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Policies for Reducing the Impacts of Power Sector Air Pollution on Disadvantaged Americans

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Abstract

Environmental policymakers in the United States are giving increasing attention to reducing the burden on Americans who face both environmental and economic disadvantages. This study considers an important part of the burden: the concentration of airborne fine particulate matter ($PM_{2.5}$) due to emissions from the nation's power sector. Using a highly detailed simulation model of the US power sector paired with a model of $PM_{2.5}$ formation and dispersion, the study projects some of the environmental and economic effects of nationwide implementation of different policies to reduce power plants' contributions to $PM_{2.5}$ in environmentally overburdened, disadvantaged communities (EO DACs). Effects from reduced ground-level ozone also are addressed. Results are compared with a policy that is not geographically targeted—a national price on power sector carbon dioxide (CO_2) emissions. In addition to the effects on EO DACs, we project the effects for all Americans, Black Americans, Hispanic Americans, Americans in the lowest income quintile, and Americans in highly environmentally burdened (not necessarily disadvantaged) areas. The national power sector CO_2 emissions price is the most cost-effective policy for reducing premature mortality from $PM_{2.5}$ exposure in EO DACs. The other policies, which are geographically targeted toward reducing burdens in EO DACs, have the unintended consequence of increasing $PM_{2.5}$ exposure in some of those areas.

Keywords

Environmental justice, cumulative burdens, power plants, electricity, health, emissions, pollution, hotspots, costs.

Executive Summary

Environmental policymakers in the United States are giving increasing attention to a longstanding concern: reducing the burden on Americans who face both environmental and economic disadvantages. Ample evidence indicates that environmental burdens fall disproportionately on many people of color and low-income people. These disparities raise fundamental questions of equity and justice that policymakers and researchers are trying to address.

This study considers a particular part of that environmental burden—disparities in premature mortality from exposure to airborne fine particulate matter ($PM_{2.5}$) resulting from power sector emissions. Through simulation analysis, the study assesses the effects of several types of policies intended to improve the circumstances of people and communities facing environmental and economic disadvantages. The study assesses the health effects of the policies on certain disadvantaged communities and on different population groups at the national level, as well as on the population as a whole. It also assesses the costs of implementing the various policies, and their cost-effectiveness per death avoided by reducing $PM_{2.5}$ concentrations.[2] In our simulations, we implement each policy across the whole contiguous US.

Using a highly detailed simulation model of the power sector paired with a model of $PM_{2.5}$ formation and dispersion, the study projects the environmental and economic effects of several policies that reduce ambient $PM_{2.5}$ in geographic areas referred to as environmentally overburdened, disadvantaged communities (EO DACs). DACs are identified at the level of census tracts based on socioeconomic and environmental burdens, using the US government's Climate and Economic Justice Screening Tool. EO DACs are DACs whose environmental quality is below average relative to nearby non disadvantaged communities. In addition to the effects for EO DACs and for society as a whole, we project the effects for Black Americans, Hispanic Americans, Americans in the lowest income quintile, and Americans in areas with a high environmental burden (whether those areas are otherwise disadvantaged or not).

Three of the targeted policies we simulate are designed to restrict power plants within EO DACs ("within-DAC policies"). They are loosely inspired by a 2022 New Jersey law, though we are not modeling all of the specific provisions of that legislation, and how it will be implemented is uncertain. Another targeted policy, which we call Upwind Limits, is designed to prevent any power plant from contributing more than a de minimis amount of pollution to any EO DAC. It is loosely inspired by a 2023 New York law, though again, we are not modeling all of the specific provisions of that legislation, and how it will be implemented is uncertain. For comparison, the study also analyzes the effects of a hypothetical $15-per-ton CO_2 Pricing policy, which by its nature does not target EO DACs.

2 The model also accounts for the considerably smaller number of deaths avoided by the effects of policies in reducing ground level ozone.

In our results, the Upwind Limits policy, CO_2 Pricing policy, and best-performing within-DAC policies reduce per capita mortality across the country by approximately 1.4 to 1.5 times as much for EO DAC residents as for Americans living outside EO DACs. Thus, those policies reduce the $PM_{2.5}$ mortality disparity between EO DAC residents and other Americans. The main reasons are that EO DACs have higher baseline $PM_{2.5}$ concentrations, and some populations in EO DACs are known to be more sensitive to the harms of $PM_{2.5}$ exposure. However, the targeted policies are, at best, only slightly more effective than the carbon price at targeting the $PM_{2.5}$ reductions they cause in EO DACs.

The average per capita mortality reduction for Black Americans is 4.3 to 4.8 times the reduction for other Americans, for two reasons. Black Americans tend to live in areas with above-average $PM_{2.5}$ from power plants (40 percent higher on average), and Black Americans experience a higher average mortality rate from a given $PM_{2.5}$ exposure than other Americans.

The average national per capita mortality reduction for Hispanics as a group in the study is only 0.5 to 0.7 times the reduction for other Americans, mostly because Hispanics tend to live in areas with below-average $PM_{2.5}$ from power plants (the emissions source type considered in this study), though their exposure to other $PM_{2.5}$ sources is substantial. Our estimate of the per capita mortality risk reduction for Americans in the lowest income quintile is not significantly different from the reduction for the entire population. However, the estimate is based on using the same estimated exposure-response function across all income quintiles, since we could not find an estimate of how much more sensitive to $PM_{2.5}$ Americans in the lowest income quintile are compared with other Americans.

The costs of the policies differ greatly. Counting deaths from both $PM_{2.5}$ and ozone, the increased cost of supplying electricity per avoided death in the United States is $12 million for the best-performing within-DAC policy, $2.1 million for the Upwind Limits policy, and $0.6 million for the CO_2 Pricing policy.

The CO_2 Pricing policy also has a much higher ratio of estimated total health benefits and benefits from climate change mitigation relative to costs of policy implementation than the targeted measures. This is because it delivers significant co-benefits from local pollutant reductions in DAC and non-DAC areas. Also, unlike the policies targeted toward EO DACs, the CO_2 Pricing policy does not create significant pollution hotspots.

Extensions of the study could provide additional insights. One extension would be to investigate the potential advantages of combining broadly applied, cost-effective measures, such as emissions pricing, with targeted policies to further reduce local harms in EO DACs. That research also would shed further light on the pros and cons of policies restricting emissions from having more than a de minimis effect on any EO DAC, versus policies focused on power plants within DACs.

Contents

Abbreviations

ATB Annual Technology Baseline

BAU business-as-usual, the scenario that has none of the policies whose effects we are estimating in this study

CEJST Climate and Economic Justice Screening Tool, developed and maintained by the US government (Council on Environmental Quality, n.d.)

CCUS carbon capture and utilization or storage

DAC disadvantaged community

EGU electricity-generating unit

EJ environmental justice

EO DAC environmentally overburdened disadvantaged community

EPA US Environmental Protection Agency

MW megawatt, a measure of generation capacity

MWh megawatt-hour, a measure of energy produced in some time period. In this document, that time period is the year 2030.

$PM_{2.5}$ particulate matter (ground-level airborne particles) less than 2.5 microns in diameter. Also known as fine particulate matter.

RGGI Regional Greenhouse Gas Initiative (northeastern states)

Terminology

Americans all the residents of the contiguous US, regardless of citizenship

capacity factor the average utilization rate of an EGU in a given time period, such as a year. The actual electrical energy produced is divided by the electrical energy the generator would produce if it operated at maximum output (with no outages).

census block group block group a subdivision of a census tract, as defined by the US Census Bureau. Census block group is the geographic unit used in the 2022 New Jersey policy and in our policy representations. Most of the approximately 240,000 census block groups in the US (US Census 2020b) contain 600 to 3,000 people.

census tract a geographic division comprising between one and nine census block groups, defined by the US Census Bureau. The approximately 84,000 census tracts in the US have an average of 4,000 people each.

community, neighborhood synonyms for census block group. CEJST defines DACs at the census tract level. A typical census tract consists of two or three block groups, allowing us to assign block groups a DAC status based on their census tract.

contiguous US the 48 contiguous US states and the District of Columbia. Contains 98% of the US population.

disadvantaged Americans, disadvantaged groups five groups of people in the contiguous United States: people in environmentally overburdened DACs (as defined in Section 2), people in block groups with high environmental burden (as defined in Appendix D), Americans in the lowest income quintile, Black Americans, and Hispanic Americans. We investigate the effects of the policies on the air quality and health of these groups.

disadvantaged community a geographic area deemed to have a high proportion of people who are likely to be disadvantaged based on wealth, racial or ethnic discrimination, language, and/or other factors. Different governments have different criteria for determining which areas to designate as disadvantaged. The definition we use in this study, described in the Methods section, is from the CEJST and is mainly based on income.

environmentally overburdened community as defined in Section 2, people in a block group whose environmental burden index value is above the median of nearby block groups that are not DACs.

existing EGU an electricity-generating unit that was in place before any of the policies in our non-BAU scenarios take effect. A unit can retire as a result of the policies, but its construction cannot be prevented by the policies.

gas natural gas

leakage an increase of generation and emissions at one set of generators as a result of a policy that reduces generation at another set of generators

new EGU an electricity-generating unit that is or can be built in our simulations. The policies can affect whether it is built.

policies the proposed actions whose effects we test. They are absent from our BAU scenario. Each other scenario contains only one policy.

policy costs the net costs of a policy to electricity customers, governments, and producers. The costs of a policy to one or more of these groups can be negative, meaning the policy reduces net expenses or increases profit. Also called pocketbook costs or economic costs.

shut down to cease operation; retire. We assume that EGUs that shut down cannot provide generation and cannot provide capacity reserves or any other ancillary services, since those actions would require burning fuel when called on to provide power.

1. Introduction

Environmental policymakers in the United States are giving increasing attention to a longstanding concern: reducing the burden on Americans who face both environmental and economic disadvantages. Ample evidence indicates that environmental burdens fall disproportionately on many people of color and low-income people (e.g. Declet-Barreto and Rosenberg 2022, Liu et al. 2021, Banzhaf et al. 2019, Anderson et al. 2018, Cushing et al. 2018, and Miranda et al. 2011). These disparities raise fundamental questions of equity and justice that policymakers and researchers are trying to address.

This study considers a particular part of that environmental burden—disparities in premature mortality from exposure to airborne fine particulate matter ($PM_{2.5}$) resulting from power sector emissions. The study assesses the projected effects of several policies designed to reduce environmental harms to environmentally overburdened (EO) disadvantaged communities (DACs) from air pollution produced by power plants.[2] It compares the health effects of the policies on certain disadvantaged communities and on different population groups at the national level, as well as on the population as a whole. It also considers the economic (or pocketbook) costs to electricity consumers, producers, and governments of implementing the various policies, and their cost-effectiveness per death avoided by reducing $PM_{2.5}$ concentrations. In our simulations, all the policies examined are implemented in the 48 contiguous US states and the District of Columbia.

The study projects the effects of the policies on air quality, on deaths and illness from air pollution, and on estimated climate change damage, as well as the economic effects for electricity bill payers, governments, and generation owners.[3] For this purpose, it uses a highly detailed simulation model of the power sector paired with a model of $PM_{2.5}$ formation. It also uses an estimate of ozone-caused mortality from power plant NO_X emissions. The study puts particular emphasis on $PM_{2.5}$, which is estimated to cause the most harm among the local pollutants from power plants.[4] The aim of the study is to provide information for advocates, policymakers, regulators, judges, and other researchers about the potential effects of different types of policies that reduce pollution from power plants affecting disadvantaged Americans, both in absolute and relative terms.

2 The formal characterizations of DACs and EO DACs are provided in Section 2.

3 The study does not consider the other effects of power plants, such as other air pollution, water pollution, ecosystem effects, aesthetic effects, tax revenues, employment, or general equilibrium effects in and via other markets.

4 An estimated 9,000 deaths in 2020 were attributed to power plants' contributions to $PM_{2.5}$ concentrations in US air. This estimate of premature deaths from $PM_{2.5}$ is based on 2020 US power plant SO_2, NO_X, and $PM_{2.5}$ emissions totals (US EPA 2024, 2023a) and on mortality-per-ton estimates (US EPA 2023b). Airborne $PM_{2.5}$ from fossil fuel combustion emissions causes an estimated 300,000 premature deaths per year in the United States and 8.7 million globally (Vohra et al. 2021).

1.1. Scope of the Study

The study projects premature deaths from power plant–caused $PM_{2.5}$ for each of five subgroups of individuals: those in EO DACs; those in areas with high environmental burdens, whether DACs or not; Americans in the lowest income quintile (the lowest 20 percent); Black Americans; and Hispanic Americans.

The study examines the potential effects across the contiguous US of four policies (explained in Section 4) that seek to target environmental benefits to EO DACs by prohibiting, shutting down, or reducing output of EGUs or power plants that are in EO DACs or contribute more than a de minimis amount of pollution in an EO DAC. These policy effects are compared with those of a geographically uniform and constant price on CO_2 emissions that also significantly reduces $PM_{2.5}$. The modeling of these policies is carried out using an analytical framework for power plant operation and investment (explained in Section 3) that accounts for every existing EGU in the United States and a comprehensive inventory of potential locations for new EGUs.

Comparison of power sector emissions reduction policies is one important element in the larger discussion about how to reduce environmental injustice. This study does not address numerous other elements—among them, policies to control $PM_{2.5}$ from sources other than EGUs, the degree of reduction in disparity of environmental burdens achieved by the policies, and the effects of combining policies.

1.2. Plan of the Study

The next section of the study provides our definitions of DACs and EO DACs. Section 3 summarizes the analytical framework, and Section 4 describes the policy scenarios. Section 5 presents and discusses findings from the study. Section 6 summarizes policy effects for each policy design. Concluding observations are in Section 7. Additional details are presented in several appendices, referenced in the main text.

2. Specifying Disadvantaged and Environmentally Burdened Communities

2.1. Disadvantaged Communities

US federal agencies and various state governments have definitions for what geographic areas qualify as DACs. For instance, New York State uses extensive criteria, including "geographic, public health, environmental hazard, and socioeconomic criteria," to define DACs in a way that is tailored to its existing conditions and environmental justice (EJ) goals (New York State Senate 2020).

This study uses a characterization of DACs from the US Council on Environmental Quality (CEQ n.d.), by which communities are considered disadvantaged if they are "at or above the threshold for one or more environmental, climate, or other burdens, and … at or above the threshold for an associated socioeconomic burden;"[5] or if they are within the boundaries of Federally Recognized Tribes. "Low income" is a socioeconomic burden associated with seven of the eight categories of environmental, climate, and other burdens, so in CEQ's definition, income strongly influences whether a community is considered disadvantaged.

The categories of environmental, climate, and socioeconomic burdens and the associated thresholds are built into the US government's Climate and Economic Justice Screening Tool (CEJST) (CEQ n.d.).[6] This study defines DACs using the CEQ criteria and the CEJST across the contiguous US. An area is considered low-income if it is at or above the 65th percentile of census tracts for percentage of population in households whose income is at or below twice the federal poverty level.[7] Under the CEQ criteria, 97 percent of the low-income areas in the study are considered disadvantaged, and only 11 percent of disadvantaged areas are not low income.

