal and 1,000 lbs/MWh for gas. It allows additional renewable energy and energy efficiency to count toward compliance. It also allows emissions averaging across all existing and new fossil units in a state, as well as interstate averaging or credit trading.

In 2020, Scenario 2 results in markedly less power generation from coal without CCS compared to the reference case and Scenario 1, and a substantial increase in new demand-side energy efficiency (Table

1). It results in an estimated annual 23.6% decrease in CO_2 emissions from the 2020 reference case (35.5% decrease from 2005), a 27% decrease in SO_2 and Hg emissions, and 22% decrease in NO_x emissions from the 2020 reference case.

Scenario 3: Cost of Carbon Improvements (high stringency, moderate flexibility/no user efficiency)
Scenario 3 requires supply-side power sector CO_2 emissions reductions that can be implemented up to a cost of $43 per metric ton in 2020. It is referred to as the "A4" scenario by BPC. Scenario 3 is designed to mimic a national tax on CO_2 emissions for existing and new power plants that is equivalent to the social cost of carbon (Interagency Working Group 2013). It is a high stringency scenario with compliance options across the power sector, but does *not* include new policy-mandated investments in demand-side energy efficiency. However, increases in electricity prices reduce demand and generation in this scenario. Compliance options include on-site heat rate improvements, co-firing or converting to lower emitting fuel (i.e., natural gas, biomass), or shifting generation dispatch to favor lower carbon-emitting sources. New coal plants are required to have CCS installed. In 2020, Scenario 3 is projected to achieve average national CO_2 emissions rates of 1200 lbs/MWh for coal-fired power plants and 850 lbs/MWh for gas plants.

In 2020, Scenario 3 estimates a marked increase in generation from coal-fired power plants with CCS and an increase in natural gas production (Table 1). It results in an estimated annual 39.8% decrease in CO_2 emissions from the 2020 reference case (a 49.2% decrease from 2005), a 27% decrease in SO_2 and Hg emissions, and a 16% decrease in NO_X emissions compared to the 2020 reference case (Table 1).

Of the three scenarios, Scenario 2 is most similar to the standards in the EPA-proposed Clean Power Plan. The Clean Power Plan achieves an estimated 30% reduction in CO_2 emissions from 2005 levels by 2030, compared to the 35.5% decrease by 2020 in Scenario 2. Like the EPA proposal, Scenario 2 offers flexibility for compliance through: (1) power plant heat rate improvements, (2) substituting less CO_2-intensive sources, (3) switching to renewable energy sources, and (4) adding demand-side energy efficiency measures.

These electricity generation and emissions results for each of the scenarios highlight that, in addition to addressing global climate change, a stringent carbon pollution standard for existing power plants can reduce power plant emissions of co-pollutants that contribute to state and local air pollution. The comparison shows that the policy option with the most flexible framework and greatest investments in demand-side energy efficiency (Scenario 2) provides the greater air quality improvements in total tons per year and per ton of CO_2 reduced than the alternatives. The results show how a carbon standard with low stringency that is limited upgrades as existing power plants (Scenario 1) can result in increased power sector emissions of SO_2 by 2020. Finally, the results for Scenario 3 indicate that a high stringency approach can produce greater CO_2 emissions reductions but could result in greater decreases in SO_2 and NO_x emissions per ton of CO_2 reduced if implemented through a more flexible framework with more demand-side energy efficiency.

Table 1. Energy generation and electricity sector emissions

Energy generation by source category (in TWh) and emissions by CO_2, SO_2, NO_x and Hg in the year 2005 and for the reference case, three scenarios, and EPA standards in the year 2020. The values in bold highlight important similarities between the proposed EPA Clean Power Plan. Columns may not sum to totals due to rounding.

		2005	Reference case 2020	Scenario 1 2020	Scenario 2 2020	Scenario 3 2020	EPA Clean Power Plan 2020 scenario[1]	EPA Clean Power Plan 2030 scenario[1]
Energy generation (TWh)	Total	4 055	4 213	4 212	4 227[2]	4 172	4 235[2]	4495[2]
	Total fossil generation	2 909	2 770	2 770	2 362	2 608	2651	2630
	Combined cycle (gas)	761	1 030	1 001	1 013	1 297	1 281	1313
	Combustion turbine (gas)	--	75	72	75	84	33	32
	Coal (no CCS)	2 013	1 639	1 671	1 217	764	1 335	1246
	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[3]	135	19	19	19	26	30	37
	Other renewables[4]	37	66	63	63	66	62	70
Annual power sector emission (short tons)	CO_2 (million)	2 651	2249	2198	1718	1352	1973	1886
	SO_2 (thousand)	10519	1742	1 791	1 267	1 257	1 184	1106
	NO_x (thousand)	3 951	1 331	1 291	1032	1 112	1 213	1131
	Hg	52	5	5	3	4	7	7

[1]Based on IPM emissions estimates for EPA's Option 1 – Regional illustrative compliance scenario in 2020. Full implementation occurs in 2030 (USPEA 2014c).
[2]New demand-side energy efficiency included in total generation. EPA estimate based on projected 3% decline in total energy demand in 2020 and11% decline in 2030 from demand-side energy savings (USEPA 2014c).
[3]Other non-renewables includes generation from petroleum and other gases.
[4]Other renewables includes generation from waste products, geothermal, and solar/PV.

Air Quality Results

To characterize changes in air quality under each policy scenario, we used emissions results for the reference case and each of the three scenarios in the year 2020 as input to the CMAQ model. CMAQ was used to estimate and map changes in $PM_{2.5}$ and ozone concentrations from the 2020 reference case for the entire continental U.S. The major air quality findings were reported in Driscoll et al. (2014) and are summarized below. The detailed air quality results for all three scenarios and both pollutants are provided in Appendix 4. The maps that follow show the results for Scenarios 1 and 2, the lowest and highest performing scenarios respectively.

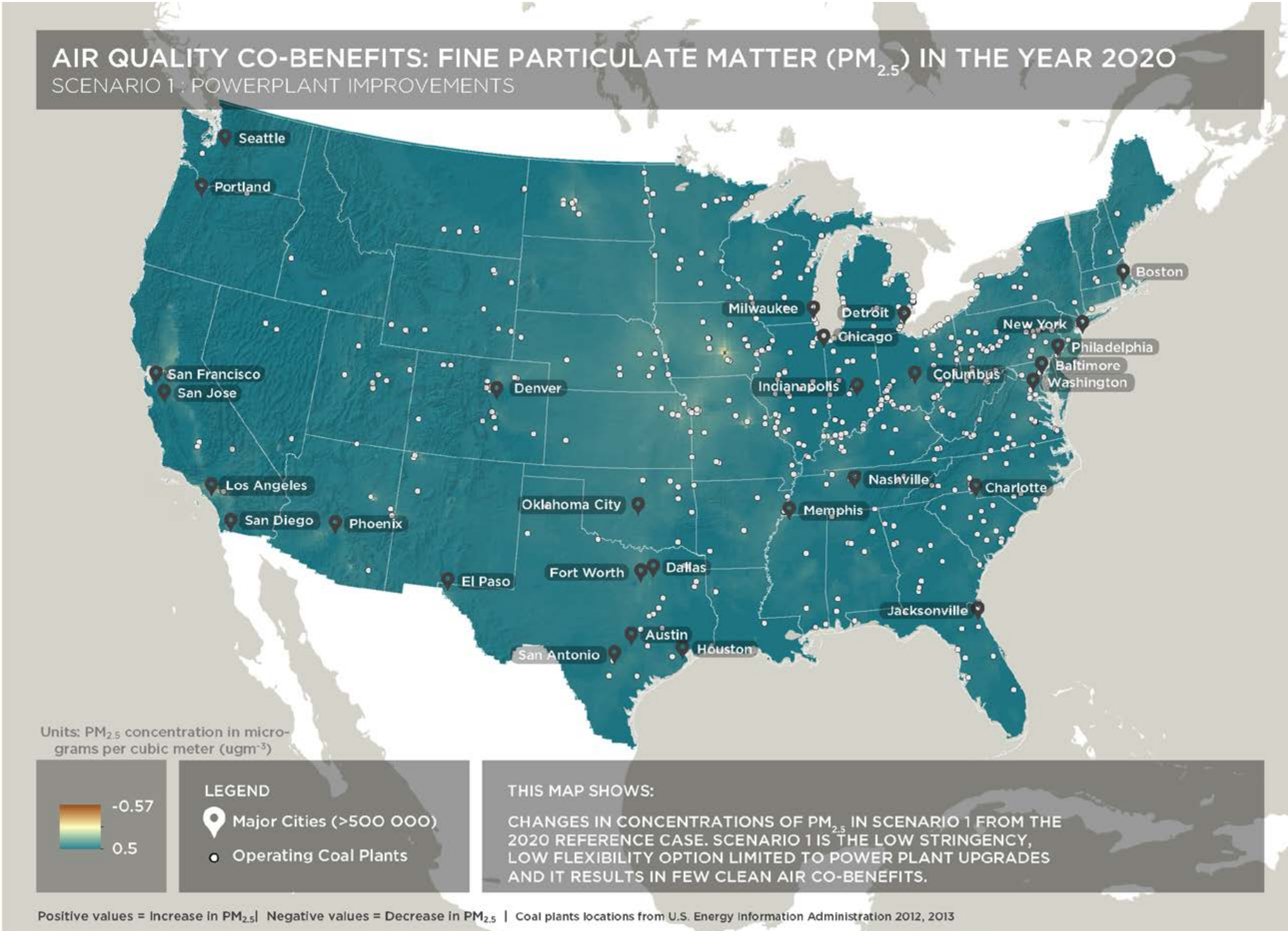
Scenario 1 results show that if a carbon standard has low stringency and compliance options limited to power plant heat rate upgrades and improvements in operating efficiency, national emissions of SO_2 from power plants could increase, reducing air quality. Scenario 1 results in higher concentrations of $PM_{2.5}$ across large areas compared to the reference case with little to no improvement in most of the remaining area (Figure 2a). It also results in limited change in summertime ozone in the U.S. (Figure 3a). This result is likely due to an "emissions rebound" (Phillips 2014). Emissions rebound occurs when heat rate upgrades improve the operating efficiency of fossil-fuel-fired power plants causing them to move up in the dispatch order and operate more often or for longer time periods, resulting in higher emissions of co-pollutants.

Scenario 2 results show that a carbon standard that is moderately stringent and flexible enough to give credit to both cleaner sources of electricity and demand-side energy efficiency will reduce emissions of SO_2 and NO_x, achieving improved air quality at the state level. The air quality improvements achieved in 2020 under this scenario are widespread for both annual $PM_{2.5}$ (Figure 2b) and summer ozone (Figure 3b), with every state receiving some benefit.

Scenario 3 results show that the carbon standard with the highest stringency resulted in the highest reduction in annual CO_2 emissions but lower decreases in total and per ton of CO_2 reduced SO_2 and NO_x emissions than Scenario 2 (0.84 thousand tons of SO_2 and NO_x reduced per million tons of CO_2 reduced under Scenario 3 compared to 1.46 under Scenario 2; Appendix 3) (Driscoll et al. 2014). As a result, the improvements in annual $PM_{2.5}$ and peak annual and summer ozone from the 2020 reference case are similar to Scenario 2 despite larger decreases in CO_2 (Driscoll et al. 2014).

The results from the CMAQ model show marked differences in the changes in air quality among the three scenarios. The lowest improvements and some worsening of air quality occur in Scenario 1 and the greatest improvements occur under Scenario 2. The air quality results underscore that the final policy design of the power plant carbon standard will influence greatly the co-benefits that states and local communities gain.

