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Article

# Designing Retirement Strategies for Coal-Fired Power Plants to Mitigate Air Pollution and Health Impacts

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**Abstract:** Retiring coal power plants can reduce air pollution and health damages. However, the spatial distribution of those impacts remains unclear due to complex power system adjustments and pollution chemistry and transport. Focusing on coal retirements in Pennsylvania (PA), we analyze six counterfactual scenarios for 2019 that differ in retirement targets (e.g., reducing 50% of coal-based installed capacity vs. generation) and priorities (e.g., closing plants with higher cost, closer to Environmental Justice Areas, or with higher CO<sub>2</sub> emissions). Using a power system model of the PJM Interconnection, we find that coal retirements in PA shift power generation across PA and the Rest of PJM region leading to scenario-varying changes in the plant-level release of several air pollutants. Due to air pollution chemistry and transport and socio-demographics, these changes in turn give rise to a reduction of 10 to 182 PM<sub>2.5</sub>-attributable deaths in PJM across the six scenarios, with most reductions occurring in PA. Scenarios that reduce more coal power generation yield greater aggregate health benefits due to air quality improvements in PA and adjacent downwind regions. In addition, vulnerable populations—in both PA and Rest of PJM—benefit most in scenarios that prioritize plant closures in PA near Environmental Justice Areas. These results demonstrate the importance of considering cross-regional linkages and socio-demographics in designing equitable retirement strategies.

**Keywords:** coal retirement; air quality; human health; environmental justice

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## Synopsis

Retiring coal power plants in Pennsylvania can improve air quality and health outcomes throughout the PJM Interconnection.

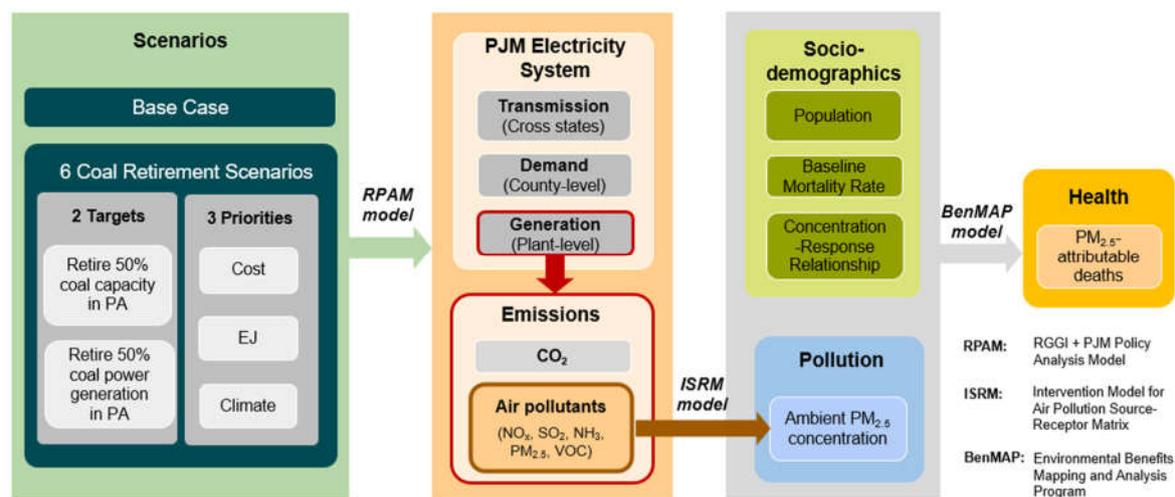
## 1. Introduction

The U.S. is in the midst of a significant energy transition. The last decade has seen a national decline in coal-fired electricity generation of nearly 50%.<sup>1,2</sup> Pennsylvania (PA) mirrors this trend due to its policy landscape and access to cheap and plentiful natural gas and renewable energy sources.<sup>3–5</sup> Coal plant retirements in PA provide a potential avenue for mitigating emissions of not only carbon dioxide (CO<sub>2</sub>), but also criteria air pollutants such as nitrogen oxides (NO<sub>x</sub>), sulfur dioxide (SO<sub>2</sub>), and fine particulate matter (PM<sub>2.5</sub>)<sup>6,7</sup>. Accordingly, such closures are expected to improve air quality and reduce health damages<sup>8–11</sup>.