DACs are defined at the census tract level in the study because it is the smallest geographical area to which the CEJST can be applied. An even smaller area, the block group, is the geographic unit of the policies we model. A census tract commonly

5 See **https://screeningtool.geoplatform.gov/en/methodology#3/33.47/-97.5**. There are eight categories of environmental, climate, and other burdens: climate change, energy, health, housing, legacy pollution, transportation, waste and wastewater, and workforce development. Each category has specific criteria. One example of a health criterion is that the share of people in the tract who have asthma is greater than the 90th percentile of census tracts. There are a total of 30 such thresholds.

6 For a look at how CEJST is correlated to socioeconomic status and environmental burdens, see Bakkensen et al. (2024).

7 This count excludes students enrolled in higher education.

comprises two or three block groups, and each block group lies entirely within one tract. All the census block groups in a disadvantaged census tract also are treated as disadvantaged in the analysis.

By that definition, 35 percent of the census block groups in the contiguous US are considered DACs. As shown in the first row of Table 1, they contain 33 percent of the population and 46 percent of the land area of the contiguous US. They also contain 37 percent of the emitting generation capacity as of 2024, according to our data. They are, on average, less densely populated than other block groups in the contiguous US, and correspondingly larger. They have a slightly higher ratio of emitting generation capacity to population but a smaller ratio of generation capacity to land area.

Table 1. Population, Land Area, and Emitting Power Plants in Disadvantaged Communities

	Percentage of contiguous US residents	Percentage of contiguous US land	Percentage of contiguous US emitting generation capacity
DACs	33%	46%	37%
EO DACs	29%	20%	30%

2.2. Environmentally Overburdened Communities

The procedure for defining EO DACs begins with calculating an environmental burden score for each census block group and comparing it with the environmental burden scores of surrounding block groups that do not qualify as DACs. The Environmental Protection Agency's EJScreen: Environmental Justice Screening and Mapping Tool (US EPA n.d.-a) contains 13 indicators of environmental burden, including air pollution, proximity to existing sites of pollution, proximity to heavy traffic, and other conditions that affect human health in each census block group. We sum them to produce an overall environmental burden index.[8] A higher number indicates a higher burden.

The threshold for being environmentally overburdened is defined at the county level, meaning the same threshold applies to all block groups in a given county. The first step is to calculate the median state and county block group environmental burden index values for non-DAC block groups. Any DAC census block group in the county with an environmental burden index value above the lower of those two median values is classified as environmentally overburdened.

8 The 13 indicators all range from 0 to 1, so summing them weights each equally in the environmental burden index.

About 86 percent of all DAC block groups are EO DAC areas, according to this criterion.[9] However, the procedure accounts only for existing environmental burdens. One of the policies for protecting EO DACs (Section 4) entails identifying DAC block groups that would likely become environmentally overburdened with the addition of a power generation facility in their area. To increase the prospects for identifying such "close to environmentally burdened" block groups, each county's EJScreen index threshold is reduced by 5 percent of its value. Lowering the EO threshold in that way increases the percentage of DACs that are EO DACs from 86 percent to 88 percent.

As shown in Table 1, census block groups that meet the definitions of both disadvantaged and environmentally overburdened contain 29 percent of the residents US and 30 percent of the emitting generation capacity of the contiguous US, and only 20 percent of the contiguous US land area. They have more emitting generation capacity, and more overall generation capacity, per land area than the rest of the country because as a whole, environmentally overburdened block groups, both those that are DACs and those that are not, are on average more densely populated, hence smaller in area, than other block groups.

Among Americans in the lowest income quintile, 66.1 percent live in DACs, and 62.3 percent in EO DACs. Of Black Americans, 53.2 percent live in DACs and 52.1 percent in EO DACs. And of Hispanic Americans, 53.4 percent live in DACs, and 51.8 percent in EO DACs.[10]

Figure 1a is a map of the census block groups that are EO DACs and those that are DACs but not environmentally overburdened. EO DACs are present in every state. In densely populated areas, such as most of New Jersey, they tend to be small because of high population density coupled with the fact that the populations of all block groups are similar. In less densely populated areas, such as most of North Dakota, EO DACs tend to be large because of the low population density. Figure B-1 in Appendix B shows just the northeastern states, at a larger scale.

As noted, DACs are defined in reference to environmental as well as associated socioeconomic disadvantages, and environmentally overburdened communities are defined by comparing a range of environmental indicators with those in other locations. It should not be too surprising, therefore, that DACs and EO DACs tend to have higher baseline levels of EGU-caused particulate concentrations than other communities. This can be seen heuristically by noting the high incidence of DACs in Figure 1a from roughly the Louisiana-Texas border into the Ohio Valley and Middle Atlantic states—areas with high EGU-caused particulate levels in Figure 1b. The differences in baseline concentrations have important implications for interpreting our modeling results in Section 5. In particular, the same percentage reduction in EGU-caused particulate concentration will reduce the absolute level more in EO DACs than in other locations.

9 If the same threshold was applied to all US block groups, regardless of DAC status, then roughly 70 percent of all block groups would qualify as environmentally overburdened.

10 Population demographic data are drawn from the 2020 US Census American Communities Survey.

Figure 1a. Environmentally Overburdened and Disadvantaged Census Block Groups in Contiguous US

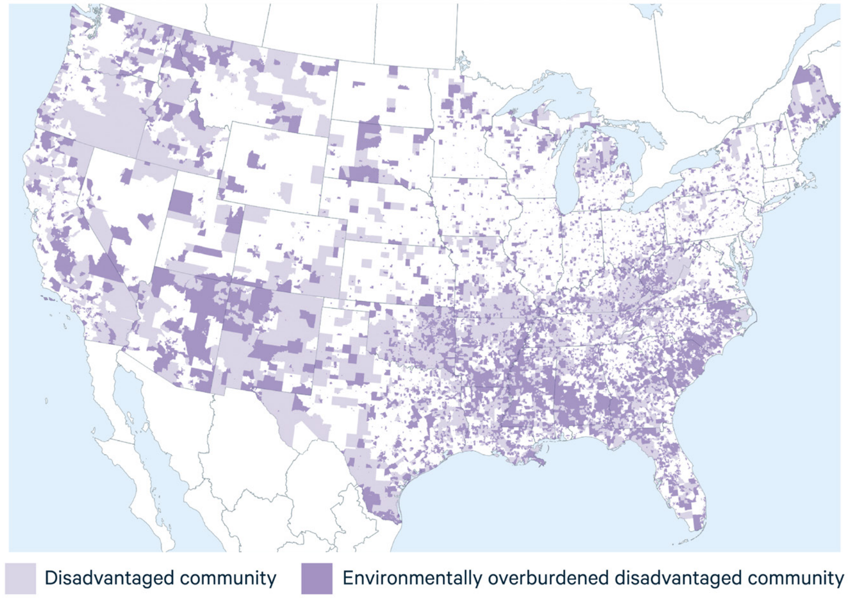
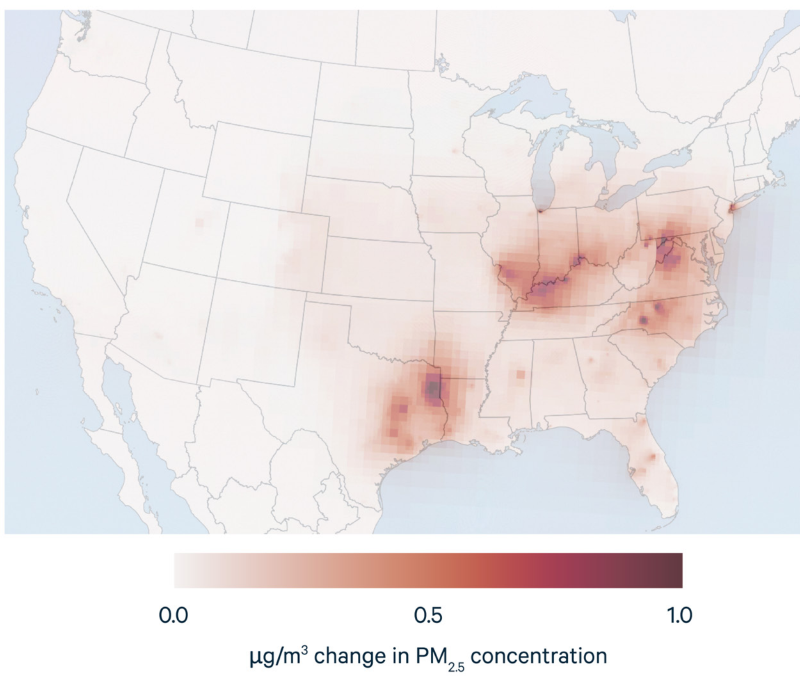


Figure 1b. Concentrations of $PM_{2.5}$ from Power Plant Emissions, in Business-as-Usual Scenario



3. Modeling Approach

3.1. Power Sector Model

We use the Engineering, Economic, and Environmental Electricity Simulation Tool (E4ST 2022), a power sector simulation model with a detailed representation of the US and Canadian electricity sector. E4ST is a capacity expansion and system operation (optimal power flow) model that projects the effects and estimates the benefits and costs of policies, infrastructure investments, and other potential factors.[11]

E4ST uses detailed representations of existing generating units and location-specific, hour-specific wind and solar data for each current and potential wind farm and solar array site. E4ST also contains a detailed model of the transmission system, with all of the high-voltage (over 200-kilovolt) transmission lines and a modified "Ward reduction" representation of the lower-voltage transmission lines (Shi et al. 2012). The model simulates a year of power sector operation using 16 selected and weighted representative days that capture typical conditions as well as challenging extremes of load size and resource availability in all regions of the contiguous United States and Canada. The hours also approximately match the joint frequency distribution of load, wind, and sun in each region. To simplify the analysis, the model treats electricity demand as essentially price-inelastic,[12] though total demand grows over time with increases in population and economic activity.

Using a standard linear approximation of the physics of how power distributes itself across the many transmission lines, the model realistically represents the effects of power flow limits and transmission congestion. We assume that the capacity of all transmission lines expands in proportion to system-wide electricity consumption growth.

The model also represents capacity reserve requirements. Generators and energy storage facilities earn capacity payments in accordance with their availability to generate at the times of greatest scarcity in their balancing area. In most areas, the highest scarcity and highest reserve prices occur when electricity consumption is high and most wind and solar generators have low availability. Consequently, wind and solar generators tend to receive much lower capacity credit and capacity payments per MW than do non variable generators and energy storage facilities. Appendix A contains more information about the modeled requirements. As in reality, these reserve requirements and payments affect the capacity mix that remains online. One effect is that when a policy to reduce emissions in disadvantaged communities requires certain generators to have low capacity factors for curbing their emissions (as do some of

11 For an illustration of a prior application of E4ST, see Shawhan and Picciano (2019).

12 Demand becomes completely price-elastic at a price of $5,000/MWh, which serves to provide an upper bound on the price. This price is reached at some times and nodes in the model, but very rarely.

the policies we model, as explained in Section 4), those generators do not necessarily shut down since reserve payments can create an incentive for them to remain online. Another effect is that emitting capacity that retires because of an EJ policy is likely to be replaced mainly by thermal capacity or storage, through a combination of new capacity and deferred retirement of other existing capacity.

3.2. Air Pollution Modeling and Valuation

To model the effects of emissions changes on $PM_{2.5}$ concentrations and the consequent health effects, we use the Intervention Model for Air Pollution (InMAP) (Tessum et al. 2017). InMAP is a pollution fate and transport model with high spatial resolution in population-dense areas and with mortality functions that can vary by demographic group. These two characteristics are useful in work that examines effects on mortality of demographic groups. For the people in each major racial or ethnic group in the United States, we use group-specific estimates of the relationship between $PM_{2.5}$ exposure and consequent deaths (Di et al. 2017), and group-specific data about underlying mortality at the county level[13] (CDC 2020).

Our modeling also provides estimates of the effect of each policy on national health damage from ground-level ozone pollution. However, ozone formation is considerably more nonlinear and dependent on background conditions than $PM_{2.5}$ formation, and we do not have group-specific exposure-mortality functions for ozone, so we use national average estimated ozone-season NO_X-to-ozone health damage (including premature deaths) per power plant NO_X ton (US EPA 2023b), rather than modeling the geographic distribution of ozone changes or estimating ozone effects by demographic group. We assume that 45 percent of annual NO_X emissions cause that damage, since historically about 45 percent of power plant NO_X emissions have been in the ozone season (May 1–September 30). Appendix B contains more information about the data sources and assumptions used in the air pollution modeling.

We use the USEPA estimated value of each premature death avoided from reduced $PM_{2.5}$ and ozone (approximately $12 million, from USEPA 2023b) and the USEPA estimates of the social costs per ton of CO_2 and methane (from USEPA 2023e), which are both supported by extensive research literature.

3.3. Major Inputs

The cost to build and operate new generators is drawn from the National Renewable Energy Laboratory's 2023 Annual Technology Baseline (ATB) (Mirletz et al. 2023). We use 2030 cost projections from the moderate development, "mid" pathway.[14] Projected

13 We use age-adjusted mortality rates by race.

14 For carbon capture and utilization or storage (CCUS), we allow both retrofits of existing coal power plants and construction of new gas power plants. Our coal power plant retrofit cost assumptions come from a more specialized source. For additional detail on how we represent CCUS, including retrofit costs and build limits, see Appendix A.

2030 regional natural gas, coal, and oil costs are taken from the Annual Energy Outlook 2023 (US EIA 2023) reference case.

We include representations of state and federal policies in all our simulations. At the federal level, we represent tax credits for clean energy and carbon capture from the Inflation Reduction Act, as well as a price on NO_x during ozone season.[15] We include state clean energy standards and renewable portfolio standards, including sub-requirements for specific technologies ("carveouts") (Barbose 2023). We further assume that between the years of announced policy targets, there are linearly increasing intermediate targets. We also include the Regional Greenhouse Gas Initiative (RGGI) of states in the Northeast and Mid-Atlantic, California's cap-and-trade program (AB32), and CO_2 prices in Canada and Mexico, since the model includes most of Canada and a small part of México.

Additional details on our modeling inputs and assumptions can be found in Appendices A and B.

3.4. Caveats

Although our model is carefully constructed to reflect expected conditions, our inputs surely deviate from future reality by varying amounts. This applies to both power sector and air pollution modeling.

The sensitivity of people's mortality to $PM_{2.5}$ concentrations, known as their "concentration response," is important in this study. The real concentration response coefficients for particular people or demographic groups might be higher or lower than we have assumed. We have used coefficients estimated for 2000–2012 by Di et al. (2017), since only that study has coefficients for all major racial and ethnic groups. Di et al. (2017) and a follow-on study by Josey et al. (2023) indicate that the coefficients for the U.S. population as a whole are likely to be higher now than they were in 2000-2012, because concentrations are lower now and the data seem to indicate that people's mortality is more sensitive to concentration changes when concentrations are low. Josey et al. (2023) also indicates that the coefficient for Black Americans is now lower than the one we use, albeit still higher than the coefficient for White Americans.

We also do not incorporate different $PM_{2.5}$ exposure-mortality functions based on income. Di et al. (2017) and Josey et al. (2023) have estimates of exposure-mortality functions for American retirees who are eligible for Medicaid (health insurance for people with very low incomes), but we are not aware of an exposure-mortality function for income quintiles. The income information we have in the model is about income quintile, not Medicaid eligibility.