Figure 2a



AIR QUALITY CO-BENEFITS: FINE PARTICULATE MATTER ($PM_{2.5}$) IN THE YEAR 2020
SCENARIO 1 : POWERPLANT IMPROVEMENTS
Seattle
Portland
San Francisco
San Jose
Los Angeles
San Diego
Phoenix
Denver
El Paso
Oklahoma City
Fort Worth
Dallas
Austin
San Antonio
Houston
Milwaukee
Chicago
Detroit
Indianapolis
Columbus
Nashville
Memphis
Charlotte
Jacksonville
New York
Philadelphia
Baltimore
Washington
Boston
Units: $PM_{2.5}$ concentration in micro-grams per cubic meter (ugm^{-3})
-0.57
0.5
LEGEND
Major Cities (>500 000)
Operating Coal Plants
THIS MAP SHOWS:
CHANGES IN CONCENTRATIONS OF $PM_{2.5}$ IN SCENARIO 1 FROM THE 2020 REFERENCE CASE. SCENARIO 1 IS THE LOW STRINGENCY, LOW FLEXIBILITY OPTION LIMITED TO POWER PLANT UPGRADES AND IT RESULTS IN FEW CLEAN AIR CO-BENEFITS.
Positive values = Increase in $PM_{2.5}$ | Negative values = Decrease in $PM_{2.5}$ | Coal plants locations from U.S. Energy Information Administration 2012, 2013

Figure 2b

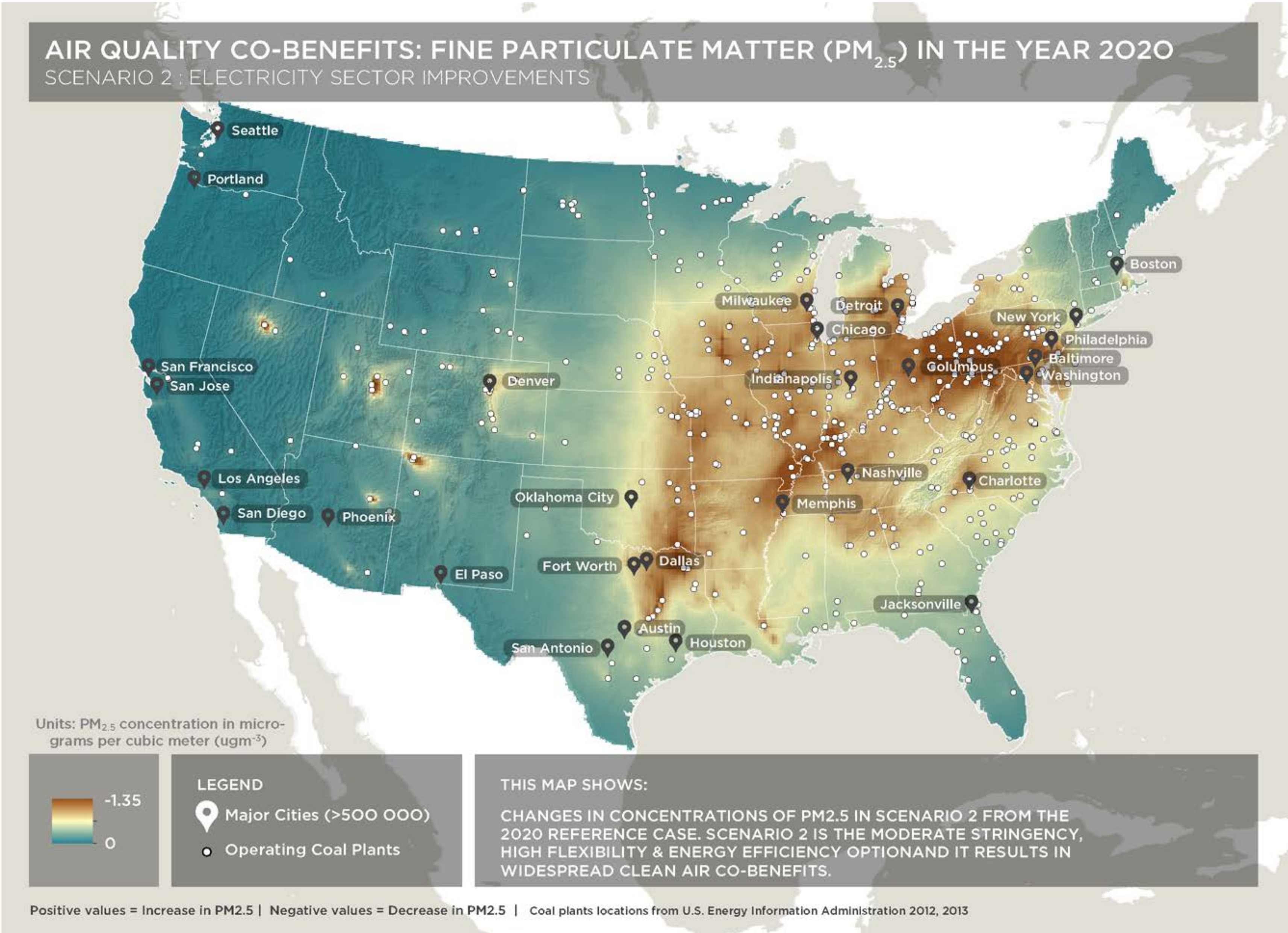

AIR QUALITY CO-BENEFITS: FINE PARTICULATE MATTER (PM2.5) IN THE YEAR 2020
SCENARIO 2 : ELECTRICITY SECTOR IMPROVEMENTS
Seattle
Portland
San Francisco
San Jose
Los Angeles
San Diego
Phoenix
El Paso
Denver
Oklahoma City
Fort Worth
Dallas
Austin
San Antonio
Houston
Milwaukee
Chicago
Detroit
Indianapolis
Columbus
Nashville
Memphis
Charlotte
Jacksonville
New York
Philadelphia
Baltimore
Washington
Boston
Units: PM2.5 concentration in micro-grams per cubic meter (ugm-3)
-1.35
0
LEGEND
Major Cities (>500 000)
Operating Coal Plants
THIS MAP SHOWS:
CHANGES IN CONCENTRATIONS OF PM2.5 IN SCENARIO 2 FROM THE 2020 REFERENCE CASE. SCENARIO 2 IS THE MODERATE STRINGENCY, HIGH FLEXIBILITY & ENERGY EFFICIENCY OPTIONAND IT RESULTS IN WIDESPREAD CLEAN AIR CO-BENEFITS.
Positive values = Increase in PM2.5 | Negative values = Decrease in PM2.5 | Coal plants locations from U.S. Energy Information Administration 2012, 2013

Figure 3a

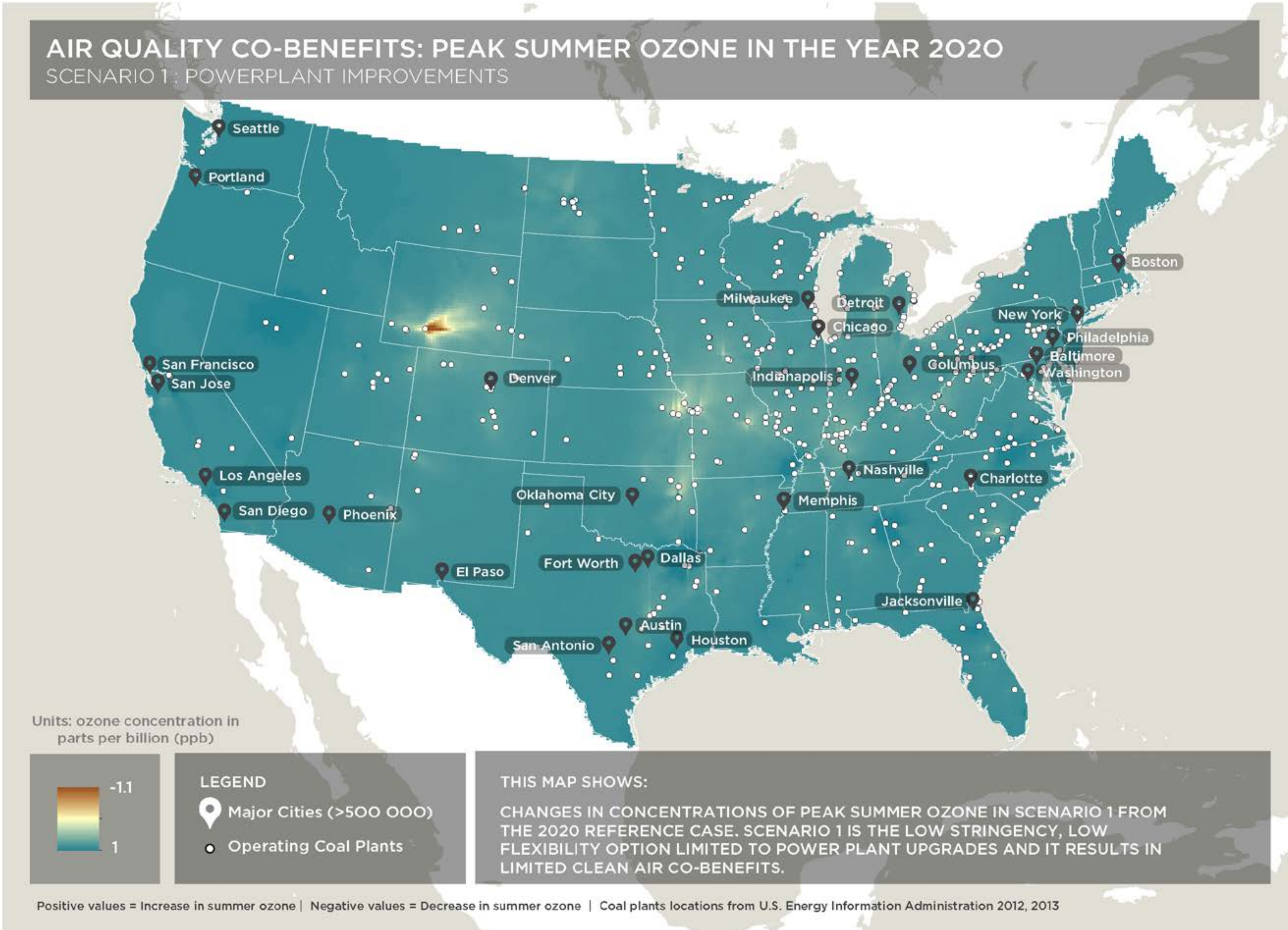
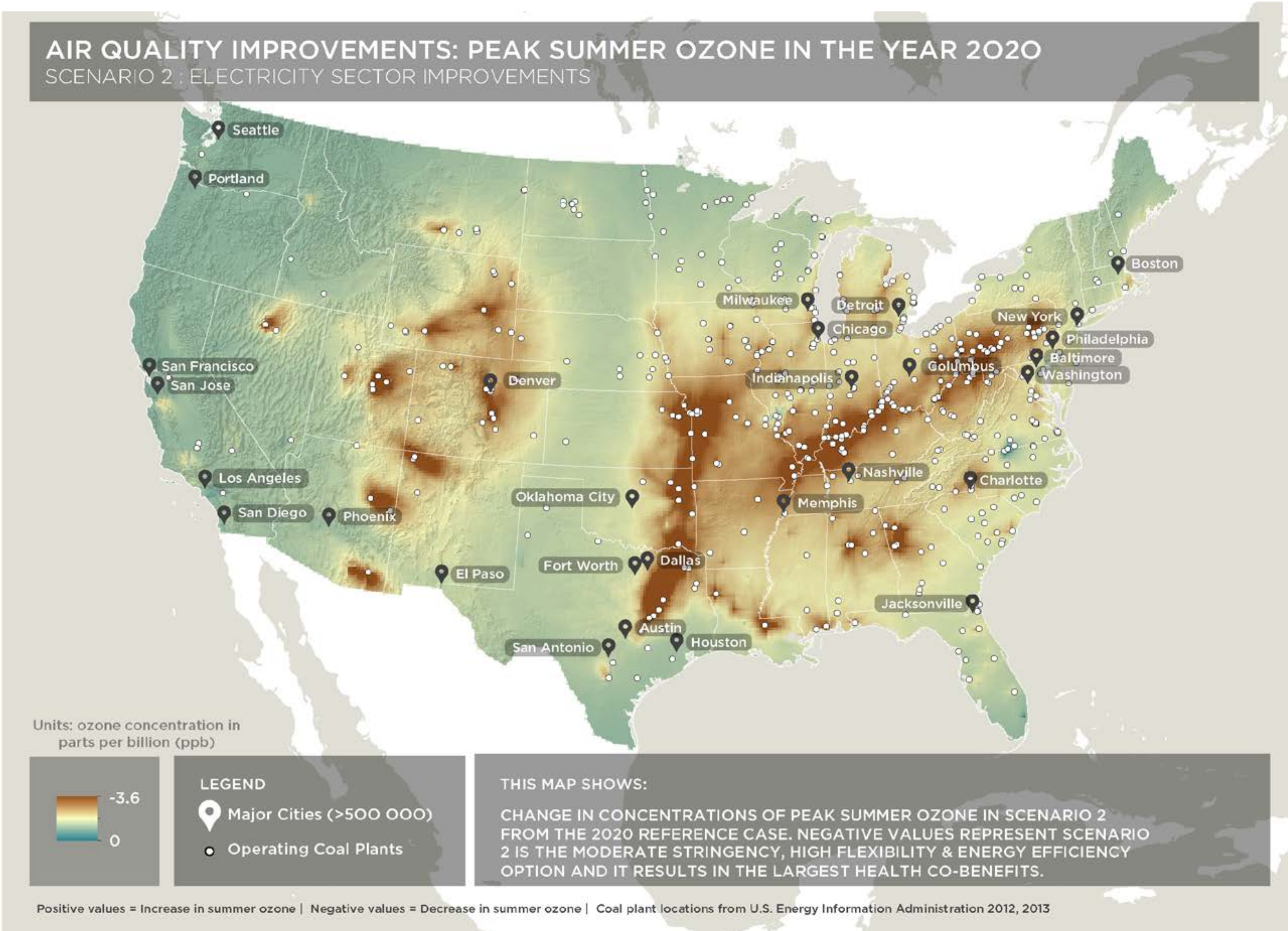

AIR QUALITY CO-BENEFITS: PEAK SUMMER OZONE IN THE YEAR 2020
SCENARIO 1 : POWERPLANT IMPROVEMENTS
Seattle
Portland
San Francisco
San Jose
Los Angeles
San Diego
Phoenix
Denver
El Paso
Oklahoma City
Fort Worth
Dallas
Austin
San Antonio
Houston
Milwaukee
Chicago
Detroit
Indianapolis
Columbus
Nashville
Memphis
Charlotte
Jacksonville
Boston
New York
Philadelphia
Baltimore
Washington
Units: ozone concentration in parts per billion (ppb)
-1.1
1
LEGEND
Major Cities (>500 000)
Operating Coal Plants
THIS MAP SHOWS:
CHANGES IN CONCENTRATIONS OF PEAK SUMMER OZONE IN SCENARIO 1 FROM THE 2020 REFERENCE CASE. SCENARIO 1 IS THE LOW STRINGENCY, LOW FLEXIBILITY OPTION LIMITED TO POWER PLANT UPGRADES AND IT RESULTS IN LIMITED CLEAN AIR CO-BENEFITS.
Positive values = Increase in summer ozone | Negative values = Decrease in summer ozone | Coal plants locations from U.S. Energy Information Administration 2012, 2013

Figure 3b


AIR QUALITY IMPROVEMENTS: PEAK SUMMER OZONE IN THE YEAR 2020
SCENARIO 2 : ELECTRICITY SECTOR IMPROVEMENTS
Seattle
Portland
San Francisco
San Jose
Los Angeles
San Diego
Phoenix
El Paso
Denver
Oklahoma City
Fort Worth
Dallas
Austin
San Antonio
Houston
Milwaukee
Chicago
Detroit
Indianapolis
Columbus
Nashville
Memphis
Charlotte
Jacksonville
New York
Boston
Philadelphia
Baltimore
Washington
Units: ozone concentration in parts per billion (ppb)
-3.6
0
LEGEND
Major Cities (>500 000)
Operating Coal Plants
THIS MAP SHOWS:
CHANGE IN CONCENTRATIONS OF PEAK SUMMER OZONE IN SCENARIO 2 FROM THE 2020 REFERENCE CASE. NEGATIVE VALUES REPRESENT SCENARIO 2 IS THE MODERATE STRINGENCY, HIGH FLEXIBILITY & ENERGY EFFICIENCY OPTION AND IT RESULTS IN THE LARGEST HEALTH CO-BENEFITS.
Positive values = Increase in summer ozone | Negative values = Decrease in summer ozone | Coal plant locations from U.S. Energy Information Administration 2012, 2013

Health Co-Benefits Analysis

Six health outcomes, for which there is extensive evidence of health effects from air pollution, were used to quantify and map the health co-benefits for each carbon standards scenario (see lists below). For mortality, we calculated the percent change in premature deaths avoided by county as well as the change in total cases of premature deaths avoided nationally and in each state.

$PM_{2.5}$-related Health Co-Benefits

1. Premature deaths avoided (i.e., lives saved)
2. Heart attacks avoided
3. Other cardiovascular hospital admissions avoided
4. Respiratory hospital admissions avoided

Ozone-related Health Co-Benefits

5. Premature deaths avoided (i.e., lives saved)
6. Respiratory hospital admissions avoided

While numerous health outcomes have been associated with $PM_{2.5}$ and ozone, we selected a subset of outcomes for which there is concentration-response functions derived from large cohort studies with large populations residing in different locations, multi-city studies simultaneously examining populations in many locations across the U.S., or meta-analyses of a significant number of publications across many locations. The outcomes we chose account for most of the monetized benefits associated with air pollution control strategies. We also constrained the analysis to $PM_{2.5}$ and ozone, and did not include the direct health benefits of mitigating climate change or decreasing mercury emissions.

In this analysis, we used the model BenMAP CE and data on population, age structure, and baseline prevalence and incidence rates that are similar to the values used by the U.S. EPA in their regulatory impact assessment (USEPA 2012, USEPA 2014c). Population data are from Woods & Poole (Woods & Poole 2008); data on baseline hospitalizations and myocardial infarctions are from the Healthcare Utilization and Cost Program (HCUP 2007); data on mortality rates are from the U.S. Centers for Disease Control and Prevention WONDER database, projected to 2020 (CDC WONDER 2009). BenMAP CE accepts two air quality grids as inputs, representing air pollutant concentrations under a policy scenario and a baseline (or reference) case. It then calculates the benefits of a policy as the difference between the two. BenMAP CE performs the health impact calculations of a scenario using an equation that approximates to:

Change in health impact = Exposed population × baseline incidence or prevalence of health endpoint × concentration-response function × change in concentration of air pollutant

We used concentration-response functions to estimate expected changes in health outcomes associated with changes in exposure to both $PM_{2.5}$ and ozone in the year 2020. Concentration-response functions relate changes in air pollution to an increase or decrease in the rate of an adverse health outcome. The functions are expressed as a percent increase or decrease in the rate per unit concentration change of a given pollutant over a given time period, and are based on published epidemiological literature. The concentration-response functions used in this study are summarized in Table 2 and described below.

Concentration-response functions for $PM_{2.5}$ exposure

1. Premature deaths avoided (adult mortality): We used a concentration-response function relating long-term exposure to $PM_{2.5}$ to all-cause mortality rate in adults 25 years of age. There have been many studies published on this in the last twenty years. The concentration-response function we used was derived from an expert elicitation study in which experts in this field of study were asked to synthesize the published literature and determine an appropriate concentration-response function (Roman et al. 2008). The resulting change in mortality cases is largely due to cardiovascular and respiratory causes. This concentration-response function has a central estimate of a 1% increase in mortality rate per $\mu g/m^3$ increase in annual average $PM_{2.5}$ concentrations. This value has been used in regulatory impact analyses performed by the U.S. EPA, and is bounded by the central estimates from multiple publications derived from two major cohort studies (Krewski et al. 2009, Laden et al. 2006, Lepeule et al. 2012, Pope et al. 2002). We determined uncertainty bounds for this function that approximately encompass the range of estimates from these two cohorts, with a standard error of 0.4%.

2. Heart attacks avoided (acute non-fatal myocardial infarction): We used a concentration-response function derived from Mustafic et al. (2012), a meta-analysis of 34 studies examining the relationship between short-term exposure to $PM_{2.5}$ in adults over 18 years of age and risk of non-fatal myocardial infarction (heart attack).

3. Other cardiovascular hospital admissions avoided (excluding myocardial infarctions): We selected two large multi-city studies as the foundation for these estimates – Levy et al. (2012), a multi-city study that used a cohort of Medicare enrollees from 119 communities; and Zanobetti et al. (2009) which used a cohort of Medicare enrollees from 26 communities. Both studies related short-term $PM_{2.5}$ exposure and hospital admissions for cardiovascular causes other than myocardial infarctions (heart attacks) in adults 65 years of age and over. We pooled the estimates from these two studies using inverse variance weighting, which places a greater weight on more statistically precise estimates. This may underestimate the risk of these outcomes due to long-term exposure, which has been documented in the published literature. For example, Kloog et al. (2012) found that the increase in risk due to long-term exposure was approximately a factor of six greater than for short-term exposures for respiratory hospitalizations, and approximately a factor

of three greater for cardiovascular hospitalizations (Kloog et al. 2012). However, here we focus on the impact of short-term exposures to be consistent with current U.S. EPA regulatory impact analysis methods.

4. Respiratory hospital admissions avoided: We selected two large multi-city studies as the foundation for these estimates – Levy et al. (2012), a multi-city study that used a cohort of Medicare enrollees from 119 communities; and Zanobetti et al. (2009) which used a cohort of Medicare enrollees from 26 communities. Both studies related short-term $PM_{2.5}$ exposure and hospital admissions for respiratory causes in adults 65 years of age and over. As above, we pooled the estimates from these two studies using inverse variance weighting. As above, we risk underestimating the overall effect by not including results for long-term exposure.

Concentration-response function for change in ozone exposure

5. Premature deaths avoided (adult mortality): We used a concentration-response function derived from the Jerrett et al. (2009) study of the American Cancer Society cohort for the ozone season average 1-hour maximum and respiratory mortality risk in adults 30 years of age and over. We note that several recent Medicare cohort studies have reported associations between summer ozone exposure and cardiovascular deaths, so this may be an underestimate of the true benefits of ozone reduction.

6. Respiratory hospital admissions: We used a concentration-response function derived from Ji et al. (2011), a meta-analysis of 96 studies relating short-term ozone exposure and increased risk of hospital admissions for respiratory causes in adults 65 years of age and over.

Table 2: Concentration-Response Functions

Concentration-response functions from the literature used to estimate health co-benefits from changes in air pollutant concentrations for the three policy scenarios.

Study	Health Outcome	Pollutant	Metric	Response (% increase or decrease in rate)	Standard Error (% increase or decrease in rate)
Roman et al. 2008	Premature death (all causes)	$PM_{2.5}$	Annual average concentration ($\mu g/m^3$)	1.0	0.4
Levy et al. 2012, Zanobetti et al. 2009, pooled	Respiratory hospitalizations	$PM_{2.5}$	Daily average concentration ($\mu g/m^3$)	0.11	0.027
Levy et al. 2012, Zanobetti et al. 2009, pooled	Cardiovascular hospitalizations	$PM_{2.5}$	Daily average concentration ($\mu g/m^3$)	0.094	0.015
Mustafic et al. 2012	Heart attack (acute non-fatal myocardial infarction)	$PM_{2.5}$	Daily average concentration ($\mu g/m^3$)	0.25	0.0536
Jerrett et al. 2009	Premature death (respiratory causes)	Ozone	April – Sept. average of the 1-hour maximum (ppb)	0.39	0.13
Ji et al. 2011	Respiratory Hospitalizations	Ozone	Annual average of the 8-hour maximum (ppb)	0.16	0.052

Health Co-benefits Results

Using the BenMAP CE model and the concentration response functions described above, we estimated the increase or decrease in each of the six health co-benefits based on the projected change in air quality for each scenario relative to the reference case in the year 2020. The estimated total national health co-benefits for each of the scenarios and health outcomes are presented in Table 3. We present the central estimate and the 95% confidence interval around that estimate. The 95% confidence interval represents the range of values within which there is 95% likelihood that the true value falls. The uncertainty bounds only reflect reported uncertainty in the epidemiological studies.