15 As discussed more fully in Appendix C, annual SO_2 and NO_x emissions caps in the eastern United States under the Cross-State Air Pollution Rule have been slack for several years, and that is assumed to continue until 2030. However, the cap on power plant and industrial NO_x from May 1 to September 30 of each year in selected states has not been slack in recent years.

We have assumed a set of background conditions that include state and federal policy representations and technology and fuel prices. We have also applied particular definitions of DACs and “environmentally overburdened.” Different assumptions about these definitions might change the effects of these policies and their distribution across groups. The effects of the EO and DAC definitions should be investigated further during the policy design process for any given region.

Our modeling for this project, though detailed and realistic in many ways, does not cover everything. We have not included $PM_{2.5}$, NO_X, and SO_2 emissions control investment stimulated by the policies (endogenous investment). We also have not made electricity consumption quantities as sensitive to electricity prices as they are in reality. More highly price-responsive electricity consumption would somewhat reduce the electricity rate increases caused by all the policies. We have not made fuel prices respond to the electricity sector’s use of those fuels. The sign of the effect of consumption-responsive fuel prices is difficult to predict because each policy moves gas and coal consumption in opposite directions.

Finally, our results are a snapshot for the year 2030. The results of the policies over a longer period would be somewhat different, for two reasons. First, the share of coal-fueled generation is expected to continue to decline after 2030, especially if the new US greenhouse gas (US EPA 2023d) and NO_X (US EPA 2023c) emissions rules for power plants survive. Second, emitting EGUs built between 2025 and 2030, which in our results mainly consist of gas combined-cycle EGUs, are likely to remain in service for decades. They could be good or bad for disadvantaged Americans, and different policies have different effects on how much of such capacity is built.

4. Policy Scenarios

To provide insight into the effects of existing and potential policies, we simulate nationwide implementation of several policies that seek to reduce pollution in EO DACs. Three of the policies restrict power plants located within census tracts that are considered EO DACs; another policy considers the air pollution that might drift into other EO DACs. For comparison, we simulate a CO_2 pricing policy that does not target DACs but can have significant emissions and health benefits across all communities.

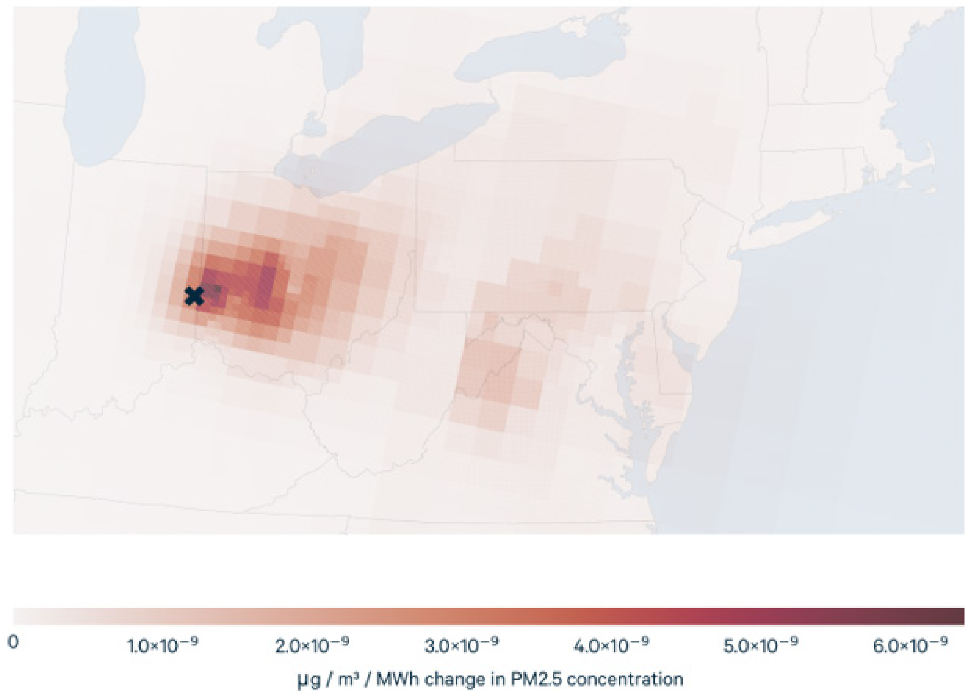
Our targeted environmental policies are broadly inspired by new environmental justice laws in New Jersey and New York that aim to reduce the pollution exposure of EO DACs. However, we have not modeled all of the fine points of those laws, and we make no claim that our results can be used to evaluate their prospective benefits. Both laws are going through procedural steps in preparation for implementation of new standards.

Both laws restrict the permitting and re-permitting of electric power plants (along with some other major stationary emissions sources). Re-permitting is required every several years, so these policies apply to both new and existing emitters.

The New Jersey Law (NJDEP 2022) prohibits the permitting of new emitting facilities in DACs that also would have high or medium environmental burdens. These are the communities defined in Section 2 as "environmentally overburdened" (EO) DACs. Existing facilities in an EO DAC must be re-permitted, and the renewed permits can impose new restrictions that could reduce the facility's operation or even cause it to shut down. The geographic unit used in the New Jersey law, as in our modeling, is the census block group. All census block groups have roughly similar numbers of residents, with an average of 1,400 per block group, but vary considerably in area because of differences in population density.

A fundamental challenge for a policy to improve air quality for EO DAC residents or other disadvantaged Americans is that emissions from power plants travel far, affecting air quality for hundreds or thousands of miles downwind (Tessum et al. 2017). Our air pollution modeling indicates that approximately 85 percent of the ambient $PM_{2.5}$ from power plants is secondary, forming from gaseous NO_x and SO_2 and taking up to hundreds of miles to transform into $PM_{2.5}$ or ozone (US EPA n.d.-b). Figure 2 shows an example of the estimated effect of a single power plant on annual average $PM_{2.5}$ concentration, according to our air pollution model. The plant is in one of the 4,814 census block groups in Indiana. Most of its aggregate effect on airborne $PM_{2.5}$ is outside that block group. On the map, the plant visibly affects air quality in 14 states and imperceptibly affects it in other states. In block groups that host emitting power plants, only 0.3 percent of the $PM_{2.5}$ from power plant smokestack emissions comes from power plants within that block group, according to 2020 power plant emissions and the air pollution model we are using.

Figure 2. Geographic Distribution of Estimated Annual Average Effect of One Power Plant on $PM_{2.5}$ Concentrations



The New York Law (New York State Senate 2023) takes an approach that accounts for the downwind nature of power plants' air quality effects. It restricts permitting and re-permitting of power plants if they would contribute more than a de minimis amount to the environmental burden in any New York DAC that has a high environmental burden. The affected DAC that triggers permit denial need not host the power plant. It could instead be downwind of, or close to, the plant. At the time of this writing, the New York policy, while already law, is undergoing a design process to set features not firmly specified in the legislation, including how much a facility would need to contribute to the environmental burden in a highly environmentally burdened DAC to have its permit denied.

4.1. Policies Simulated in This Study

Table 2 summarizes the policies we simulate.

Table 2. Policy Scenarios

Policy scenario	Location of EGUs to which policy applies	EGUs to which policy applies	Treatment of EGUs covered by policy	Comments
Business as Usual (BAU)	No policy other than background policies that apply in all scenarios.			
No New	In EO DAC census block groups	New emitting EGUs (those not yet built)	EGUs prohibited	One possible "within-DAC" approach to targeting
Reduction	In EO DAC census block groups	All emitting EGUs	New EGUs prohibited Existing EGU's annual capacity factor is capped at 20% of class average from preliminary simulation	One possible "within-DAC" approach to targeting
Shutdown	In EO DAC census block groups	All emitting EGUs	New EGUs prohibited Existing EGUs shut down	One possible "within-DAC" approach to targeting
Upwind Limits	Anywhere	All emitting EGUs	EGU's contribution to $PM_{2.5}$ in any EO DAC is limited to 0.01 $\mu g/m^3$	One possible "upwind limits" approach to targeting
CO_2 Pricing	Anywhere	All emitting EGUs	EGUs pay $15 per CO_2 ton emitted.	—

4.1.1. Business-as-Usual (BAU)

In the BAU scenario, the only policies in effect are the national, state, and utility policies that have already been adopted (as of December 2023) plus our standard projections of state continuations of clean and renewable energy standards. These "background" policies are in effect in all the scenarios.

4.1.2. No New

It is uncertain how existing emitting EGUs in EO DACs will be affected by the New Jersey law. At one end of the spectrum of possibilities, the law will not result in any restrictions that affect an existing emitting EGU's retirement or operation decisions.

This policy scenario represents that kind of situation: no restrictions are placed on existing emitting EGUs that affect their operation. However, under this policy, as under the other two policy cases that are based on the New Jersey law, new (i.e., post-2024) emitting EGUs are not allowed in EO DAC census block groups.

4.1.3. Reduction

Under the New Jersey law, qualifying existing EGUs could be subject to restrictions on their operation but not to a shutdown requirement. For example, a ceiling on their annual capacity factor would reduce their air pollution by reducing total generation while still allowing the generator to operate at select times. We represent this type of policy in our Reduction case, in which every existing emitting generator in an EO DAC census block group is subject to an annual capacity factor limit equal to approximately 20 percent of the average capacity factor of its class in the BAU simulation. The classes and limits are as follows:

- coal, biomass, waste, and “other,” 12 percent;
- gas combined cycle, 6.8 percent;
- peakers (gas-fueled non-combined-cycle EGUs, oil EGUs), 0.6 percent;
- coal with CO_2 capture, 17 percent; and
- gas with CO_2 capture, 8.8 percent.

As in the other two within-DAC policies, new emitting facilities cannot be built in EO DAC census block groups.

4.1.4. Shutdown

Under the New Jersey law, the restrictions applied to qualifying existing EGUs might cause them to shut down. In the Shutdown scenario, no EGUs that emit $PM_{2.5}$, NO_X, or SO_2 can be built or re-permitted in EO DACs: new ones are prohibited and existing ones must be retired. We assume that retirement would be required by the beginning of 2030.

4.1.5. Upwind Limits

This policy sets a limit on generation that prevents an emitting EGU from contributing more than 0.01 microgram per cubic meter to the annual average $PM_{2.5}$ concentration of the air in any EO DAC. This is similar to one possible implementation of the 2023 New York law, except that our policy imposes restrictions based on the effect on EO DACs both inside and outside the EGU’s state. A similar federal law would presumably base the restrictions on EO DACs both inside and outside the EGU’s state, and similar future state laws could as well.[16]

16 Also, we apply the policy to somewhat different aggregations of EGUs. Whereas a federal policy might apply one limit to each facility, we apply the policy separately to each EGU

Upwind Limits tends to require larger emissions reductions for EGUs with higher emissions rates because, other things being equal, a higher emissions rate requires a lower limit on annual generation. This could give the Upwind Limits policy a cost-effectiveness advantage over some other policies at reducing $PM_{2.5}$-caused deaths.[17]

4.1.6. CO_2 Pricing

To evaluate a policy that seeks to reduce overall emissions from the power sector, we model a national carbon price of $15 per short ton (in year-2020 dollars, like all dollar values in this paper except where otherwise noted). We assume the policy is revenue neutral; that is, the CO_2 emissions fee proceeds are returned to electricity users. This facilitates comparisons because the within-DAC and Upwind Limits policies also do not raise government revenue.[18] We will also briefly discuss the differences that other CO_2 emissions-pricing policies would cause. Although many real and proposed CO_2 prices[19] are higher, we chose a relatively low price of $15 per short ton so that the resulting air pollution reductions are more comparable with those caused by the within-DAC and Upwind Limits policies.

The advantage of an emissions price is that it creates incentives for all emissions reductions that cost less than the emissions price, and for no emissions reductions that cost more. This maximizes the cost-effectiveness of the reductions of the emissions type that is priced, which in this case is CO_2. Although CO_2 does not form $PM_{2.5}$, CO_2 emissions rates of EGUs are positively correlated with their $PM_{2.5}$, NO_X, and SO_2 emissions rates, so there is reason to expect ex ante that the policy might still have a cost-effectiveness advantage over some others at reducing $PM_{2.5}$-caused deaths.

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in our model. To form the EGUs in our model, we combine existing real EGUs if they have the same fuel type, are connected to the same transmission node in our model (the model has approximately 5,000 nodes), and have similar heat rates and emissions rates. Consequently, many of the EGUs in our model represent a whole facility, but some represent less than a whole facility, and a few represent real EGUs from more than one facility.

17 This policy, unlike the others, involves air pollution modeling, to estimate how much each ton of each emissions type from each EGU contributes to the ground-level $PM_{2.5}$ concentration in each EO DAC. Such modeling is not perfect, but it is feasible.

18 Because we assume electricity demands to be essentially price-inelastic in this analysis, we can calculate the amount each household should receive from the government to offset the income effects of the emissions price. With more elastic demands, it would be possible only to, for example, calculate lump-sum rebates that would offset the higher electricity cost for some sort of median household. Appendix D shows results for a $15 price without returning revenues to households.

19 For example, the European CO2 price was approximately $70 per short ton in December 2023 (Trading Economics n.d.), and the California CO2 price was approximately $35 per short ton in the fourth quarter of 2023 (California Air Resources Board n.d.). However, the RGGI CO2 price was $15 in December 2023 (RGGI n.d.).

4.2. Implementation of the Policy Scenarios

We estimate the effects of the policies on the outdoor $PM_{2.5}$ concentrations and associated premature mortality experienced by the whole US population and by each of the five groups of disadvantaged Americans that we consider. We also estimate the effects of the policies on electricity bills, government net revenues,[20] power plant profits, premature deaths from ground-level ozone, and dollar value of harm to people from climate change.

Each simulation includes one policy. The scenarios are otherwise identical in their inputs, assumptions, and setup. In Section 5, we compare the results of each scenario with the results of the BAU scenario, which has none of the potential new EJ and emissions policies. The differences in results between each policy scenario and the BAU scenario are therefore the effects of the policy.

In each policy scenario, we assume that the policy of interest is enacted in 2025. We start with a set of generators representing 2024 and use this starting set in all our simulations. All our simulations are for 2030 and the generator additions and retirements that will occur between 2024 and 2030. The model has information about planned retirements through 2030 and endogenously predicts which other generators will retire or be built by 2030. The results we report for generation, cost, and benefit are for a single year, 2030. Each policy affects the generator additions and retirements from 2024 through 2030 and the generation, costs, and benefits in 2030. The reported costs per year include one year of levelized recovery of the costs to build and finance the new capacity. The recovery period varies by technology from 10 to 30 years, as described in Appendix A. The results are also indicative of the effects the policies would have if adopted in later years.

Although the policies of interest are modeled separately, they are not in fact mutually exclusive. More than one could be adopted in the same place. This is the situation, for example, in New Jersey and New York: each has both a CO_2 price on power plant emissions (as part of RGGI) and targeted measures that apply to power plant effects in EO DACs.

It is helpful to recognize that the effects of the policies will vary from state to state due to differences in BAU emission rates. For example, in a state with little or no coal-fueled generation, the benefits might be smaller and cost-effectiveness differences between the policies smaller since there is less generation with very high emissions and since the $PM_{2.5}$ emissions from gas-fueled EGUs tend to be much more geographically concentrated than those produced by coal-fueled generators. (The greater concentration is because gas-fueled EGUs often have shorter smokestacks, and directly emitted $PM_{2.5}$ tends to constitute more of their contribution to $PM_{2.5}$ concentrations.) Moreover, very high emissions rates imply low-cost emissions

20 The government net revenues we report consist of proceeds from government sales of emissions allowances in the emissions-pricing programs that involve such sales, minus clean generator subsidies like those in the Inflation Reduction Act.

reduction opportunities. The findings show that the largest changes in emissions are in areas of the country with significant existing coal capacity.