Table 3: Total National Health Co-Benefits

The central estimate and 95% confidence intervals for the change in total national health co-benefits under the three scenarios from 2020 reference case. CI = confidence interval. All results are rounded to whole numbers with two significant figures.

Health Outcome	Pollutant	Scenario 1 Central estimate (95% CI)	Scenario 2 Central estimate (95% CI)	Scenario 3 Central estimate (95% CI)
Premature deaths avoided (all-cause)	$PM_{2.5}$	-44 (-79 to -9)	3200 (680 to 5600)	3000 (650 to 5400)
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 death avoided (respiratory causes)	Ozone	34 (11 to 56)	300 (100 to 500)	200 (68 to 340)
Respiratory hospitalizations avoided	Ozone	25 (9 to 41)	410 (150 to 680)	260 (94 to 430)
Total premature deaths avoided	$PM_{2.5}$ and Ozone	-11 (-23 to 2)	3500 (780 to 6100)	3200 (720 to 5700)
Total hospitalizations avoided (respiratory and cardiovascular)	$PM_{2.5}$ and Ozone	15 (3 to 27)	1000 (530 to 1500)	860 (460 to 1300)
Total heart attacks avoided (acute non-fatal myocardial infarction)	$PM_{2.5}$	-3 (-5 to -2)	220 (130 to 310)	210 (120 to 300)

Comparison of Total National Health Co-Benefits

The central estimates for the national results show that Scenario 1 has the lowest health co-benefits of the three scenarios. It results in modest estimated increases in hospitalizations avoided and a slight increase in premature deaths and heart attacks from the 2020 reference case. This produces a negative value for the number of -0.2 premature deaths avoided per million tons of CO_2 reduced (based on the central estimate). These results are consistent with the projected increase in SO_2 emissions and decrease in air quality under this scenario. Scenario 2 achieves the largest total health co-benefits for all health outcomes examined. It also has the highest number of premature deaths avoided per ton of CO_2 reduced (6.6 per million tons of CO_2; based on the central estimate). Scenario 3 results high total national health co-benefits that are slightly lower than those under Scenario 2. It also has much lower benefits per ton of CO_2 reduced for premature deaths avoided (3.6 per million tons of CO_2; based on the central estimate).

Geographic Distribution of Health Co-Benefits

In addition to estimating total national health co-benefits, we used BenMAP CE to determine the magnitude and geographic distribution of health co-benefits at the state level for the continental U.S. The major findings for all three scenarios are summarized here. Tables with detailed state level results for all scenarios and all health endpoints are provided in Appendix 5.

The maps in Figures 4-7 show the geographic distribution of the health co-benefits for Scenarios 1 and 2, the lowest and highest performing scenarios. The four sets of maps depict: (1) the percent change in premature deaths avoided from the 2020 reference case at the county level (Figures 4a and b); (2) the combined results for premature deaths avoided due to changes in both $PM_{2.5}$ and ozone (Figures 5a and b); (3) the combined results for hospitalizations due to cardiovascular and respiratory illness due to changes in $PM_{2.5}$ and ozone (Figures 6a and b); and (4) the results for heart attacks avoided due to changes in $PM_{2.5}$ (Figures 7a and b).

Scenario 1

Percent change in premature deaths avoided: Scenario 1 results in little to no improvement in the percent change in premature deaths avoided in counties across much of the U.S. (0% to 0.12% increase) and a slight decrease of up to 0.19% in counties where air quality is projected to decline relative to the 2020 reference case (Figure 4a).

Change in cases of health co-benefits: Scenario 1 generates state-level co-benefits that range from 21 to -33 per premature deaths avoided per year (Figure 5a), 5 to -10 hospitalizations avoided per year (Figure 6a), and 2 to -2 heart attacks prevented per year (Figure 7a). Note: a decrease in premature deaths avoided is the same as an increase in premature deaths from the 2020 reference case.

Spatial pattern: For premature deaths avoided, Scenario 1 results in 23 states with 1 or more premature death avoided each year and 17 states with 1 or more additional premature deaths per year.

<u>Scenario 2</u>

Percent change in premature deaths avoided: Scenario 2 results in an increase in the percent change in premature deaths avoided from the 2020 reference case for most of the U.S. (0% to 0.96%), as indicated by the widespread green area on the map (Figure 4b).

Change in cases of health co-benefits: The change in state-level health co-benefits ranges from 1 to 330 premature deaths avoided per year (Figure 5b), up to 71 hospitalizations avoided per year (Figure 6b), and up to 19 heart attacks prevented per year (Figure 7b).

Spatial pattern: The 12 states with the greatest estimated number of premature deaths avoided under Scenario 2 are those where there are a large number of exposed people and air quality improves the most (Figures 5b). They are (in order): Pennsylvania, Ohio, Texas, Illinois, Michigan, New York, North Carolina, Georgia, Missouri, Virginia, Tennessee, and Indiana. The 12 states with the greatest percent change in premature deaths avoided are (in order): Pennsylvania, Ohio, West Virginia, Missouri, Michigan, Kentucky, Maryland, District of Columbia, Illinois, Delaware, Indiana, and Arkansas. The geographic distribution of health outcomes for hospitalizations and heart attacks follow a similar spatial pattern as mortality (Figures 6b, 7b).

<u>Scenario 3</u>

Percent change in premature deaths avoided: Like Scenario 2, Scenario 3 results in widespread but slightly lower increases in the percent change in premature deaths from the 2020 reference case avoided from the 2020 reference case (0% to 0.72%).

Change in cases of health co-benefits: The change in estimated state-level co-benefits ranges from 1 to 260 premature deaths avoided per year, up to 56 hospitalizations avoided per year, and up to 16 heart attacks prevented per year (Appendix 5).

Spatial pattern: The 12 states with the greatest estimated number of premature deaths avoided under Scenario 3 are (in order): Pennsylvania, Illinois, Texas, Ohio, Michigan, New York, Tennessee, North Carolina, Missouri, Indiana, Florida, and Georgia (Appendix 5). The geographic distribution of health outcomes for hospitalizations and heart attacks follow a similar spatial pattern as mortality (Appendix 5).

Figure 4a

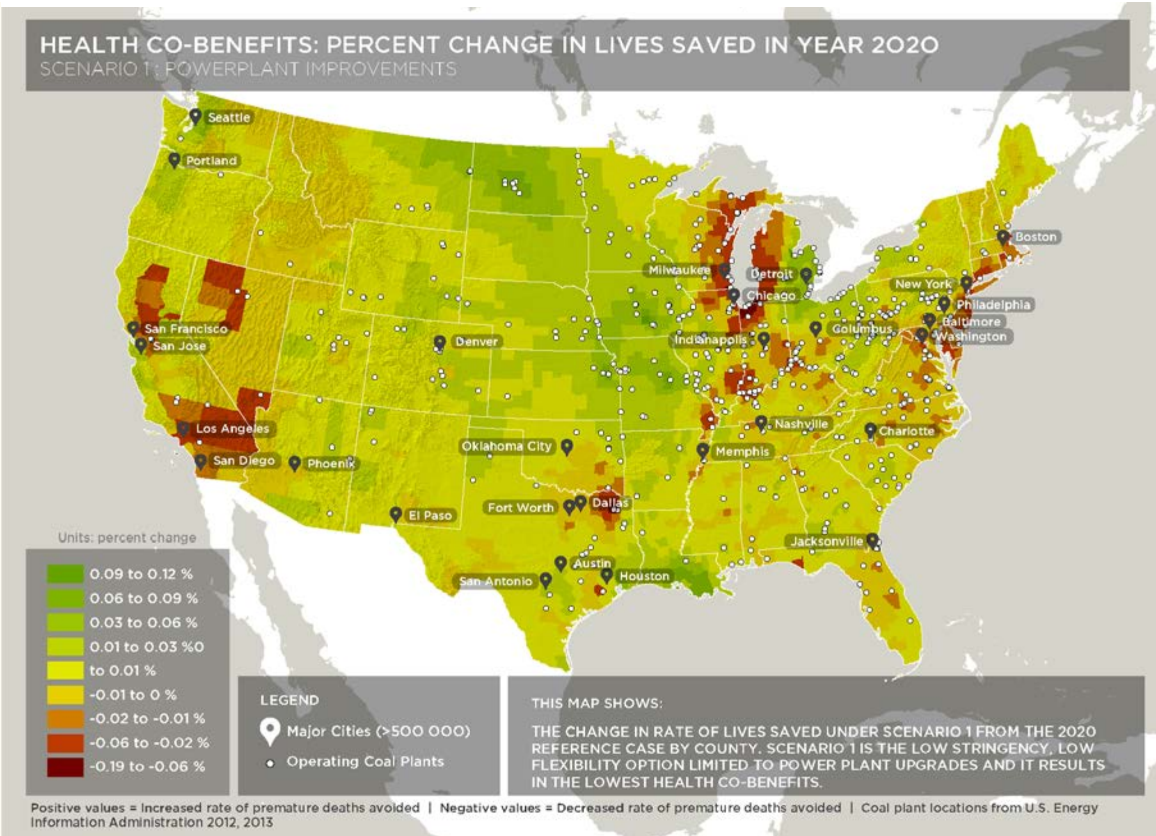


Figure 4b

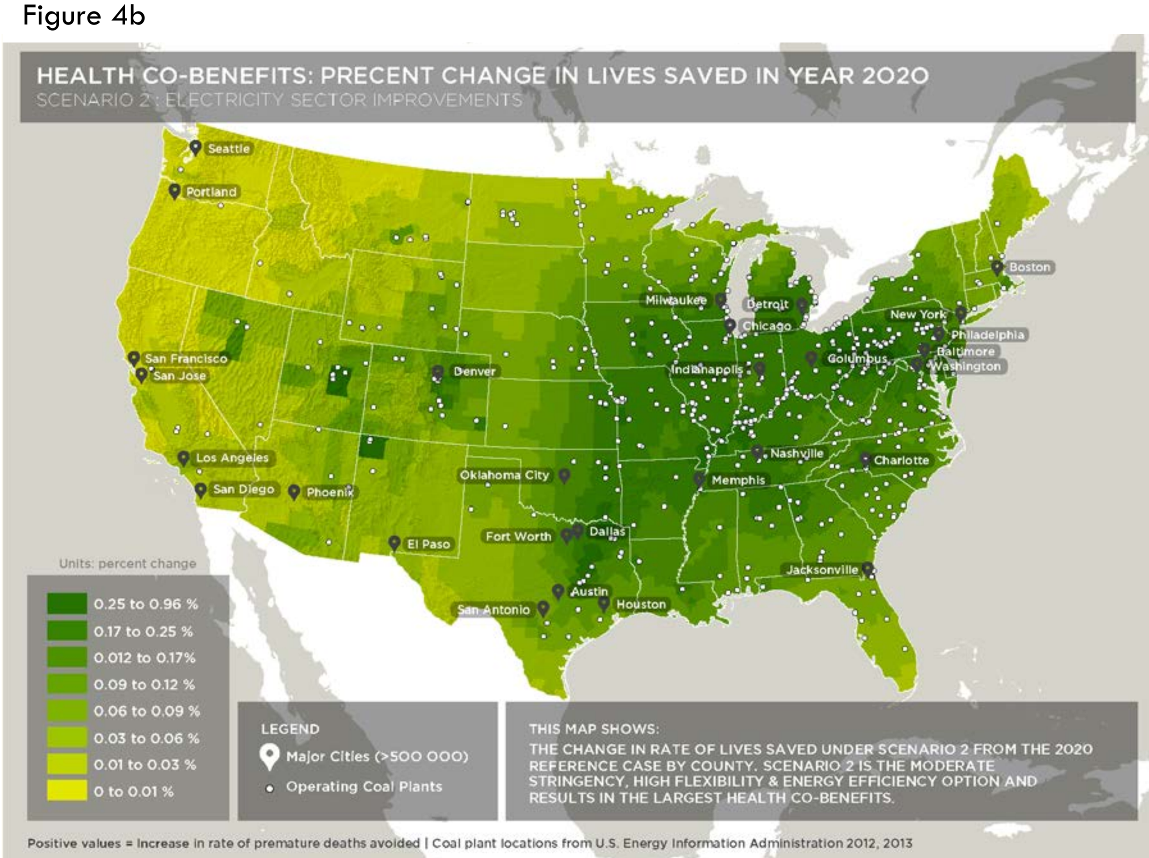


Figure 5a

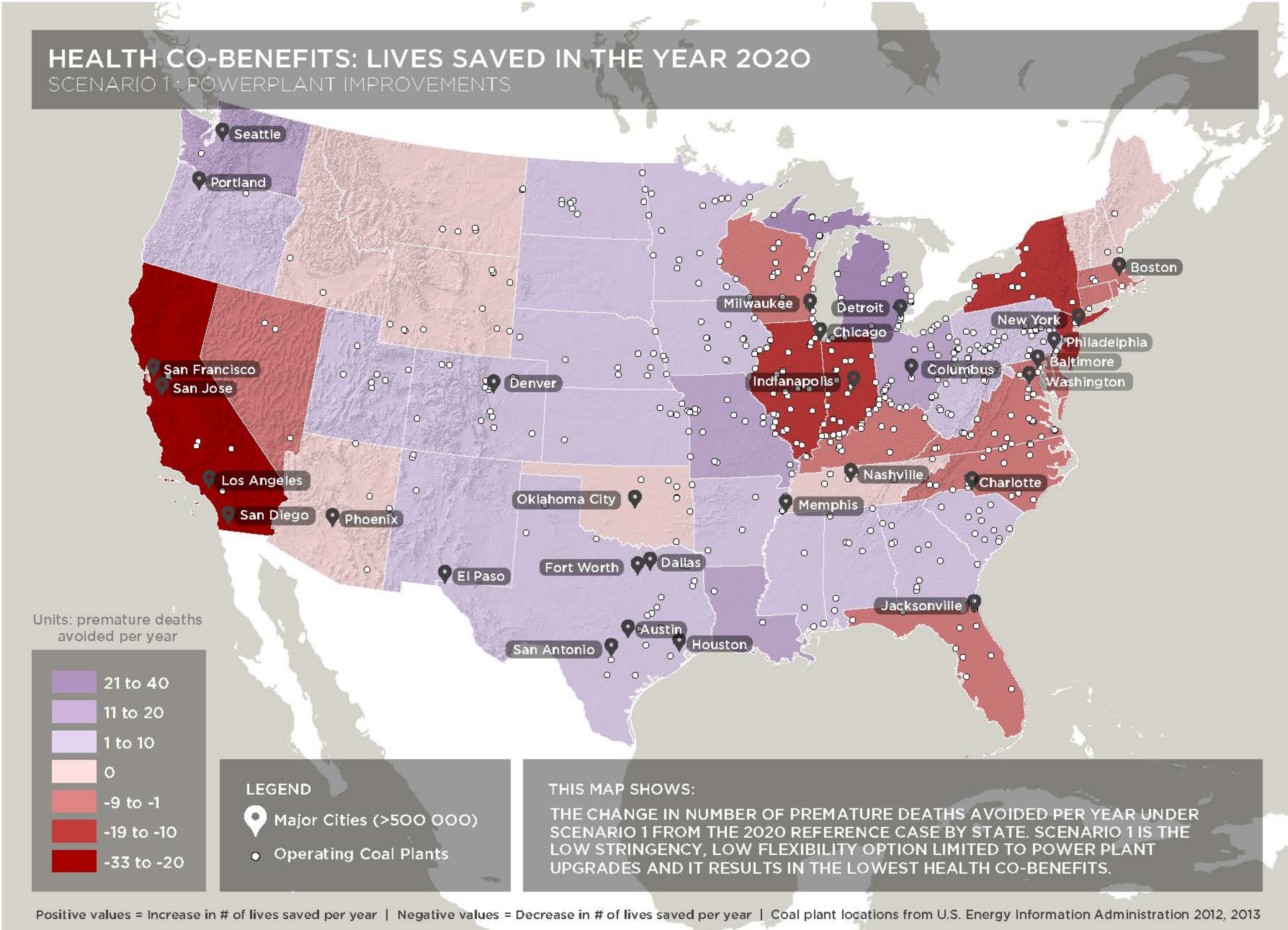
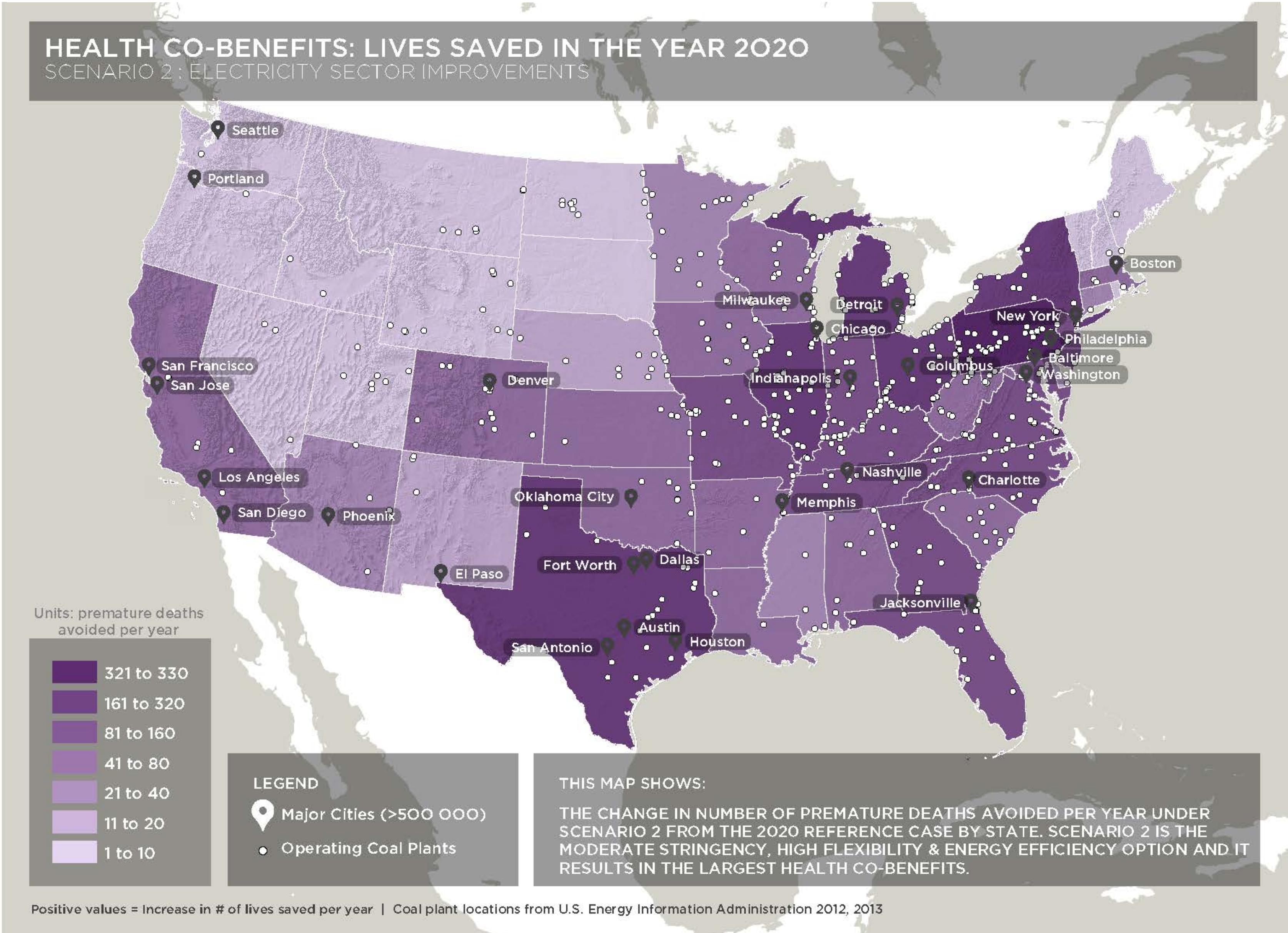

HEALTH CO-BENEFITS: LIVES SAVED IN THE YEAR 2020
SCENARIO 1 : POWERPLANT IMPROVEMENTS
Seattle
Portland
San Francisco
San Jose
Los Angeles
San Diego
Phoenix
El Paso
Denver
Oklahoma City
Fort Worth
Dallas
Austin
San Antonio
Houston
Milwaukee
Detroit
Chicago
Indianapolis
Columbus
Nashville
Memphis
Charlotte
Jacksonville
New York
Philadelphia
Baltimore
Washington
Boston
Units: premature deaths avoided per year
21 to 40
11 to 20
1 to 10
0
-9 to -1
-19 to -10
-33 to -20
LEGEND
Major Cities (>500 000)
Operating Coal Plants
THIS MAP SHOWS:
THE CHANGE IN NUMBER OF PREMATURE DEATHS AVOIDED PER YEAR UNDER SCENARIO 1 FROM THE 2020 REFERENCE CASE BY STATE. SCENARIO 1 IS THE LOW STRINGENCY, LOW FLEXIBILITY OPTION LIMITED TO POWER PLANT UPGRADES AND IT RESULTS IN THE LOWEST HEALTH CO-BENEFITS.
Positive values = Increase in # of lives saved per year | Negative values = Decrease in # of lives saved per year | Coal plant locations from U.S. Energy Information Administration 2012, 2013

Figure 5b



HEALTH CO-BENEFITS: LIVES SAVED IN THE YEAR 2020
SCENARIO 2 : ELECTRICITY SECTOR IMPROVEMENTS
Seattle
Portland
San Francisco
San Jose
Los Angeles
San Diego
Phoenix
El Paso
Denver
Oklahoma City
Fort Worth
Dallas
Austin
San Antonio
Houston
Milwaukee
Chicago
Detroit
Indianapolis
Columbus
Nashville
Memphis
Charlotte
Jacksonville
New York
Philadelphia
Baltimore
Washington
Boston
Units: premature deaths avoided per year
321 to 330
161 to 320
81 to 160
41 to 80
21 to 40
11 to 20
1 to 10
LEGEND
Major Cities (>500 000)
Operating Coal Plants
THIS MAP SHOWS:
THE CHANGE IN NUMBER OF PREMATURE DEATHS AVOIDED PER YEAR UNDER SCENARIO 2 FROM THE 2020 REFERENCE CASE BY STATE. SCENARIO 2 IS THE MODERATE STRINGENCY, HIGH FLEXIBILITY & ENERGY EFFICIENCY OPTION AND IT RESULTS IN THE LARGEST HEALTH CO-BENEFITS.
Positive values = Increase in # of lives saved per year | Coal plant locations from U.S. Energy Information Administration 2012, 2013