The effects of the policies will also vary due to differences in population density. The health benefits of the policies, and absolute benefit differences among the policies, may tend to be larger in areas with higher population densities because there are more people who can be harmed and because such areas tend to have more generation and emissions than lower-population areas with a similar generation energy source mix.

5. Results

Section 4.1 has described the five power plant emissions-control policies that we simulate across the United States:

- No New emitting EGUs in EO DACs;
- specified Reduction in emissions of all emitting EGUs in EO DACs;
- Shutdown of all emitting EGUs in EO DACs;
- Upwind Limits on emissions of all emitting EGUs to prevent more than de minimis contribution of any one EGU to $PM_{2.5}$ concentrations in any EO DAC; and
- CO_2 Pricing, at $15 per short ton, paid by all EGUs with CO_2 emissions (with revenues returned to households).

The first three restrict EGUs within EO DAC census block groups, whereas the fourth seeks to prevent any EGU from causing a large $PM_{2.5}$ increase in any EO DAC, regardless of the source's location, and the fifth applies to all EGUs.

In this section, we first present findings from the model regarding the effects on air pollution of the five policies. In the second and third parts, we present findings about how the air pollution changes alter premature mortality, particularly premature mortality of disadvantaged Americans. In the fourth part, we present results on the society-wide net benefits of the policies, followed by a section summarizing other findings.

5.1. Effects on Air Pollution

Figure 3 shows the average contribution of US electric power plants to the average $PM_{2.5}$ concentration in the United States under the different policies. The policies reduce average $PM_{2.5}$ in the following order, from most reduction to least: CO_2 Pricing, Upwind Limits, Shutdown, Reduction. They reduce the contribution by 57, 51, 19, and 0.4 percent, respectively. No New increases rather than decreases the sector's contribution to $PM_{2.5}$, by 4 percent.

Figure 3. Power Sector Contribution to US Average $PM_{2.5}$ Concentration

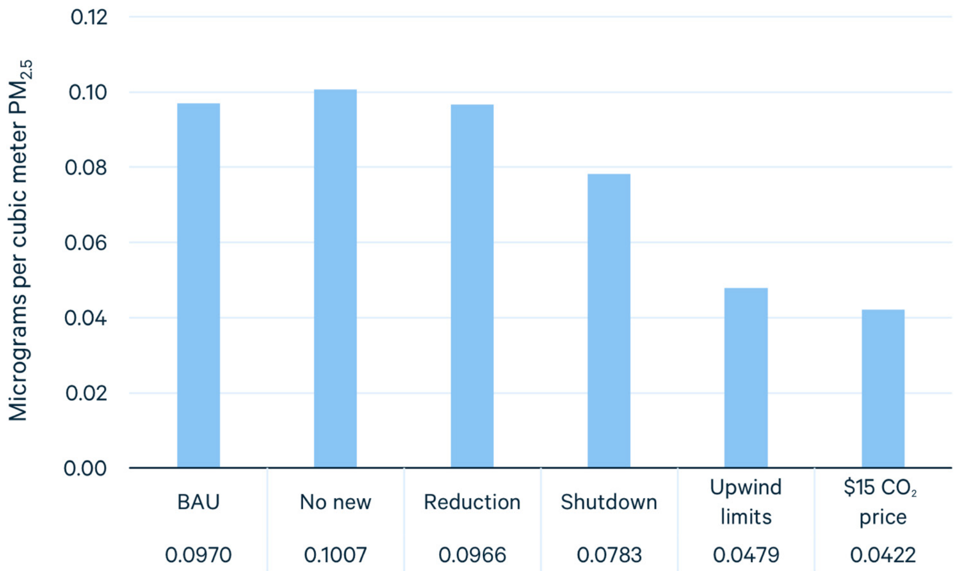
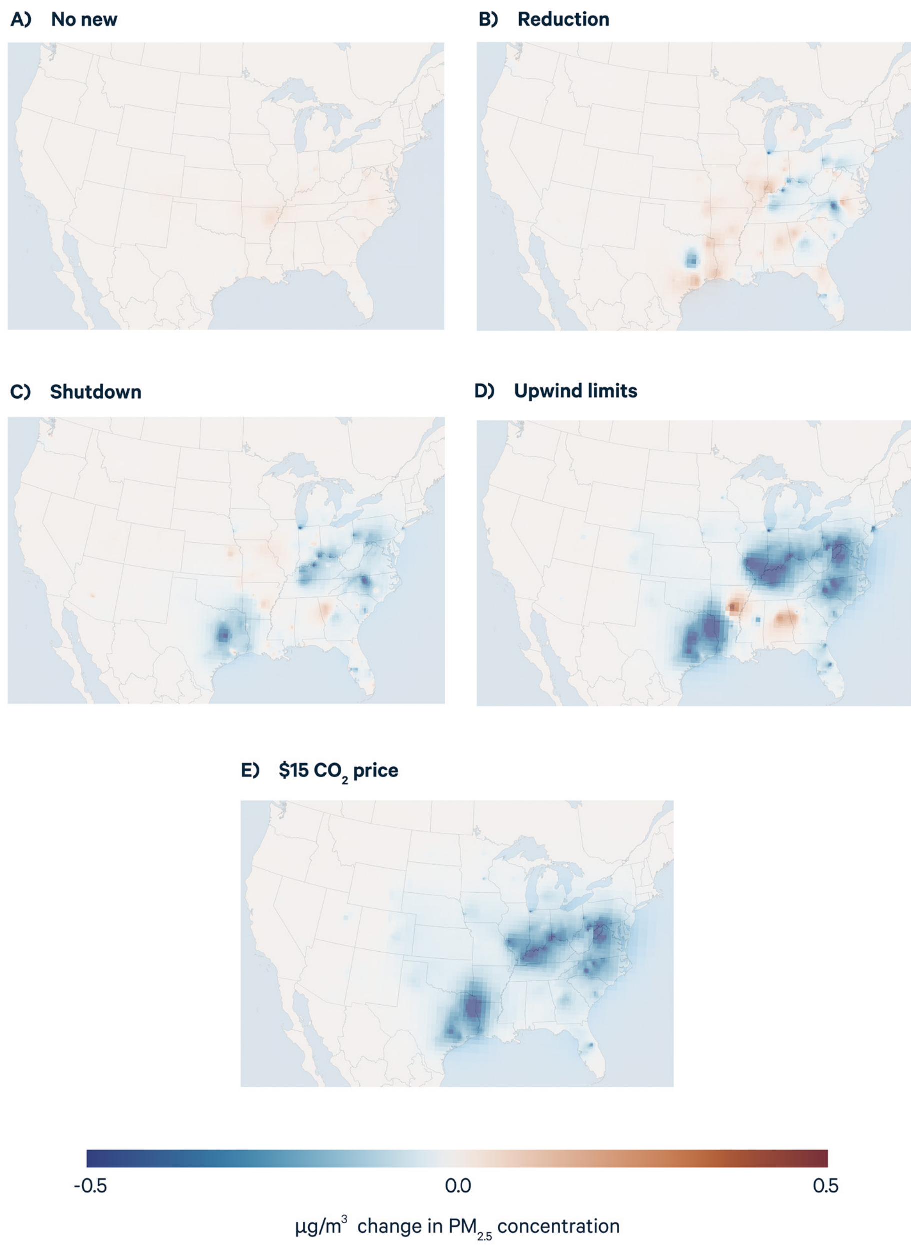


Figure 4 maps the projected effects of the policies on fine airborne particulate matter. The maps are necessarily consistent with the national average effects just reported. The largest changes in $PM_{2.5}$ concentrations are in the eastern United States in a polygon bounded by New York City, Chicago, south-central Texas, and coastal North Carolina. This polygon contains or is downwind of most US coal-fired power generation, with its high $PM_{2.5}$, NO_X, and SO_2 emissions.

The policies that are designed to especially reduce emissions in EO DACs also cause $PM_{2.5}$ concentrations to increase in some locations, including EO DACs, so these policies cause some hotspots. The reason $PM_{2.5}$ concentrations increase in some locations is that the generation reductions in some locations (a direct effect of the policies) have to be offset by generation increases in other locations (an indirect effect of the policies). Some of those increases are from emitting generators, and in some places the $PM_{2.5}$ increases from the indirectly caused generation are larger than the $PM_{2.5}$ reductions from the directly caused generation reductions. The only modeled policy that does not cause a significant $PM_{2.5}$ concentration increase anywhere is CO_2 Pricing, since it applies a similar emissions disincentive to all fossil-fueled generators.

Figure 4. $PM_{2.5}$ Concentration Changes Relative to BAU Scenario

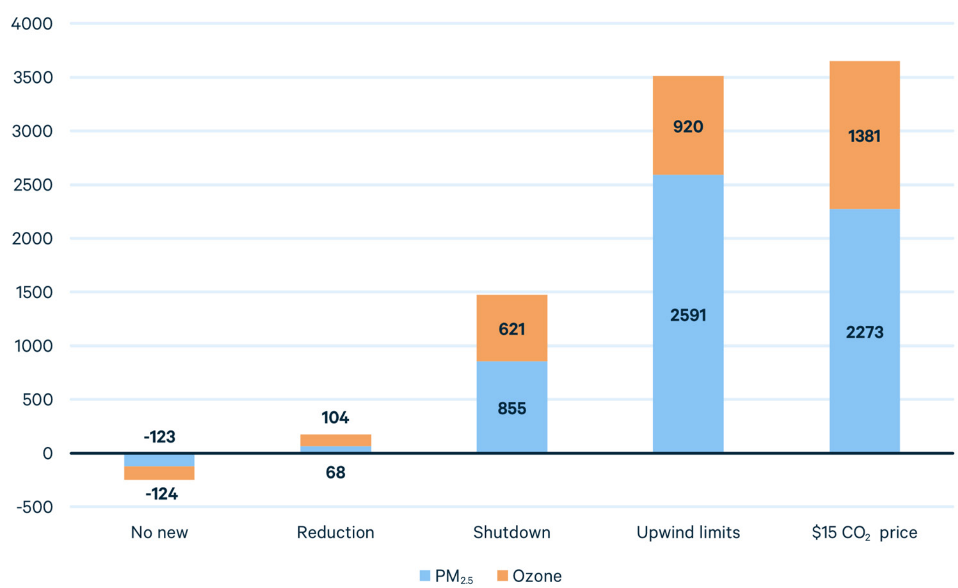


Note: Blue shows improvements; red shows worsening

5.2. Effects on Premature Deaths

Figure 5 shows avoided mortality for all Americans from reductions in $PM_{2.5}$ and ozone. Except for No New, the policies decrease premature mortality because they reduce $PM_{2.5}$-forming emissions and ozone-forming NO_X emissions. The total avoided deaths for Shutdown (the best-performing within-DAC policy), Upwind Limits (the New York–style policy), and CO_2 Pricing are 1,390, 3,270, and 3,443, respectively. Upwind Limits has a smaller net NO_X emissions reduction than CO_2 Pricing because it causes an increase in generation by peakers, which have high NO_X emissions rates relative to their other emissions rates.

Figure 5. Avoided Annual Premature Deaths from $PM_{2.5}$ and Ozone Nationally, Relative to BAU

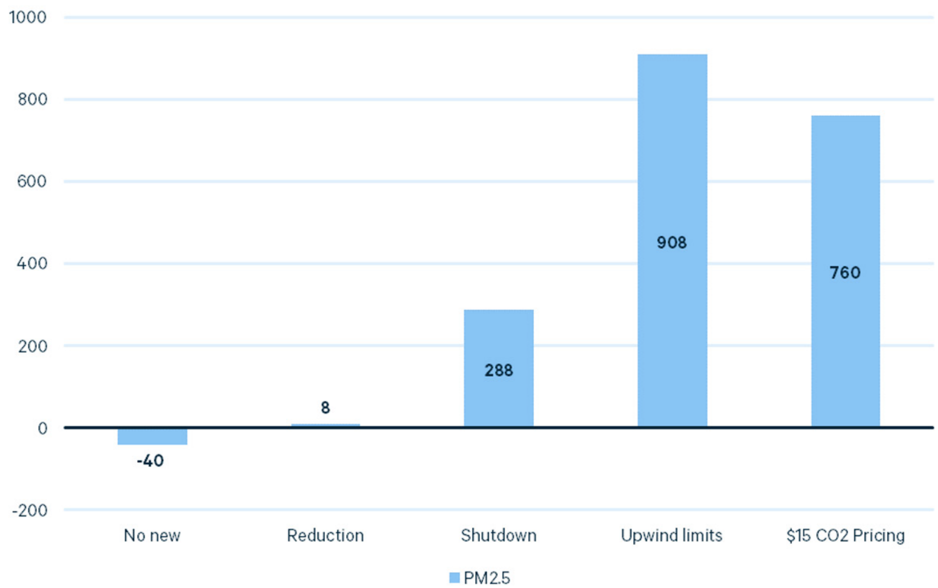


Note: Negative avoided deaths indicate an increase in premature deaths as a result of the policy.

Figure 6 shows avoided mortality within EO DACs just from $PM_{2.5}$ reductions.[21] Within EO DACs, the total avoided deaths for Shutdown (the best-performing within-DAC policy), Upwind Limits (the New York–style policy), and CO_2 Pricing are 288, 908, and 760, respectively. Going forward, we focus on findings related to avoided deaths from reduced $PM_{2.5}$.

21 The methodology used for calculating reductions in ozone-related deaths does not allow the mortality reductions to be separated by EO DACs versus other areas.

Figure 6. Avoided Premature Deaths from $PM_{2.5}$ in EO DACs, Relative to BAU



Note: Negative avoided deaths indicate an increase in premature deaths as a result of the policy.

5.3. Policy Costs and $PM_{2.5}$ Mortality Reductions in EO DACs

Cost-effectiveness is important for two reasons. Because increases in electricity costs matter, especially for low-income people, achieving a particular improvement at lower cost is desirable. Also, in a world of limited willingness to pay for benefits, a more cost-effective policy type may be able to achieve larger benefits.

5.3.1. Cost-Effectiveness at Saving Lives in EO DACs

Figure 7 compares both the $PM_{2.5}$ mortality reductions and the policy costs of the five policies. A dot for each policy indicates the prevented $PM_{2.5}$-caused premature deaths in EO DACs per year as of 2030 on the horizontal axis, and its (levelized) policy cost per year on the vertical axis. Consequently, the slope of the line from the origin to the point shows the average policy cost per avoided $PM_{2.5}$-caused premature death in EO DACs.

The slopes of the lines, in millions of dollars per prevented death in EO DACs, are 524 for Reduction, 58 for Shutdown, 7.7 for Upwind Limits, and 2.5 for CO_2 Pricing. The differences among the targeted policies are substantial (two orders of magnitude), and CO_2 Pricing has a lower cost per prevented EO DAC death than any of those options..

Because of the poor performance of No New and Reduction, our discussion in the remainder of Section 5 will focus primarily on Shutdown, Upwind Limits, and CO_2 Pricing.