Figure 6a

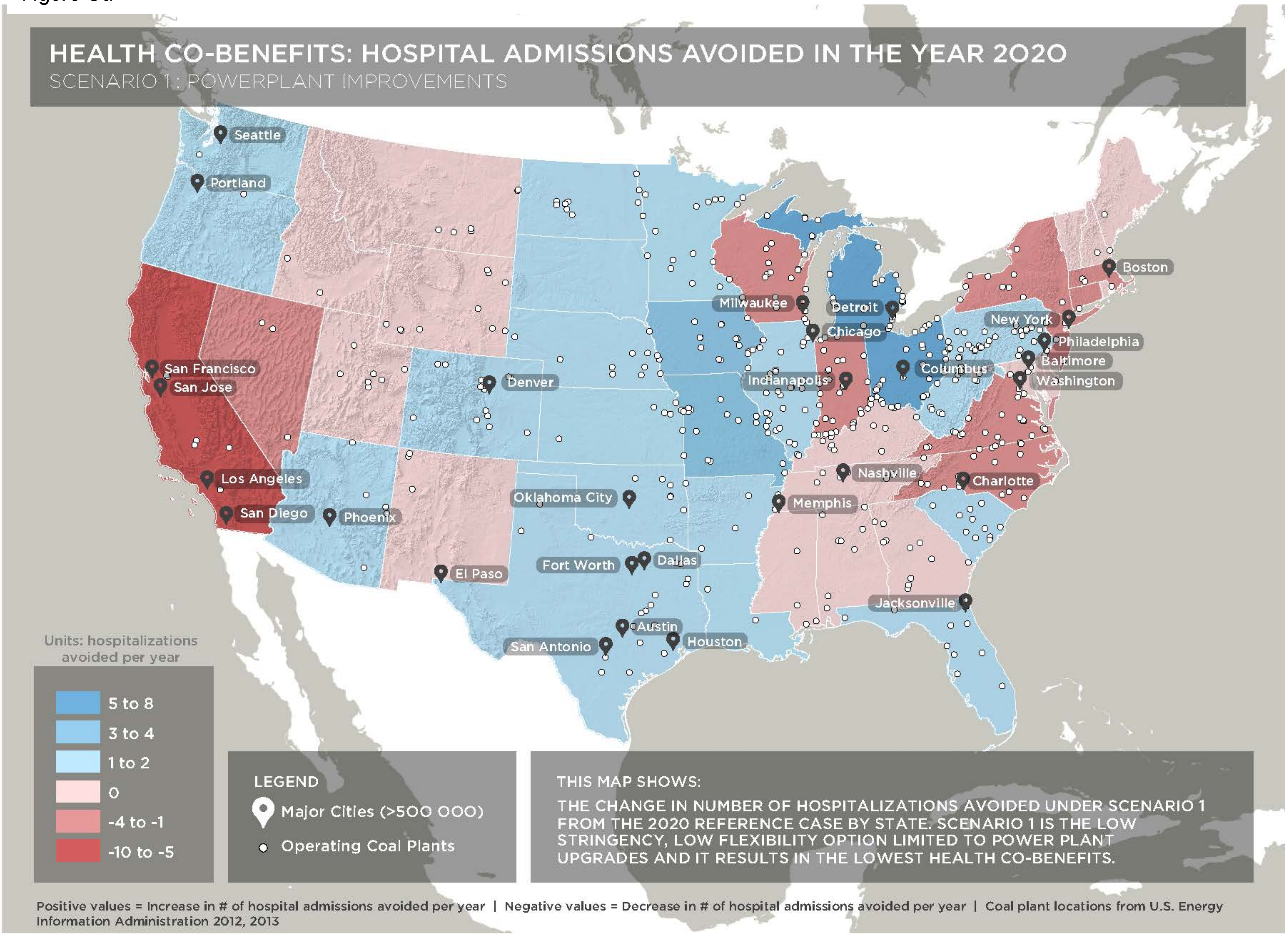

HEALTH CO-BENEFITS: HOSPITAL ADMISSIONS AVOIDED IN THE YEAR 2020
SCENARIO 1: POWERPLANT IMPROVEMENTS
Seattle
Portland
San Francisco
San Jose
Los Angeles
San Diego
Phoenix
El Paso
Denver
Oklahoma City
Fort Worth
Dallas
Austin
San Antonio
Houston
Milwaukee
Detroit
Chicago
Indianapolis
Columbus
Nashville
Memphis
Charlotte
Jacksonville
Boston
New York
Philadelphia
Baltimore
Washington
Units: hospitalizations avoided per year
5 to 8
3 to 4
1 to 2
0
-4 to -1
-10 to -5
LEGEND
Major Cities (>500 000)
Operating Coal Plants
THIS MAP SHOWS:
THE CHANGE IN NUMBER OF HOSPITALIZATIONS AVOIDED UNDER SCENARIO 1 FROM THE 2020 REFERENCE CASE BY STATE. SCENARIO 1 IS THE LOW STRINGENCY, LOW FLEXIBILITY OPTION LIMITED TO POWER PLANT UPGRADES AND IT RESULTS IN THE LOWEST HEALTH CO-BENEFITS.
Positive values = Increase in # of hospital admissions avoided per year | Negative values = Decrease in # of hospital admissions avoided per year | Coal plant locations from U.S. Energy Information Administration 2012, 2013

Figure 6b

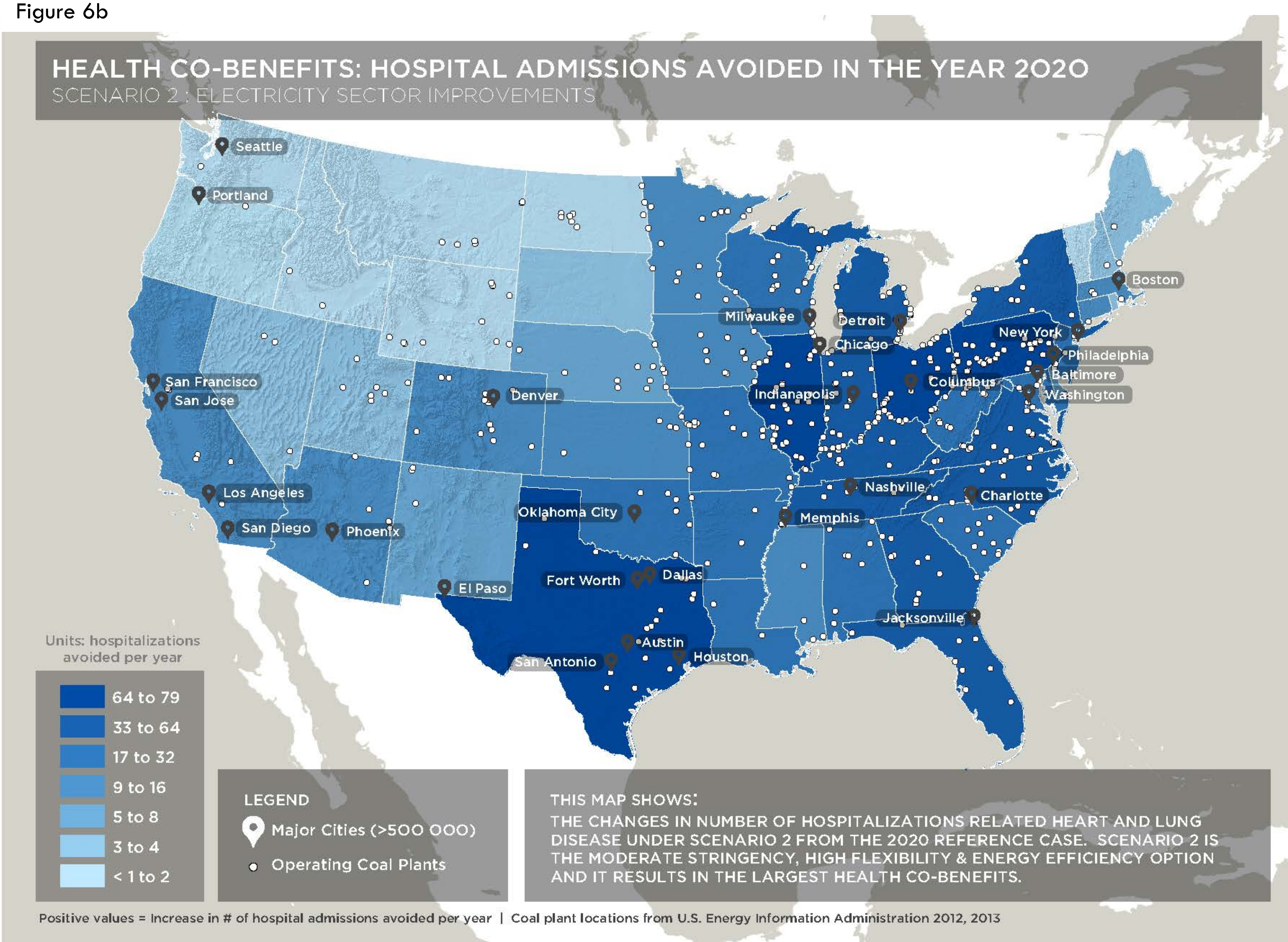
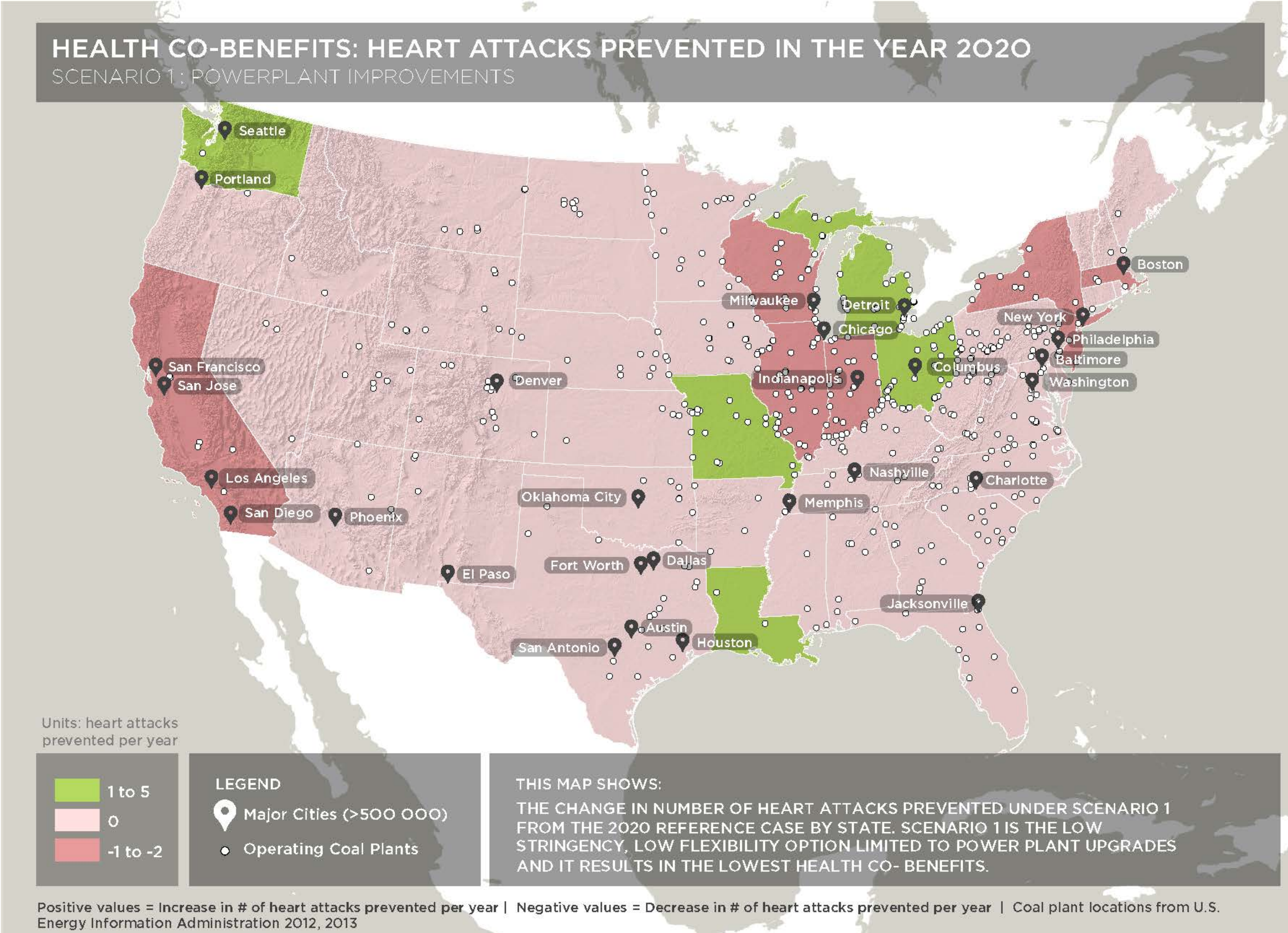
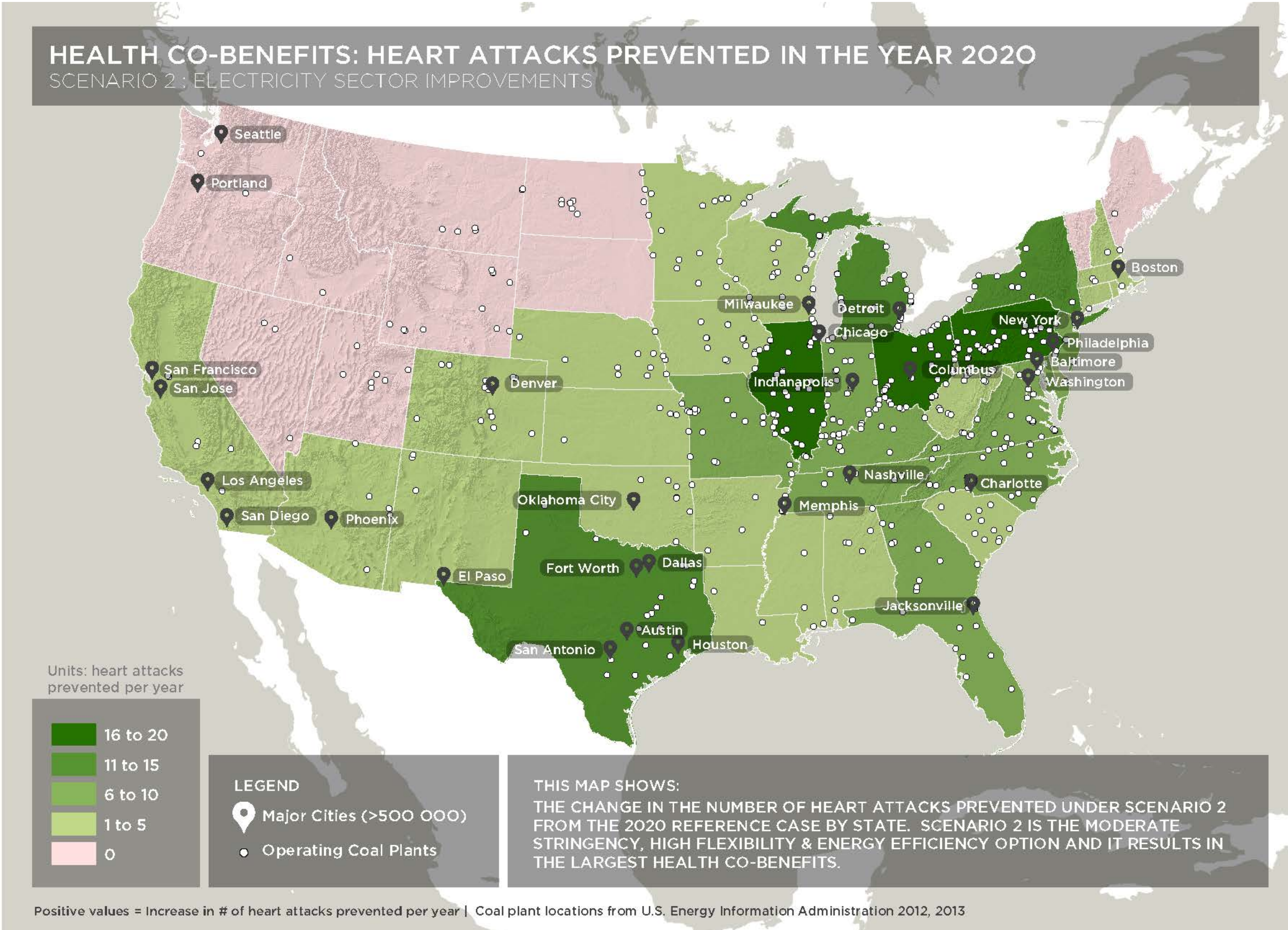