Figure 7. Avoided $PM_{2.5}$-Related Deaths and Net Costs in EO DACs

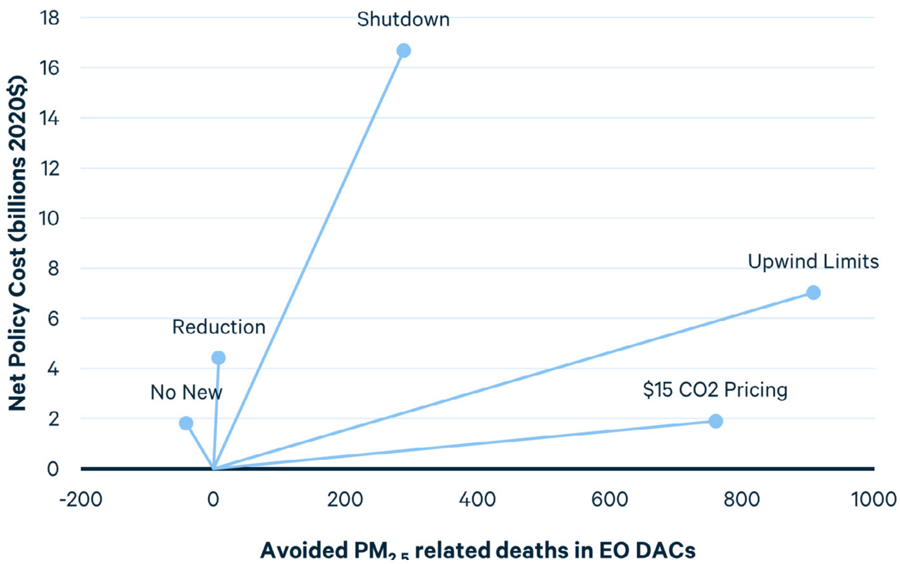
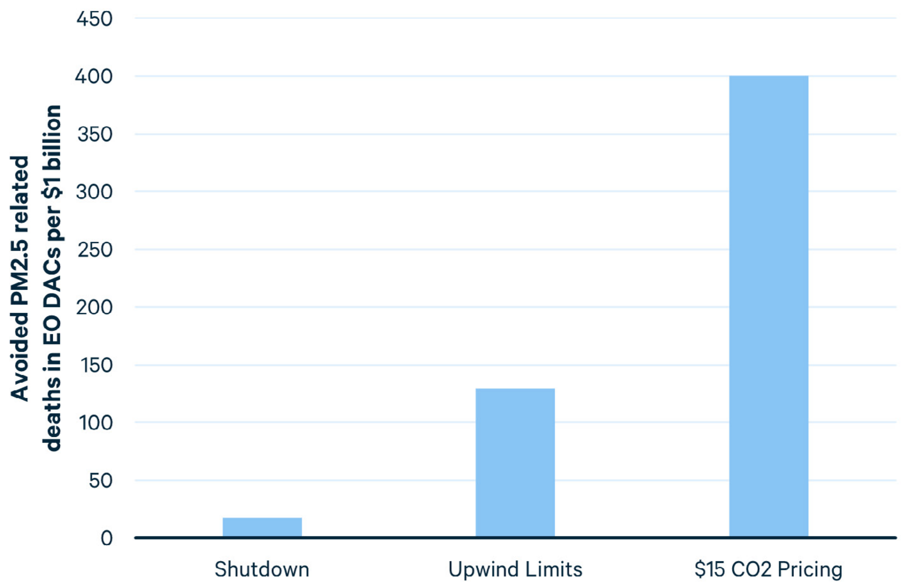


Figure 7 also shows that Upwind Limits prevents more $PM_{2.5}$-caused deaths in EO DACs than the other policies we are considering, followed by CO_2 Pricing. However, the average policy cost for Upwind Limits is more than three times the average policy cost of CO_2 Pricing. Shutdown prevents approximately a third as many $PM_{2.5}$-caused deaths in EO DACs and has a considerably higher average policy cost than Upwind Limits or CO_2 Pricing.

Figure 8 shows the same information in inverse form: the $PM_{2.5}$-caused deaths per year that each policy prevents in EO DACs, per billion dollars of policy cost. CO_2 Pricing prevents approximately three times as many as Upwind Limits, which in turn prevents approximately eight times as many as Shutdown.

CO_2 Pricing and Upwind Limits are the most cost-effective policies among those we consider because, by their nature, they tend to disproportionately reduce the operation of EGUs with high $PM_{2.5}$-forming emissions rates. Under Upwind Limits, EGUs with higher $PM_{2.5}$ rates require more control to satisfy the condition of no more than de minimis effects on EO DACs. CO_2 Pricing cost-effectively reduces $PM_{2.5}$ because there tends to be a significant positive correlation between EGUs' greenhouse gas and $PM_{2.5}$ emissions. The findings also apply nationwide, not just in EO DACs. This greater control of plants with higher $PM_{2.5}$ rates does not occur with the within-DAC policies.

Figure 8. Lives Saved in EO DACs, per Billion Dollars of Policy Cost



5.3.2. Mortality Reductions in EO DACs versus Elsewhere

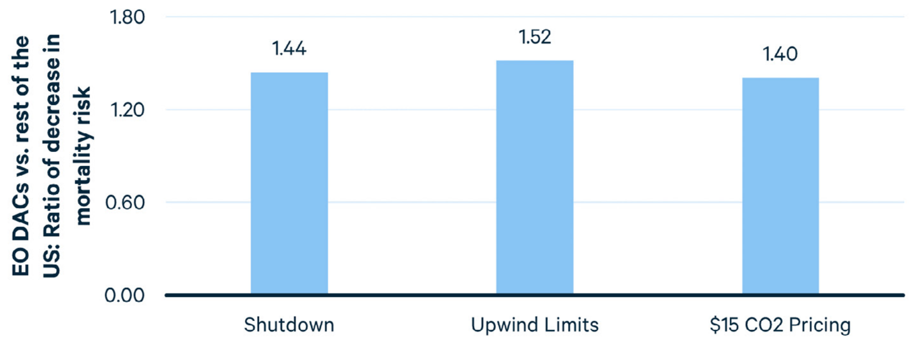
Our data indicate that in the business-as-usual scenario, people in EO DACs are, on average, 1.55 times as likely to die from EGU-caused $PM_{2.5}$ as people elsewhere. One reason is that EO DACs have a higher average concentration of EGU-caused $PM_{2.5}$. Another is that Black Americans' mortality is more sensitive to $PM_{2.5}$ exposure than that of other groups (Di et al. 2017), and Black Americans tend to be more concentrated in EO DACs.

The observation that EO DACs have 1.55 times the mortality risk from EGU-caused $PM_{2.5}$ implies that a policy proportionately reducing EGU-caused pollution concentrations by the same amount across the country (for example, a 50 percent reduction from every EGU) would reduce mortality risk in EO DACs, on average, by 1.55 times the average reduction in other locations. None of the policies achieves that ratio, as shown in Figure 9. The reason seems to be that emissions are more difficult to reduce near EO DACs than elsewhere because such areas tend to have high population densities and consequently be expensive places to build new, non-emitting generation, such as wind and solar farms.

While all the policies have EO-DAC-vs.-elsewhere mortality reduction ratios lower than 1.55, the ratios for Shutdown, Upwind Limits, and CO_2 Pricing are well above 1.0, implying greater mortality risk reductions in EO DACs than outside them. Those three policies' ratios range from 1.4 to 1.52.

The ratios for Upwind Limits and Shutdown are about 8 percent and 3 percent larger than for CO_2 Pricing, respectively. Thus, the results with these two targeted policies get

Figure 9. Ratio of Mortality Rate Decreases in EO DACs Versus Elsewhere



somewhat closer than CO_2 Pricing to causing a proportionate drop in concentrations everywhere. However, these differences do not come close to making Upwind Limits or Shutdown as cost-effective as CO_2 Pricing at reducing premature deaths in EO DACs, as we saw in Section 5.3.1.

5.3.3. Targeting Effectiveness for Other Disadvantaged Groups

Findings are similar for the relative effectiveness of these policies in comparisons of in-group with out-of-group mortality reduction ratios for other groups of disadvantaged Americans, as shown in Figure 10.[22] At the same time, they show that this ratio differs greatly from group to group.

Black Americans have a mortality risk reduction more than four times that of other Americans, shown in the first panel of Figure 10. Consequently, whereas Black Americans constitute 13 percent of the US population, they constitute 38 to 40 percent of the people whose lives are saved by Shutdown, Upwind Limits, and CO_2 Pricing, for two reasons. Black Americans' mortality is estimated to be approximately three times as sensitive to a given concentration change in $PM_{2.5}$ (Di et al. 2017). Moreover, Black Americans are on average exposed to roughly 40 percent higher EGU-caused $PM_{2.5}$ concentrations than other Americans.

For **Hispanic Americans**, the ratios are 0.55 to 0.73, as shown in the fourth panel of Figure 10. The ratio is lower mainly because Hispanic Americans are disproportionately located in the West, where there is less EGU-caused $PM_{2.5}$ to reduce.

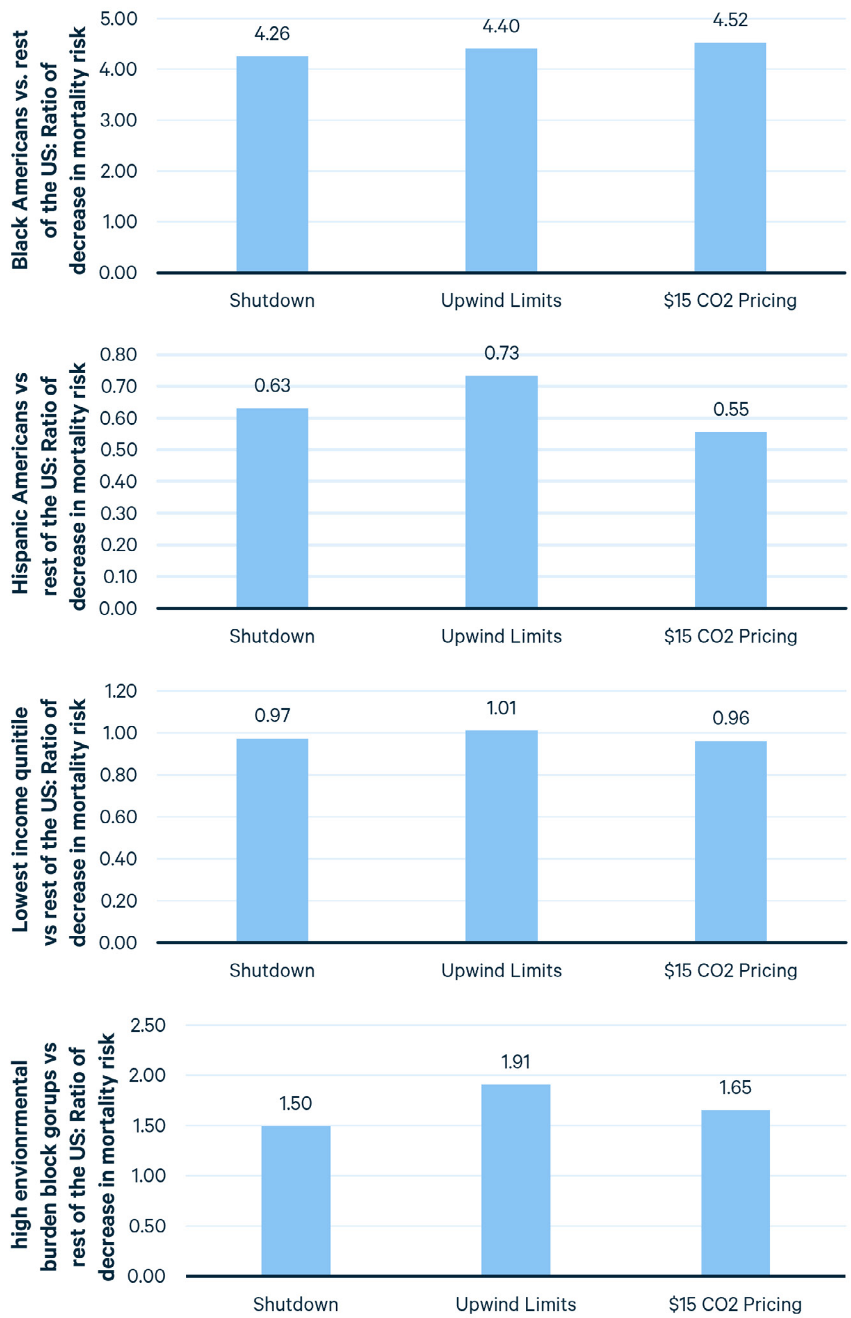
For **Americans in the lowest income quintile**, the targeting ratios are between 0.96 and 1.01, as shown in the fifth panel of Figure 10. These ratios would all be higher if we

22 Shutdown and Upwind Limits—two targeted policies—are less effective than CO_2 Pricing at targeting their mortality reductions to Black Americans. Upwind Limits is the most effective policy at targeting its mortality reductions to the other disadvantaged groups. However, the differences are small.

used a higher sensitivity coefficient for Americans in the lowest income quintile than for other Americans. However, as mentioned above, we are not aware that anyone has estimated a coefficient specifically for Americans in the lowest income quintile.

For areas with a **high environmental burden** (whether DACs or not), the ratio is between 1.5 and 1.91, as shown in the second panel of Figure 10. Like for EO DACs, the reasons are higher concentrations of $PM_{2.5}$ from power plants, and a more pollution-sensitive population due to the higher proportion of Black Americans in these areas.

Figure 10. Relative Decrease in Mortality Risk, by Demographic Group Scenario

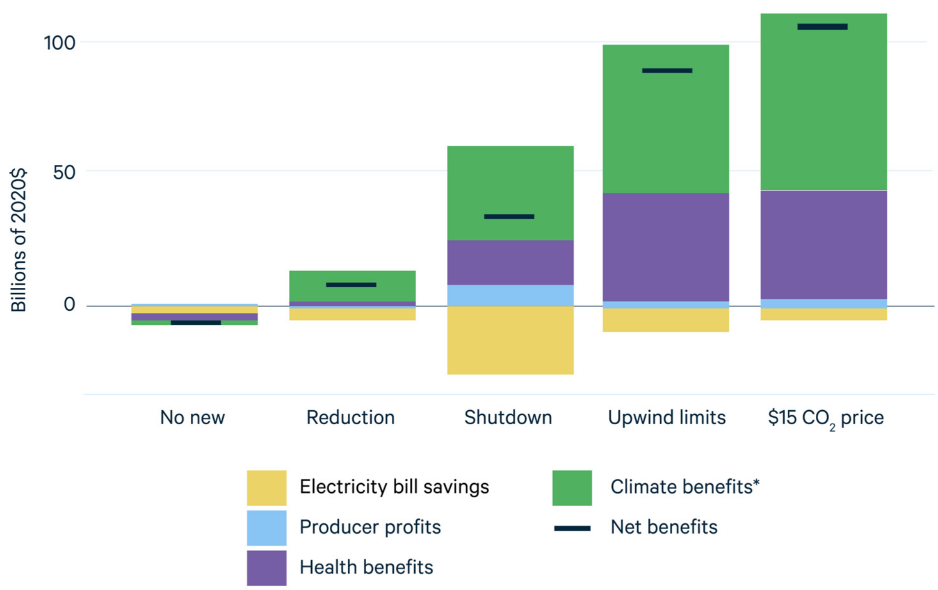


5.4. Society-Wide Net Benefits

We estimate how the five policies affect electricity bills, electricity producer profits, net government revenue, the value of avoided health damages from $PM_{2.5}$ and ozone, and avoided climate change damages, in 2030. All the policies except No New have positive net benefits, driven by significant health and climate benefits. CO_2 Pricing has the highest ratio of environmental benefits to policy costs, followed by Upwind Limits.

Figure 11 shows the estimated benefits and costs of the policies. Each segment above the zero line is a benefit; each segment below is a cost—that is, the negative of the label. For example, a yellow segment below the zero line indicates an electricity bill increase rather than electricity bill savings.[23]

Figure 11. Benefits and Costs, Compared with BAU



All the policies increase EGU profits because they increase the sum of electrical energy prices and capacity prices, which determine producer revenue, by more than they increase total costs to EGUs. This is in part because the policies do not increase the costs of existing non-emitting EGUs. Shutdown and CO_2 Pricing reduce government net revenues because they increase solar and storage installations, which are subsidized.

23 "Electricity bill savings" is actually change in electricity consumer surplus, which is appropriate for a more comprehensive measure of net benefits. However, in this project we have made electricity consumption sensitive to prices only if prices reach $5,000 per MWh. This modeling feature causes the change in electricity consumer surplus to be nearly identical to real electricity bill savings. We use "Electricity bill savings" to make the paper more easily comprehensible for readers not trained in economics.

The total estimated cost of a policy is the sum of the electricity bill savings, producer profits, and government revenue effects, times –1. For example, Shutdown raises electricity bills and reduces government net revenue, both costs, but also increases EGU profits, a benefit that reduces the policy cost.

Shutdown causes the largest increases in electricity bills and total policy costs because it requires the largest amount of new generation capacity, as shown in Figure 10. Upwind Limits causes the second-largest increases in electricity bills and total policy costs. Reduction causes the third-largest increases. Of the four policies that reduce emissions (i.e., excluding No New), CO_2 Pricing causes the smallest increase in electricity bills and total policy costs.

The ratios of environmental benefits, which include both climate and health benefits, to policy cost are 3 for Reduction, 3 for Shutdown, 13 for Upwind Limits, and 54 for CO_2 Pricing. Putting this differently, the policy cost per dollar of estimated environmental benefit is approximately four times as large for Reduction and Shutdown as for Upwind Limits, and approximately four times as large for Upwind Limits as for CO_2 Pricing.

If estimated climate change mitigation benefits are not counted, the ratios of health benefits to net policy costs are 0.3 for Reduction, 0.9 for Shutdown, 5 for Upwind Limits, and 20 for CO_2 Pricing. The ratios exceeding 1, for Upwind Limits and CO_2 Pricing, mean their domestic $PM_{2.5}$ and ozone health benefits alone are enough to justify them.

5.5. Generation, Capacity, and Greenhouse Gas Emissions Effects

5.5.1. Generation Effects

Figure 12a shows the projected generation mix without any of the policies. Figure 12b shows the generation changes caused by the policies. All policies except No New reduce generation from coal. On average, coal has by far the highest $PM_{2.5}$-forming, ozone-forming, and greenhouse gas emissions rates of any major fuel type. Those four other policies also increase gas-fueled generation, but by less than they decrease coal-fueled generation. The rest of the generation increases come mainly from more new solar and wind EGUs and increased survival of existing nuclear EGUs. These generation effects explain why Reduction, Shutdown, Upwind Limits, and CO_2 Pricing all reduce estimated $PM_{2.5}$ concentrations, ozone pollution, and greenhouse gas emissions, as shown in other sections.

Given that Reduction and Shutdown apply to the same generators, the large difference in their effects bears explaining. Under Reduction, much of the affected generation capacity reduces its generation but is not retired, so there is less need for new capacity than under Shutdown. Because there is less new capacity, the generation reductions by power plants in EO DACs are offset largely by generation increases from existing

Figure 12a. Generation Mix in BAU

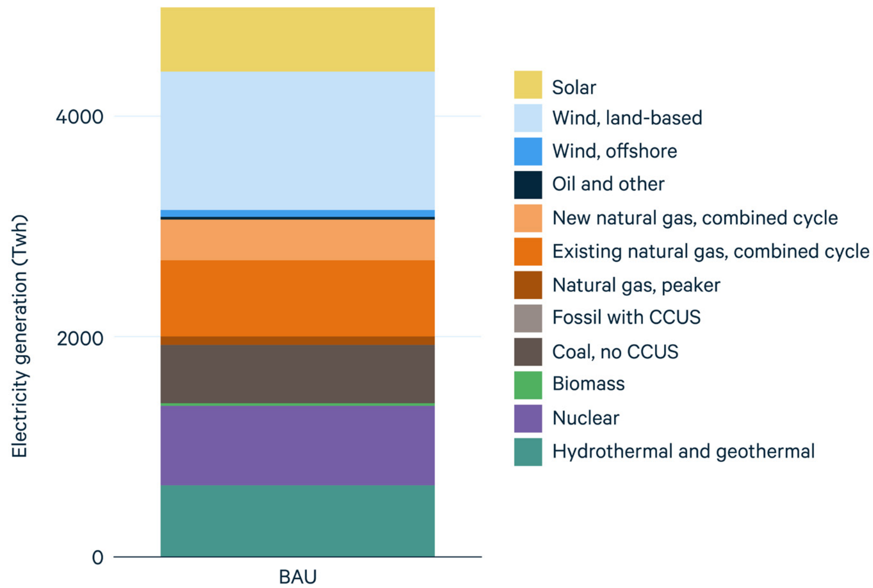
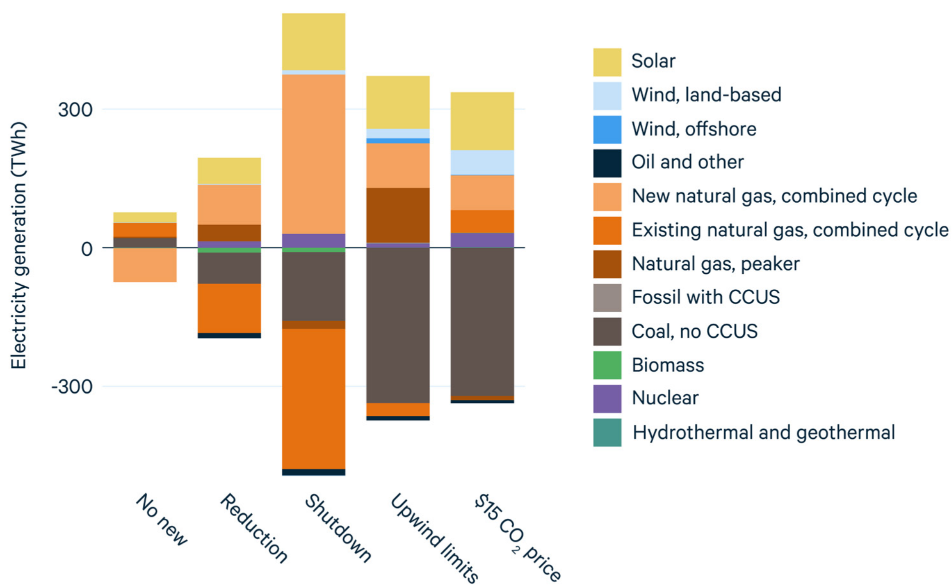


Figure 12b. Generation Mix Changes Relative to BAU



emitting EGUs not in EO DACs, including coal-fueled EGUs and peakers, which have higher emissions rates than the new gas combined-cycle EGUs that provide most of the offsetting generation increase under Shutdown.

5.5.2. Capacity Effects

As in the generation changes, the capacity changes include reductions for coal-fueled EGUs (except in No New), as shown in Figures 13a and 13b. There are also reductions of peaking capacity. These reductions are offset by increased capacity of types with lower emissions rates.

Shutdown requires more new capacity than the other policies because existing capacity in EO DACs must shut down—it cannot simply operate less, as in the otherwise similar Reduction policy. In addition to reducing emissions more, adding new capacity is generally more costly than retaining existing emitting capacity, as seen in other sections.

The capacity figures help explain how No New increases emissions. This policy eliminates generation from new emitting EGUs, mainly gas combined-cycle, in EO DACs because it prohibits their construction, and most new emitting capacity is gas combined-cycle. The compensating generation increase is mainly from new gas combined-cycle EGUs outside EO DACs (which makes the new combined-cycle reductions smaller), existing gas combined-cycle EGUs, existing coal EGUs, and new solar EGUs. The compensating generation has higher average emission rates than the prohibited EGUs.

Figure 13a. Generation Mix in BAU

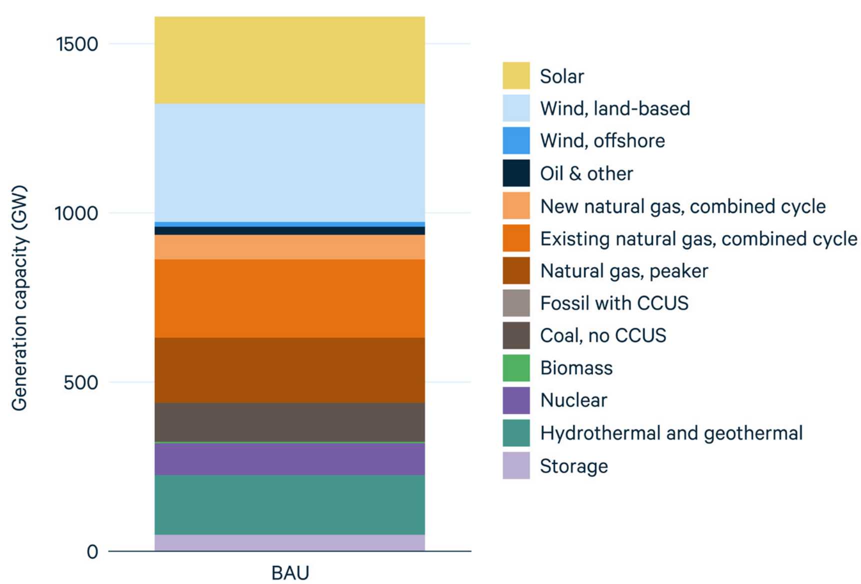
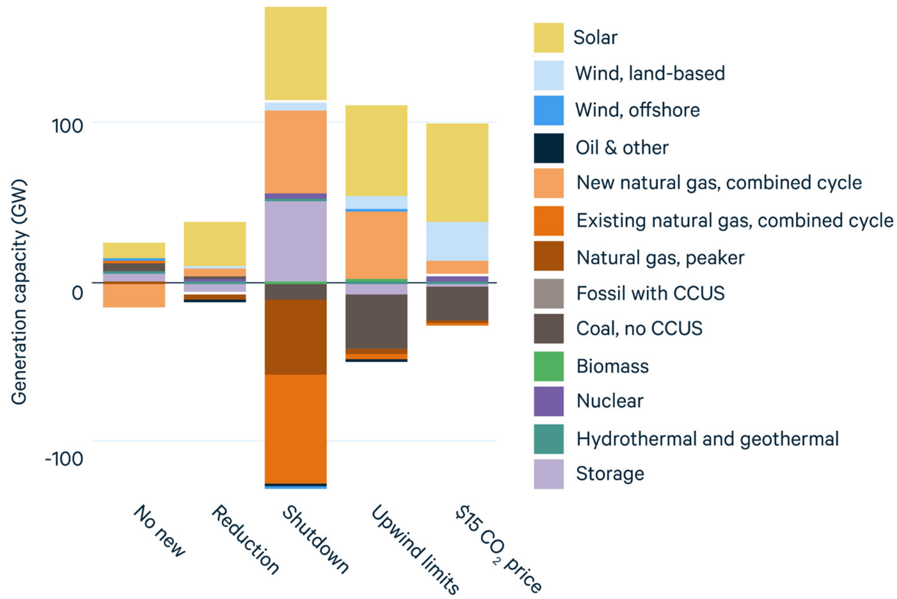


Figure 13b. Generation Mix Changes Relative to BAU



5.5.3. Greenhouse Gas Emissions Effects

Table 3 shows the annual reduction in greenhouse gas emissions (CO_2 and methane expressed as CO_2 equivalent) as of 2030 for each policy. Earlier sections have explained the causes of these emissions changes.

5.6. A Note about Policy Intensity Parameters

Reduction, Upwind Limits, and CO_2 Pricing have intensity (intensive margin stringency) parameters that can be adjusted. Respectively, these are the capacity factor cap, the maximum allowable contribution to $PM_{2.5}$ in an EO DAC, and the CO_2 price (or allowed emissions). Tightening the intensity parameter tends to increase the benefits but reduce the ratio of environmental benefits to policy costs because increased stringency induces the use of increasingly costly substitute generation. The effect of the stringency parameter for Upwind Limits plateaus: a maximum contribution one 10th as large as the one we have used for the above results causes the policy to prevent fewer deaths rather than more.

Table 3. Greenhouse Gas Effects of Policy Scenarios

Policy	Change in 2030 GHGs (short megatons)
No New	+8.81
Reduction	–54.52
Shutdown	–164.26
Upwind Limits	–260.21
CO2 Pricing	–313.29

6. Conclusions

6.1. Effects, by Policy

In this section we summarize the results for each policy. These policy cases demonstrate the consequences of different policy design decisions and stringency. A major factor in the emissions and health benefits of these policies is the extent to which they reduce the generation of existing emitting EGUs, especially those using coal. The three most effective policies, in terms of estimated mortality reduction, are CO_2 Pricing, Upwind Limits, and Shutdown.

6.1.1. No New

The No New policy is one of three within-DAC policies we model. It prohibits the building of new emitting EGUs in EO DACs but does not restrict the operation of existing EGUs. This causes an increase in $PM_{2.5}$-forming emissions because it restricts lower-emitting new generation, like combined-cycle natural gas, from replacing high-emitting generation, like existing coal, in EO DACs. Estimated power plant $PM_{2.5}$-caused deaths consequently increase by 4 percent relative to the BAU. This highlights that restricting the construction of emitting capacity can in some circumstances be harmful for air quality both inside and outside EO DACs, particularly when new capacity could have replaced higher-emitting capacity.

6.1.2. Reduction

The Reduction policy is the second within-DAC policy. It prohibits the building of new emitting EGUs in EO DACs and requires an approximately 80 percent reduction of capacity factor for existing emitting EGUs in EO DACs. This policy produces relatively small net health benefits, both nationally and in EO DACs. However, it has lower policy costs than the Shutdown policy because it does not require replacing as much existing capacity. Its ratio of estimated net health and climate benefits to net policy costs is 3.

6.1.3. Shutdown

The Shutdown policy is the final within-DAC policy. In addition to prohibiting the building of new emitting EGUs in EO DACs, it requires complete retirement of existing emitting EGUs in EO DACs, which causes a large retirement of existing gas- and coal-fueled EGUs. Sufficient capacity is still needed to meet expected peak electricity consumption plus a reserve margin, so the retired capacity is replaced by a nearly equal amount of new gas combined-cycle capacity outside EO DACs and energy storage capacity, accompanied by increased solar capacity. The result is a large reduction in generation by existing gas- and coal-fueled EGUs, which are replaced by new gas combined cycle EGUs and, to a lesser extent, solar generators. The replacement generation has much lower $PM_{2.5}$-forming emissions, so this policy prevents an estimated 1,400 premature deaths per year and reduces greenhouse gas emissions by 0.16 million short tons of CO_2 equivalent per year. However, it has the highest policy costs, mainly consisting of a 0.33-cent increase per kWh in national average electricity rates. Like the Reduction policy, its estimated net health and climate benefits are three times its estimated net policy costs. Allowing exceptions to the Shutdown policy, particularly for EGUs that are especially costly to replace, would reduce its cost.