HEALTH CO-BENEFITS: HOSPITAL ADMISSIONS AVOIDED IN THE YEAR 2020
SCENARIO 2 : ELECTRICITY SECTOR IMPROVEMENTS
Seattle
Portland
San Francisco
San Jose
Los Angeles
San Diego
Phoenix
El Paso
Denver
Oklahoma City
Fort Worth
Dallas
Austin
San Antonio
Houston
Milwaukee
Detroit
Chicago
Indianapolis
Columbus
New York
Philadelphia
Baltimore
Washington
Boston
Nashville
Charlotte
Memphis
Jacksonville
Units: hospitalizations avoided per year
64 to 79
33 to 64
17 to 32
9 to 16
5 to 8
3 to 4
< 1 to 2
LEGEND
Major Cities (>500 000)
Operating Coal Plants
THIS MAP SHOWS:
THE CHANGES IN NUMBER OF HOSPITALIZATIONS RELATED HEART AND LUNG DISEASE UNDER SCENARIO 2 FROM THE 2020 REFERENCE CASE. SCENARIO 2 IS THE MODERATE STRINGENCY, HIGH FLEXIBILITY & ENERGY EFFICIENCY OPTION AND IT RESULTS IN THE LARGEST HEALTH CO-BENEFITS.
Positive values = Increase in # of hospital admissions avoided per year | Coal plant locations from U.S. Energy Information Administration 2012, 2013

Figure 7a



HEALTH CO-BENEFITS: HEART ATTACKS PREVENTED IN THE YEAR 2020
SCENARIO 1 : POWERPLANT IMPROVEMENTS
Seattle
Portland
San Francisco
San Jose
Los Angeles
San Diego
Phoenix
El Paso
Denver
Oklahoma City
Fort Worth
Dallas
Austin
San Antonio
Houston
Milwaukee
Chicago
Detroit
Indianapolis
Columbus
Nashville
Memphis
Charlotte
Jacksonville
New York
Philadelphia
Baltimore
Washington
Boston
Units: heart attacks prevented per year
1 to 5
0
-1 to -2
LEGEND
Major Cities (>500 000)
Operating Coal Plants
THIS MAP SHOWS:
THE CHANGE IN NUMBER OF HEART ATTACKS PREVENTED UNDER SCENARIO 1 FROM THE 2020 REFERENCE CASE BY STATE. SCENARIO 1 IS THE LOW STRINGENCY, LOW FLEXIBILITY OPTION LIMITED TO POWER PLANT UPGRADES AND IT RESULTS IN THE LOWEST HEALTH CO- BENEFITS.
Positive values = Increase in # of heart attacks prevented per year | Negative values = Decrease in # of heart attacks prevented per year | Coal plant locations from U.S. Energy Information Administration 2012, 2013

Figure 7b


HEALTH CO-BENEFITS: HEART ATTACKS PREVENTED IN THE YEAR 2020
SCENARIO 2 : ELECTRICITY SECTOR IMPROVEMENTS
Seattle
Portland
San Francisco
San Jose
Los Angeles
San Diego
Phoenix
El Paso
Denver
Oklahoma City
Fort Worth
Dallas
Austin
San Antonio
Houston
Milwaukee
Chicago
Detroit
Indianapolis
Columbus
Nashville
Memphis
Charlotte
Jacksonville
New York
Philadelphia
Baltimore
Washington
Boston
Units: heart attacks prevented per year
16 to 20
11 to 15
6 to 10
1 to 5
0
LEGEND
Major Cities (>500 000)
Operating Coal Plants
THIS MAP SHOWS:
THE CHANGE IN THE NUMBER OF HEART ATTACKS PREVENTED UNDER SCENARIO 2 FROM THE 2020 REFERENCE CASE BY STATE. SCENARIO 2 IS THE MODERATE STRINGENCY, HIGH FLEXIBILITY & ENERGY EFFICIENCY OPTION AND IT RESULTS IN THE LARGEST HEALTH CO-BENEFITS.
Positive values = Increase in # of heart attacks prevented per year | Coal plant locations from U.S. Energy Information Administration 2012, 2013

Summary of Results

1. Power plant carbon standards can improve air quality and provide substantial health co-benefits. The carbon standard that is moderately stringent has the greatest health co-benefits of the three analyzed (Scenario 2). The high compliance flexibility and high end-user energy efficiency in Scenario 2 results in the greatest number of premature deaths avoided overall and per ton of CO_2 reduced. This scenario is most similar to the EPA-proposed Clean Power Plan in its design and resulting CO_2 emissions. It yields the following estimated health co-benefits in the U.S. in 2020 compared to the business-as-usual reference case:

   - 3,500 premature deaths avoided each year (that is equivalent to 9 premature deaths avoided every day).
   - 1,000 hospital admissions avoided from heart and lung disease each year.
   - 220 heart attacks prevented each year.

   It would also lead to additional health benefits not quantified here, including reduced asthma symptoms and other health benefits for children, the elderly, and vulnerable adults.

2. The geographic distribution of health co-benefits in the top-performing scenario (Scenario 2) is widespread with all lower 48 states receiving some benefit. The 12 states with the greatest estimated number of premature deaths avoided are those where there are a large number of exposed people and air quality improves the most. They are (in order): PA, OH, TX, IL, MI, NY, NC, GA, MO, VA, TN, and IN. The 12 states with the greatest estimated percent increase in premature deaths avoided are (in order): PA, OH, WV, MO, MI, KY, MD, DC, IL, DE, IN, and AR.

3. The carbon standard with the lowest stringency has the lowest health co-benefits (Scenario 1). Its low flexibility and focus on improving power plant heat rates and operating efficiency results in little to no benefit with a slight *increase* in estimated premature deaths and heart attacks per year in the U.S. from the 2020 reference case.

4. The carbon standard with the highest stringency (Scenario 3) has high health co-benefits but they are lower than Scenario 2. It results in fewer estimated premature deaths avoided per year in the U.S. from the 2020 reference case and nearly half as many avoided per ton of CO_2 reduced as Scenario 2.

5. Overall, the study shows that the health co-benefits of power plant carbon standards can be large but the magnitude depends on critical policy choices. The carbon standard scenario that combines moderately stringent carbon targets with highly flexible compliance options and more end-user energy efficiency (Scenario 2) has the greatest estimated health co-benefits.

In Conclusion

Fossil-fuel-fired power plants are the single largest source of anthropogenic CO_2 emissions in the U.S. (~39%). They emitted approximately 2.2 billion tons of CO_2 in 2012. Fossil-fuel-fired power plants are also the single-largest U.S. source of SO_2 and Hg emissions, and the second largest source of NO_x emissions. The results from this study show that carbon pollution standards for existing U.S. power plants can provide the added bonus of substantial near-term health co-benefits for by reducing emissions of co-pollutants (SO_2, NO_x, Hg and PM) and improving air quality.

The results of this health co-benefits analysis suggest that carbon standards that have stringent CO_2 emissions reductions targets but are flexible and include new investments in energy efficiency, offer greater and more widespread health co-benefits than the other alternatives examined here. Scenario 2, which is most similar to the EPA-proposed Clean Power Plan, has the greatest estimated health co-benefits of the three scenarios analyzed. The results also show that carbon standards focused strictly on power plant retrofits could increase emissions and little to no health co-benefits nationwide. The results underscore that the design of power plant carbon standards strongly influences the magnitude and distribution of air quality improvements and health co-benefits that accrue to states and to local communities. For the U.S. and other nations with significant greenhouse gas emissions and air quality challenges, quantifying and valuing local benefits could be an important additional motivator for taking action on climate change.

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SCIENCE POLICY EXCHANGE

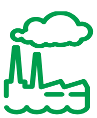
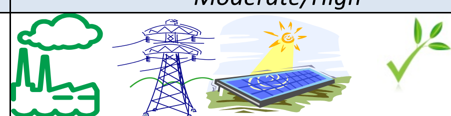
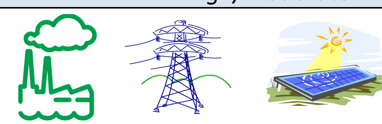
The three-part Co-benefits of Carbon Standards study is a project of the Science Policy Exchange, a research consortium dedicated to increasing the impact of science on conservation and environmental policy.

This second report in the three-part series is available at: www.chgeharvard.org/health-co-benefits

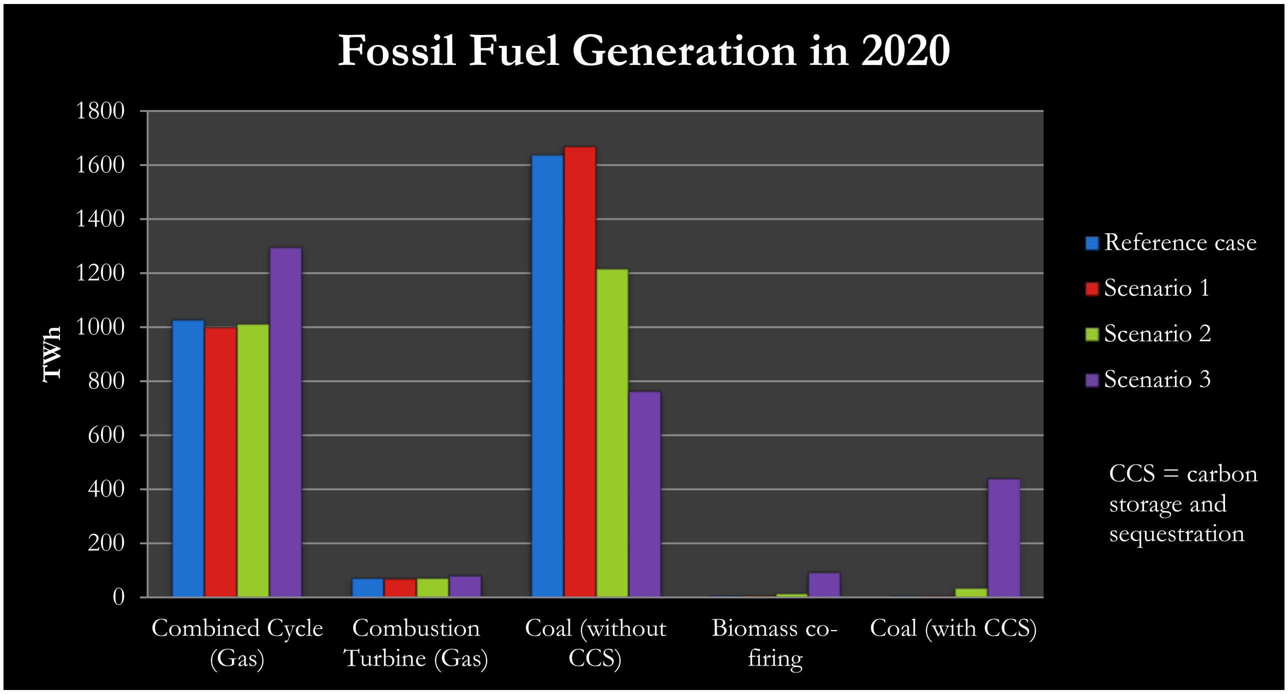
The first report in the three part-series, *Air Pollution Changes under Different 111d Options for Existing Power Plants*, is available at: http://eng-cs.syr.edu/carboncobenefits

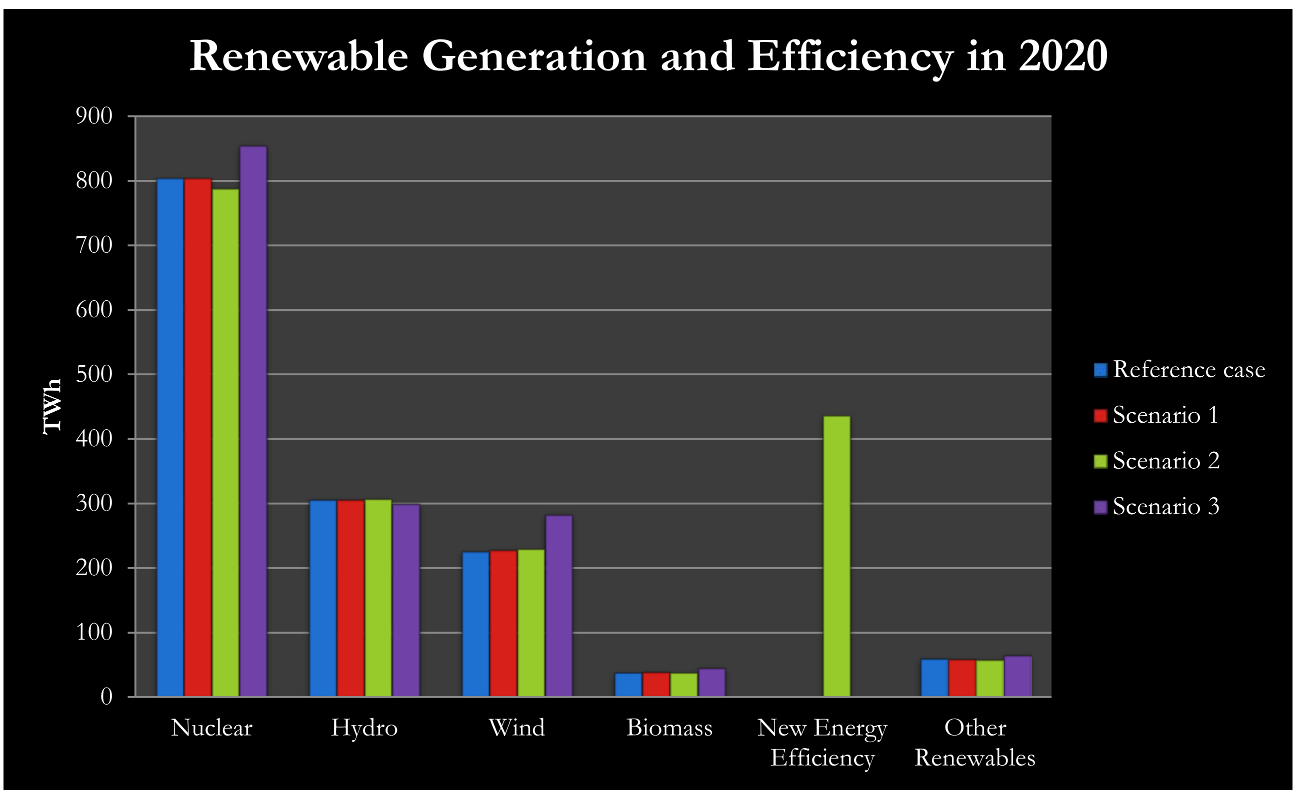
Appendix 1: Scenario Assumptions

Reference Case
Policy Assumptions: • All current air quality policies fully implemented • No carbon pollution standards
Included: • EIA 2013 Annual Energy Outlook determines energy demand • Mercury and Air Toxics Standards (MATS) implemented • Clean Air Interstate Rule implemented, including Phase II in 2015 • Regional Greenhouse Gas Initiative (RGGI) model rule for emissions trading included (w/out NJ) • CA Assembly Bill 32 (AB32) included • Regional haze rule included • Wind power production tax credit (PTC) expires • Onshore wind costs: DOE/LBL 2012 Wind Technologies Report • Nuclear units re-licensed, 20-year extension

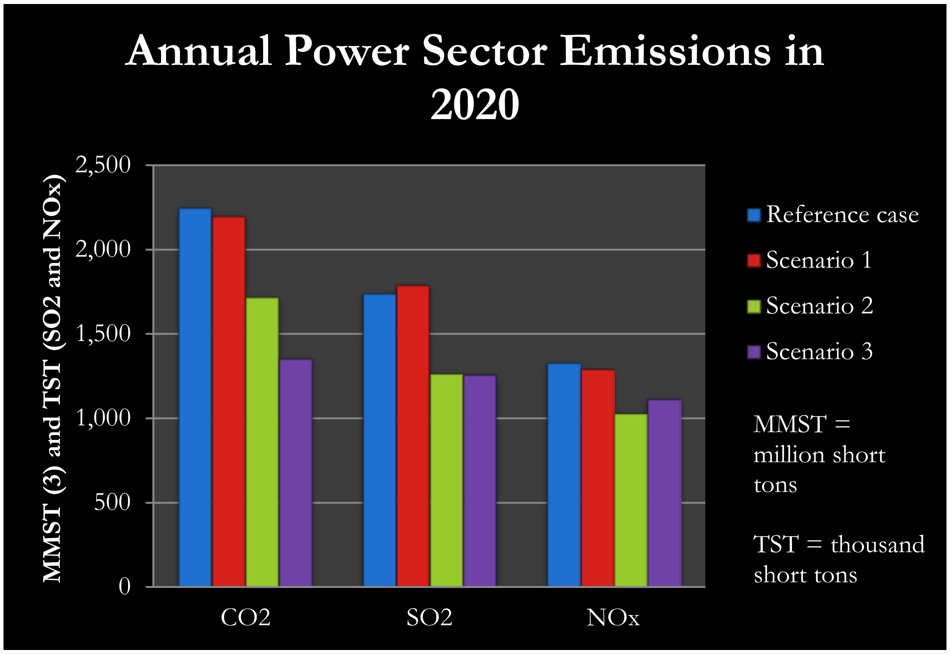
Carbon Standard Scenarios		
Policy assumptions: • All current air quality policies fully implemented as in the Reference Case • Carbon pollution standards adopted under section 111d for existing power plants		
Scenario 1: Powerplant Improvements *Low/Low*	*Scenario 2: Electricity Sector Improvements* *Moderate/High*	*Scenario 3: Cost of Carbon Improvements* *High/Moderate*
		
Low stringency, low flexibility and energy efficiency	*Moderate stringency, high flexibility and energy efficiency*	*High stringency, moderate flexibility and energy efficiency*
Stringency estimate: 2000 lbs/MWh coal; 1000 lbs/MWh gas	Stringency benchmark: 1500 lbs/MWh coal; 1000 lbs/MWh gas	Stringency estimate: 1200 lbs/MWh – coal; 850 lbs/MWh
Compliance options: • Limited to on-site carbon emission rate reductions • Power plant efficiency/heat rate upgrades • Modest natural gas & biomass co-firing	Compliance options: • Power plant efficiency/heat rate upgrades • Co-firing with lower-carbon fuels • Dispatch changes to lower-carbon generation sources • State/interstate averaging and trading	Compliance options: • Power plant efficiency/heat rate upgrades • Co-firing with lower-carbon fuels • Dispatch changes to lower-carbon generation sources
Energy efficiency: • Only efficiency measures at the power plant included	Energy efficiency: • Full supply-side and demand-side (end-user) energy efficiency included.	Energy efficiency: • Supply-side efficiency (power plant and transmission lines)

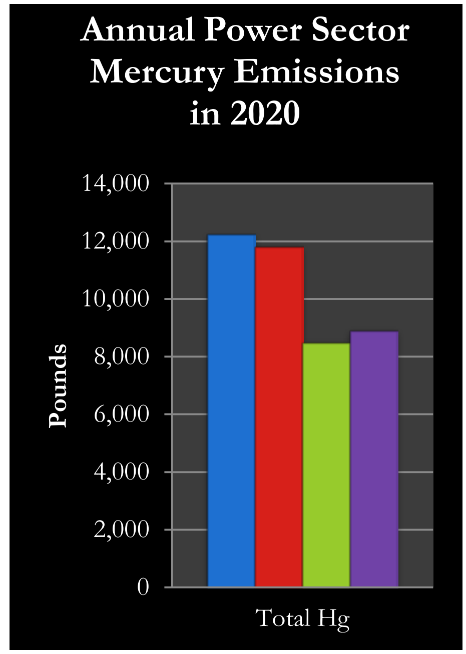
Appendix 2: Power generation mix by scenario (terawatt/hours)





Appendix 3: Air pollution emissions by scenario (million short tons, thousand short tons, and pounds)





Performance C	SO_2+NO_X reduced/CO_2 reduced (thousand tons/million tons)
Scenario 1	-0.22
Scenario 2	1.46
Scenario 3	0.84