We also simulated a version of this policy that applies to all DACs, not just EO DACs. Its aggregate effects were similar in proportion to each other and approximately 25 percent larger than restricting only in EO DACs.

One potential modification to all three within-DAC policies would be to also apply them to EGUs (new, existing, or both) that are near or adjacent to EO DACs to reduce downwind pollution. Other things being equal, this would increase both the environmental benefits and the policy costs.

6.1.4. Upwind Limits

The Upwind Limits policy restricts how much any EGU is allowed to contribute to the $PM_{2.5}$ concentration in any EO DAC, regardless of the EGU's location. This is one possible implementation of the New York law. Upwind Limits disproportionately reduces coal-fueled generation because the high $PM_{2.5}$, NO_X, and SO_2 emissions rates of a typical coal-fueled EGU limit the allowable generation far below that of a typical gas EGU in the same location. Consequently, this policy reduces coal-fueled generation slightly more than the CO_2 Pricing policy does, and much more than the other three policies do. It reduces $PM_{2.5}$ more in areas with high population density than in ones with low population density, so it causes large reductions in mortality, relative to its average effect on $PM_{2.5}$ concentrations. This policy has the second-smallest effect on electricity bills relative to its estimated health and climate benefits. Its ratio of estimated health and climate benefits to net policy costs is 13.

The magnitudes of this policy's effects depend on the maximum allowable contribution to $PM_{2.5}$ concentration in any EO DAC, among other factors. We have used a limit of 0.01 microgram per cubic meter. Tightening this policy to a lower maximum allowable contribution would, at some level, begin to increase the costs of the policy rapidly. We know this from also simulating the policy with a limit of 0.001 microgram per cubic meter. The effects on electricity rates and on total policy costs were then more than eight times as large, and the tightening actually reduced the $PM_{2.5}$ health benefits slightly by shifting more generation to peakers as well as to EGUs upwind of more densely populated areas and areas with higher proportions of Black residents. In places where this type of policy may be adopted, local studies could be used to inform the choice of a limit.

In our modeling of this policy, we restrict EGUs based on $PM_{2.5}$ contribution to any EO DAC, regardless of whether it is in the same state as the EGU. If instead each EGU's generation limit were based only on its contributions to $PM_{2.5}$ in EO DACs in the same state, the policy would be less stringent and less uniform in its stringency. It would have lower environmental benefits and policy costs.

In our modeling for this project, we have not incorporated endogenous $PM_{2.5}$, NO_X, or SO_2 or emissions control investment. The Upwind Limits policy, as we have represented it, would probably cause some EGU owners to improve the emissions controls instead of retiring or reducing generation, thereby potentially reducing the costs and climate benefits of the policy. We anticipate that the other policies, as we have represented them, would have much less effect on investment in $PM_{2.5}$, NO_X, and SO_2 emissions controls, which are less likely to help with compliance.[24]

6.2. General Findings

As noted in the Introduction, this study explores how different policies could reduce disparities in environmental consequences for people and communities facing environmental and economic disadvantages. Existing disparities are seen by many as being inequitable and unfair. Our focus is on premature mortality from exposure to airborne fine particulate matter ($PM_{2.5}$) resulting from power sector emissions.

The findings of the study enable several observations about the potential effects of policies to reduce air pollution in environmentally overburdened disadvantaged communities. Our work indicates that both the effectiveness and the cost-effectiveness of policies can differ greatly. In our results (summarized in Section 6), Upwind Limits, CO_2 Pricing, and Shutdown (the best-performing within-DAC policy) reduce per capita mortality across the country by a greater proportion for EO DAC residents compared with Americans living outside EO DACs. Thus, those policies reduce the $PM_{2.5}$ mortality disparity between EO DAC residents and other Americans. However, the targeted policies are at best only slightly more effective than CO_2 Pricing at achieving the $PM_{2.5}$ reductions they cause in EO DACs. Moreover, the more-targeted policies result in higher electricity costs per avoided death from $PM_{2.5}$ exposure than the untargeted CO_2 price. Accordingly, less targeted policies can be quite effective and less costly than some targeted policies, for disadvantaged Americans and all Americans.[25]

Table 4 compiles findings for the four policies that reduced $PM_{2.5}$ concentrations.[26] Reduction, Shutdown, Upwind Limits, and CO_2 Pricing produce net society-wide climate and health benefits, estimated in our results to be worth 3, 3, 13, and 54 times

24 Other policies can be designed such that adding emissions control systems would bring a generator into compliance, particularly as a means of mitigating environmental harms from generators that must stay online for reliability reasons.

25 Although the projected effects are in the year 2030 for policies that take effect in 2025, they can also be informative about the likely effects in other years, and for policies that take effect in other years.

26 Recall that the No New policy, the within-DAC policy that prohibits only new emitting EGUs in EO DACs, increases average $PM_{2.5}$ concentrations and resulting mortality in our simulations.

their estimated policy costs, respectively. The policies prevent 2, 17, 129, and 400 $PM_{2.5}$-caused deaths in EO DACs per billion dollars of policy cost, respectively.

Upwind Limits prevents approximately 900 deaths per year in EO DACs from $PM_{2.5}$, CO_2 Pricing prevents 800, Shutdown 300, and Reduction 8. The policies also all prevent some ozone-caused deaths.

In the simulations, the policy costs are mainly in the form of higher electricity bills. The average increase in each household's annual electricity bill total is $13, $45, $23, and $8 per year for Reduction, Shutdown, Upwind Limits, and CO_2 Pricing, respectively, not counting increases in the costs of goods and services that are supplied using electricity .

The policies all reduce $PM_{2.5}$ concentrations and resulting per capita mortality more for residents of EO DACs and high-environmental-burden areas, and for Black Americans, than for other Americans. Thus, the policies all reduce the absolute disparity in environmental burden between these population groups and other Americans. This is partly because these population groups have higher business-as-usual exposure to $PM_{2.5}$ from power plant emissions and partly because their mortality is more sensitive to changes in $PM_{2.5}$. The benefit is especially large for Black Americans. For them, the Shutdown, Upwind Limits, and CO_2 Pricing policies each reduce per capita mortality more than four times as much as for the rest of the US population, mainly because Black Americans' mortality is approximately three times as sensitive to $PM_{2.5}$.

These three policies are all effective at achieving mortality reductions in EO DACs because pollution from each EGU tends to affect a large area, much larger than a single cluster of EO DACs. As a result, $PM_{2.5}$ concentration reductions tend to apply almost equally to EO DACs and non–EO DACs, even for the targeted policies. These results

Table 4. Policy Effects Summary

Policy	Reduction	Shutdown	Upwind Limits	CO2 Pricing
Net society-wide environmental and health benefits (billion 2020$)	$13	$49	$91	$103
Net society-wide policy costs (billion 2020$)	$4	$17	$7	$1.9
Society-wide benefit-to-cost ratio	3	3	13	54
$PM_{2.5}$-caused deaths prevented in EO DACs	8	288	908	760
$PM_{2.5}$-caused deaths prevented in EO DACs, per billion dollars of society-wide costs	2	17	129	400
Society-wide $PM_{2.5}$- and ozone-related deaths prevented	147	1,389	3,269	3,443
Annual increase in average household electricity bill	$13	$45	$23	$8

indicate that cost-effective reductions of $PM_{2.5}$-forming power plant emissions can be good for environmental justice goals even if they are not targeted.

CO_2 Pricing and Upwind Limits are much more cost-effective at reducing premature air pollution–related mortality than the other policies we model because they reduce generation more at EGUs with higher rates of particle-forming emissions than at other EGUs. They also cause less emissions leakage to other emitting generators because they apply to a greater number of emitting EGUs.

Of the two policies, CO_2 Pricing is considerably more cost-effective at reducing $PM_{2.5}$-caused deaths in EO DACs and for all demographic groups we examine, even though it is the only policy not geographically targeted at EO DACs. Its cost-effectiveness arises because it uses a uniform price on CO_2, which is positively correlated with the emission types that cause airborne $PM_{2.5}$. The uniform price induces all emissions reductions expected to cost less than the price but causes no emissions reductions expected to cost more than the price. Other policies, in contrast, tend to induce some high-cost emissions reductions and fail to compel some low-cost reductions.

All the policies except CO_2 Pricing cause $PM_{2.5}$ concentrations to increase in some areas large enough to be visible on the map in Figure 4, including in some EO DACs, meaning they cause hotspots in our results. All our benefit calculations account for these areas of increased $PM_{2.5}$.

6.3. Potential Extensions

The results in this paper concern premature mortality from $PM_{2.5}$ and ozone air pollution and the costs of the electricity supply. Those are important effects, but other effects should also be considered. An important consideration for stakeholders and policy leaders is political viability. Moreover, there are policies other than the five we have simulated for this study.

One extension of this research would be to use a uniform price not just for greenhouse gas emissions but also for improvements in local air quality. Among the policies we consider, CO_2 Pricing has the highest society-wide benefit-to-cost ratio and prevents the most deaths in EO DACs per billion dollars of policy costs. A policy that applied a price to $PM_{2.5}$- and ozone-forming emissions could prevent even more $PM_{2.5}$- and ozone-caused deaths per billion dollars of policy costs.

Even better for cost-effectiveness, uniform prices can be applied to emitters based on the estimated damage they cause, such that the price is higher at locations and/or times at which emissions are more harmful to people (Muller and Mendelsohn 2009). A price that varies by location has the additional advantage that it can inherently account for the different sensitivities of different demographic groups to $PM_{2.5}$, thereby improving its effectiveness for the more sensitive groups, such as Black and low-income Americans, and for the public as a whole.

This reasoning could be applied by setting a price for emissions in proportion to the estimated effect on the health of EO DAC residents. Such a policy would be more precisely targeted than any we have simulated and would have the cost-effectiveness advantages of a pricing policy, so it could save more lives in EO DACs, both in absolute terms and per billion dollars of policy cost. It also could be beneficial for society as a whole.

In addition, policies can be combined. That can be important for addressing some of the many effects of power plants beyond the ones we have modeled, including environmental harms from power plants that are more localized than $PM_{2.5}$ air pollution. Policies designed to address very local effects can be combined with one or more emissions-pricing policies. New Jersey and New York have such combinations, as described in Section 4.

The electricity sector lends itself to modeling because the product, electricity, is relatively homogeneous. However, it is far from the only source of pollution in EO DACs. Although electricity sector policies can prevent thousands of premature deaths per year, the overall $PM_{2.5}$ and ozone pollution problem is much larger. The power sector accounts for only approximately 3 percent of $PM_{2.5}$ in US ground-level air, as indicated in the Introduction. Cutting $PM_{2.5}$ by more than 3 percent would require policies that apply to other emissions sources as well. This study might be helpful as an input to designing or analyzing policies for other sectors.

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Apendices

Appendix A. Power Sector Modeling Assumptions

A.1. General Assumptions

E4ST uses 16 representative days, comprising 52 representative hours, to represent the year. The days closely approximate the joint frequency distributions of electricity demand, wind, and sun in each region of the contiguous US and Canada in the three years for which we have hourly site-by-site wind, solar, and electricity consumption data for both countries. This includes the extreme scarcity situations (e.g. high demand with low wind and sun) in each region.[27]

Our analysis focuses on the year 2030. We simulate that year, with the projected circumstances in that year. We assume the retirement of the generating units that have announced that they will retire by 2030, as reported in the S&P generator data set (S&P Global 2020). We assume the construction of the generators that were planned for completion by the end of 2024, according to that same data set. In the simulation, the model predicts what additional generators will retire by 2030 and what additional new generators will be built by 2030.

Transmission capacity influences the ability of land-intensive renewable resources to supply power to urban areas. We make the following neutral assumption about transmission expansion: we assume that the flow limit on every segment of every transmission line increases in proportion to US and Canadian electricity consumption. For example, if projected electricity consumption is 20 percent higher in 2030 than in the year represented by our starting transmission system data, we expand the flow limit on every transmission line segment by 20 percent.

The model represents capacity reserve requirements via constraints that require that, for every representative hour, the available generation and storage capacity in each balancing authority area (areas from Sergi and Cole 2021) be greater than or equal to local load plus the area's capacity reserve margin requirement. The hourly available capacity of each wind, solar, and hydro generator accounts for hourly wind, sun, or water resource availability at its location. The hourly available capacities of all generators account for average type-specific outage rates. Battery storage capacity is further derated by 10 percent (as is done in New York; Smith 2021) to represent the effect of its limited duration. Capacity can be traded across regional capacity reserves, constrained by the dependable n-minus-one transmission limits between each adjacent pair of areas, which we calculated from simulations using the normal E4ST transmission model. There is a price for reserves in each representative hour, earned

27 For this purpose we use the Texas, Florida, Mid-Continent, Northeast, Mid-Atlantic, Southeast, Southwest, and West regions, as defined by the North American Electric Reliability Corporation.

by generators and storage capacity according to their available, operable capacity in that hour (after accounting for hourly, location-specific wind and sun and for generator outage rates).

A.2. Technology-Specific Assumptions

For the costs of new technology, we use future cost estimates from the 2023 Annual Technology Baseline (ATB) (Mirletz et al. 2023). The ATB offers multiple assumptions for cost of capital and economic lifetime. We assume a real weighted average cost of capital of 5.44 percent and technology-specific economic lifetimes. For generators with carbon capture, we assume a 12-year lifetime, corresponding to the length of the Inflation Reduction Act's 45Q tax credit. For battery energy storage, we assume a 20-year economic lifetime. For natural gas generation, we assume a 10-year economic lifetime. We assume a 30-year economic lifetime for all other new generators. We do not allow new coal generation to be built. We use the ATB's projected costs of projects completed in 2030. The assumed 2030 fuel prices for thermal generators come from the reference case projections of the 2023 Annual Energy Outlook (US EIA 2023).

We assume that utility-scale solar generation capacity can be built only in counties with population densities below 750 per square km. We assume that land-based wind farms can be built only in 2 km by 2 km grid cells with population densities below 10 per square km as measured in an approximately 1 km by 1 km grid cell that includes the center of the 2 km by 2 km grid cell. New natural gas combined-cycle generators can be built at locations where at least 100 MW of natural gas capacity has existed in our existing generator data set to ensure that the location can handle the natural gas infrastructure needed to operate a natural gas plant.

The Inflation Reduction Act has large incentives for carbon capture and sequestration. In the simulations, we allow coal-fueled power plants to be retrofitted with carbon capture, and we allow new natural gas–fueled power plants with carbon capture to be built, each with an assumed CO_2 capture rate of 90 percent. The model builds them (like all buildable power plant types) where it projects that they will be profitable. However, to represent the high marginal cost of rapidly developing and building the infrastructure for carbon capture, transport, and storage, we add a price of $80.65 per short ton of CO_2 captured (2020$). This is double[28] the price that reduces CO_2 capture, use, and sequestration to approximately 72 million metric tons per year in the BAU. That quantity is based on Jenkins et al. (2023). It is their assumed upper limit on annual CO_2 sequestration (200 million metric tons) minus their projection of non-electricity-sector CO_2 capture (128 million metric tons) in 2030.

The one type of generation capacity for which we do not use cost assumptions from the ATB is coal-fueled generators retrofitted with carbon capture, since retrofit costs depend on the EGU's characteristics, and the ATB's retrofit cost projections

28 We chose to double the computed cost adder on sequestering captured CO_2 to prevent unrealistic overbuilding of carbon capture and sequestration in the policy case with a CO_2 price while still allowing the policy to influence the rate of its deployment.

do not. Instead, we use coal plant retrofit cost and performance functions based on the cost and performance effect projections reported in the Integrated Planning Model (IPM) summer 2021 reference case (US EPA 2021) Those projections are for nine combinations of generating unit pre-retrofit generation capacity and heat rate. For each cost or performance parameter, we fit a linear or quadratic function to the set of nine effect estimates, with generating unit capacity and heat rate as the input variables. These functions then enable us to estimate the cost and performance parameters for generating units with capacity and heat rate combinations other than the nine presented in the IPM documentation. IPM is a model funded by the US Environmental Protection Agency and updated by consulting firm ICF.

To determine the costs of transporting and sequestering carbon, we use the IPM's CO_2 transportation and sequestration model, which is drawn from the National Electric Energy Data System (US EPA n.d.-c). CO_2 can be sequestered in saline aquifers or used for enhanced oil recovery (EOR). Use for the latter earns a smaller US government subsidy per ton. We assume that none of the CO_2 sequestered in a saline aquifer escapes, but that the net emissions effect of using CO_2 for enhanced oil recovery, including all upstream and downstream market effects, is equivalent to 23 percent leakage of the sequestered CO_2 (Heidug et al. 2015). To represent the demand for CO_2 storage from other sectors, we remove the cheapest CO_2 storage options, adding up to 141 million short tons of CO_2 stored. That amount, 141 million short tons, is an estimate of the amount of CO_2 from outside the power sector that will be stored in 2030 (Jenkins et al. 2023).

Coal- and gas-generating units operate more in reality than what is shown in an optimal power flow with the variable costs and fuel prices that we assume, for multiple reasons: fossil-fueled generating units provide ancillary services, they have inflexible operation, and especially in areas with cost-of-service regulation and outside organized markets, owners have incentives to operate them uneconomically. To correct for this, we add a cost to coal and natural gas fuel, calibrated to get the observed amount of generation by coal and natural gas in 2016, in a model of the power sector as it was in 2016.

We limit where new natural gas EGUs can be built to locations where such generation has been built before. Natural gas EGUs have infrastructure and siting requirements that strongly tend to make places with existing EGU infrastructure the best places to build.

Appendix B. Air Pollution Modeling Assumptions

B.1. Effects on Ambient $PM_{2.5}$ Concentration and Resulting Deaths per Demographic Group

The Intervention Model for Air Pollution (InMAP) is an air quality model that incorporates long range transport of direct $PM_{2.5}$ emissions as well as $PM_{2.5}$ formed from NO_X and SO_X emissions. The E4ST team has incorporated InMAP's source receptor matrix (SRM) into the power sector model to simulate how EGUs will change ambient $PM_{2.5}$ concentrations. The InMAP SRM estimates the effects of emissions from more than 50,000 source grid cells at three stack heights across the United States. The grid cells vary in size based on the population density, with increased detail in urban areas with high population density. As part of this effort, we have developed and released an open-source software package for working with the InMAP SRM in the Julia programming language, which can be found at **https://github.com/e4st-dev/InMAPSourceReceptorMatrices.jl**.

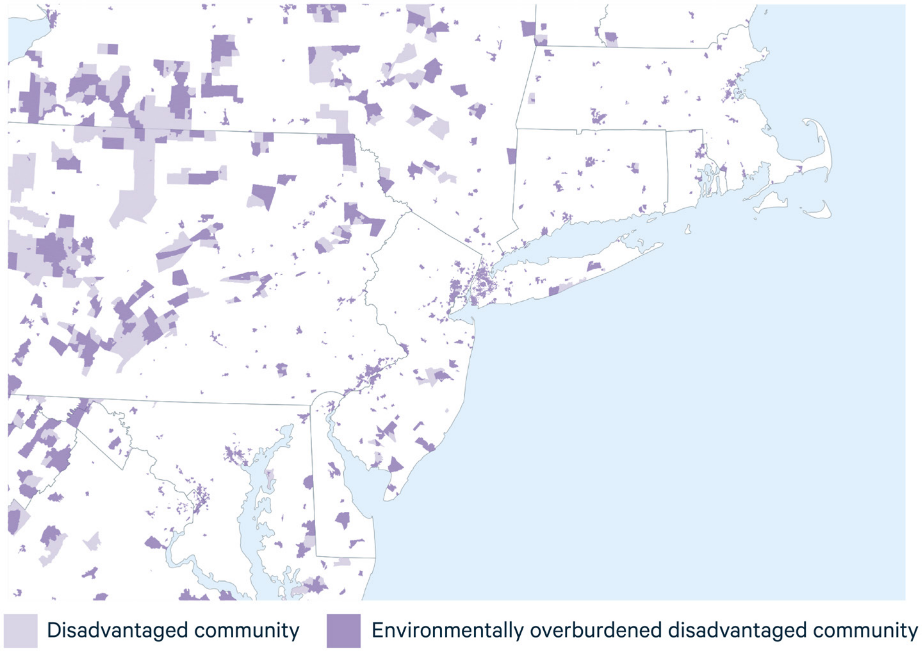
To estimate the increase in premature deaths as a result of EGU-caused $PM_{2.5}$, we use a linearized version of the Cox Proportional Hazard formula. We found that using the linearized version yielded a solution within 0.2 percent of the original exponential formula.

The number of premature deaths from EGU-caused $PM_{2.5}$ varies with underlying mortality rate, such that a higher underlying mortality rate proportionally increases the estimated deaths from $PM_{2.5}$, since people who are more susceptible to dying in general are also more susceptible to dying from $PM_{2.5}$ exposure. We use the age-adjusted mortality rate by race for each county in the nation, from the National Vital Statistics System (CDC 2020).

The E4ST team has mapped the air pollution to each census block group in the United States. Using race or ethnicity and income information from the US Census American Community Survey (US Census 2020), we are able to estimate the changes in ambient $PM_{2.5}$ for population in each racial or ethnic group and income quintile for every block group. Combining that with the race- or ethnicity-specific hazard ratios from (Di et al. 2017) and group-specific county-level mortality information from the National Vital Statistics System (CDC 2020), we estimate the number of premature deaths in each racial or ethnic group or income quintile caused by ambient $PM_{2.5}$ from power sector emissions. Finally, we use the Value of Statistical Life estimates from the Environmental Protection Agency to compute a dollar value for the health damages resulting from the $PM_{2.5}$ pollution caused by the power sector (US EPA 2023b).

We estimate the effects on mortality inside and outside EO DACs. Figure 1a in the main text is a national map of DACs and EO DACs. Figure B-1 shows the same for a portion of the eastern United States that includes the most densely populated part. The larger scale makes some characteristics of the spatial distribution of EO DACs and non-EO DACs easier to see.

Figure B1. Disadvantaged and Environmentally Overburdened Census Block Groups in Northeast



B.2. Valuation of Effects on Ground-Level Ozone Pollution

Aside from fine particulate matter, the other major ambient air pollution of concern is ground-level ozone. NO_x is the main power plant emission that contributes to ground-level ozone formation. The effect of emissions on ground-level ozone is more dependent on unpredictable conditions than is the effect of $PM_{2.5}$, SO_2, and NO_x emissions on ground-level $PM_{2.5}$, and we are not aware of a reduced-form model of the effect of NO_x emissions on the former. Consequently, to estimate and value the effects of NO_x emissions reductions on ground-level ozone pollution, we use the estimated national average effect of ozone season (May 1–September 30) power plant NO_x emissions on illness and mortality, and the estimated value of those health effects (US EPA 2023b).[29] We assume that 45 percent of annual power plant NO_x emissions cause this damage, since historically, 45 percent of power plant NO_x emissions have been in the official ozone season. We assume that the other 55 percent of NO_x emissions do not affect ground-level ozone, since there is little ground-level ozone formation in the rest of the year.

29 The US EPA study estimates the value of the health effects using 3 percent and 7 percent real discount rates. We use the values based on a 3 percent real discount rate.

Appendix C. Policy Assumptions

The most influential policy in our model is the Inflation Reduction Act of 2022, which provides incentives for clean electricity generation and for electrification of existing nonelectric energy uses. We also have state renewable and clean electricity requirements in our model. We assume that these states will have intermediate requirements, determined linearly, in each year between 2023 and the first announced requirement, and then between that and any later requirements. These are based on the information about requirements in Barbose (2023). We also assume that any requirements that end in current law will be continued at a flat percentage of the state's electricity consumption. However, in our results, few of these state requirements have an effect because the incentives in the Inflation Reduction Act induce more renewable and clean energy by 2030 than called for by most of the state requirements by that year.

The Regional Greenhouse Gas Initiative (RGGI) is a cap-and-trade policy that applies to electricity sector CO_2 emissions in 12 northeastern and Mid-Atlantic states from Maine to Virginia. Because Virginia's governor is attempting a (contested) departure, we assume that the other 11 states are in RGGI in 2030. Every few years, the state governments that manage RGGI have adjusted the number of allowances issued, largely in response to the demand for allowances. This pattern is effectively similar to a policy of trying to achieve a target RGGI emissions allowance price. In addition, the program has a soft price ceiling, a soft price floor (the emissions containment reserve at a medium price), and a hard price floor (the price floor at a low price) that further reduce the range of likely future prices. For both of these reasons, we represent RGGI as a price on power plant emissions in the RGGI states, rather than as an emissions cap or as an emissions allowance supply step function. Specifically, we assume that the allowance price will be at the emissions containment trigger price, which will be $11.77 in 2030. Given our inflation assumptions, we project that this will be equivalent to $8.98 in 2020 dollars.

Annual NO_x and SO_2 emissions caps in the eastern states, under the Cross-State Air Pollution Rule, have been slack for several years. We assume that these annual limits will be slack in 2030 as well, partly because the Inflation Reduction Act contributes to that likelihood.

However, many of the states in the central and eastern US, which together produce most US electricity sector NO_x emissions, are subject to a cap on power plant and industrial NO_x from May 1 to September 30 of each year. The cap has been binding in recent years, with a significant NO_x emissions allowance price. The cap has recently been modified in an EPA policy revision known as the Good Neighbor Plan. Under this plan, the May–September NO_x cap will, by 2030, be largely determined by the amount of emitting generation capacity that is still operable at that time. The allowed emissions per MW of existing emitting capacity will be such that most (but probably not quite all) emitting capacity will need selective catalytic reduction (SCR) as an emissions control type. This is a reason to use an estimate of the long-run marginal cost (or, equivalently, the levelized cost) of SCR as the projected price of the May–September NO_x allowance price, in the states that are subject to the cap. Under the Good Neighbor Plan, there are now 22 such states. The price estimate we use is $11,000/short ton (in 2016$, or $5.91/pound in 2020$) (US EPA 2023c).

We do not assume any new US national regulations on power plant CO_2 emissions like those proposed recently by EPA based on Section 111 of the Clean Air Act (US EPA 2023c). It is uncertain how those regulations might change and whether they will survive court challenges. Even if they do survive and are implemented and sustained, their effects on the benefits and costs of these policies in 2030 might be small. In the results of EPA modeling of the regulations' effects in 2030, 2035, and 2040, the effects are much larger in 2035 than in 2030 or 2040.

We do not model the Washington, DC, solar carveout because we do not allow utility-scale solar to be built in areas with high population density, such as the District, making this policy unrealistically binding. The actual policy may include small-scale solar and may count solar from surrounding regions, but we do not include that in our current representation. We also do not include the Maryland offshore wind carveout, although it will likely be met in 2030.

Appendix D. Additional Findings

Figure D-1 shows the US areas with high environmental burdens, regardless of whether they are also DACs. We define "high environmental burden" using the same total EJScreen index used in defining environmentally overburdened DACs, but we apply a state-by-state threshold to all block groups, regardless of DAC status. For each state, the threshold is set such that the number of high-environmental-burden census block groups equals the number of environmentally overburdened DACs. About two-thirds of the block groups in the high-environmental-burden category are among the EO DACs that some of the modeled policies directly target. However, the EO DACs with lower population densities, which therefore tend to be geographically larger, are less likely to be among high-environmental-burden block groups. The high-environmental-burden block groups are almost all densely populated, to such a degree that they cover only 3 percent of the US area.

Figure D1. Areas of High Environmental Burden

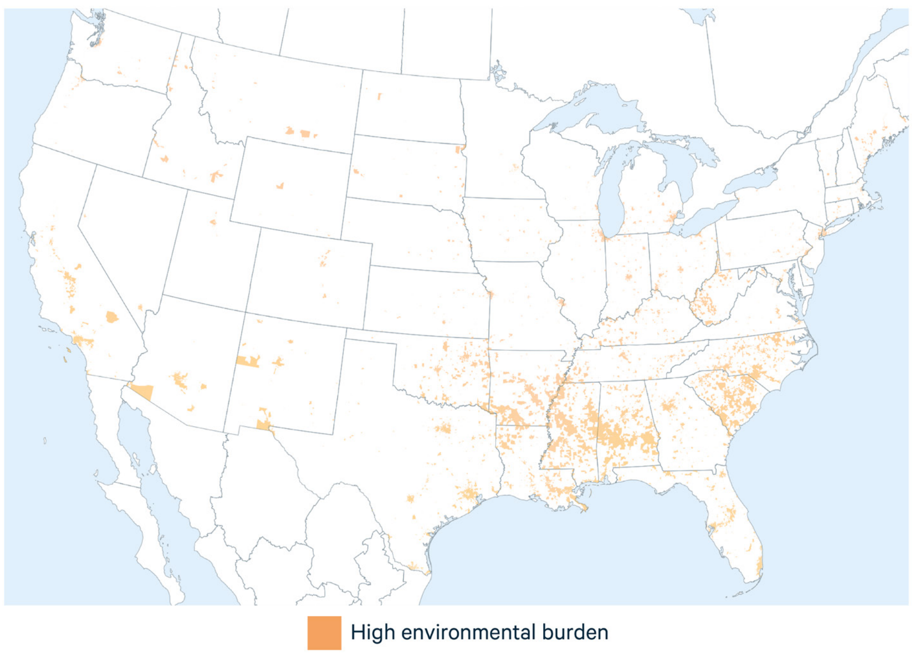


Figure D-2 shows the projected net benefits if CO_2 Pricing is not revenue neutral; that is, if the revenues are not returned to customers via their electricity bills.

Interstate emissions leakage is another factor that can cause state effects to differ from national effects. However, a CO_2 pricing policy could include a border adjustment to reduce or reverse that (Shawhan et al. 2018), and the other policies produce considerable within-state leakage, which reduces the interstate leakage they cause. Another reason that state adoption might be different than national adoption is the different emissions profiles of generators in a given state.

Figure D2. Net Benefits with Non-Revenue-Neutral CO2 Price