Prior studies have found that air quality and health benefits from coal generation are unevenly distributed across regions and sociodemographic groups.<sup>8,12–18</sup> Optimizing coal-fired power plant closures based on climate, cost, or health objectives can lead to substantial variation in both the magnitude and distribution of health benefits.<sup>9,19–21,23</sup> In practice, coal retirement decisions in PA and much of the country are largely based on economic and feasibility considerations and thus unlikely to address long-standing environmental justice concerns. This motivates a need to understand the equity implications of coal plant retirements—in particular, how to better design coal retirements so as to more effectively mitigate disproportionate environmental burdens historically borne by disadvantaged communities.

In addition, research into how cross-regional linkages across power systems, air pollution transport, and socio-demographics influence the distribution of health impacts is fairly limited. PA provides a distinctive setting to examine such linkages. First, PA is a major power exporter in the PJM Interconnection, a Regional Transmission Organization that manages a wholesale electricity market spanning thirteen states which is one of the largest in the world. Thus, coal retirements in PA affect power generation and flows throughout the PJM grid, leading to potentially significant emissions impacts elsewhere.<sup>16,19,22</sup> Second, due to historical plant siting decisions, chemical formation, and wind transport of pollution, reducing PA's emissions provide an avenue to also improve air quality in downwind states.<sup>23,24</sup> These complex dynamics and resulting distributional outcomes are not well understood nor incorporated into coal retirement decisions in PA.

In this study, we respond to the above mentioned knowledge gaps by evaluating the air quality and health effects of various coal retirement scenarios in PA. In particular, we contribute by: i) establishing a modeling system with improved representation of cross-regional linkages as key determinants of distributional air quality and health effects from coal plant retirements (Figure 1); and ii) assessing tradeoffs between aggregate and distributional effects across different coal plant retirement strategies.



**Figure 1.** Schematic diagram of our modeling framework and coal retirement scenarios.

## 2. Methodology

### 2.1. Scenario Design

Compared to generation and emissions for the year 2019 (i.e., *Base Case*), we design six counterfactual scenarios that vary across two dimensions: *targets* and *priorities*. We consider two targets—"Capacity-based" (retiring coal-fired power plants until at least 50% of PA's 2019 coal-fired baseline capacity is eliminated) and "Generation-based" (retiring coal-fired power plants until at least 50% of PA's 2019 coal-fired baseline generation is eliminated)—and three priorities—*Cost* (sorting PA's 2019 coal-fired power plants by average annual cost (\$/MWh) and retiring highest-cost plants

until reaching the target); *Environmental Justice* (sorting by the number of Environmental Justice (EJ) Areas within 10 miles of a plant and retiring plants with the most EJ Areas until reaching the target); and *Climate* (sorting by CO<sub>2</sub> emissions intensity and retiring the highest-emitting plants until reaching the target). More information on scenario design and policy relevance is provided in Table 1, the supplementary data file, and Supporting Information 2 (SI2): Section I and Section II: Figure A.1 and Table A.1.

**Table 1.** Summary of scenarios.

Scenario Name		Explanations
<i>Base Case</i>		All coal power plants active based on actual 2019 generation
	<b>Target</b>	<b>Priority</b>
Retirement Scenarios	<i>Capacity-based_Cost</i>	<p><b>Cost:</b></p> <p><b>Policy relevance:</b> Current practice of retirements based primarily on economic and feasibility considerations</p> <p><b>Method:</b> Plants with the highest marginal costs of generation are retired first</p>
	<i>Capacity-based_EJ</i>	<p><b>Capacity-based retirement:</b></p> <p><b>Method:</b> Retire ~50% of total installed coal power capacity in PA</p> <p><b>EJ:</b></p> <p><b>Policy relevance:</b> Policy efforts to prioritize EJ in PA such as the revisions to the Environmental Justice Policy</p> <p><b>Method:</b> Plants with the largest number of EJ Areas* within a 10-mile radius are retired first</p> <p>*<i>Environmental Justice (EJ) Areas are defined by the Pennsylvania Department of Environmental Protection's (PA DEP) as census tracts where at least 20% of individuals live at or below the federal poverty line and/or where at least 30% of the population identifies as a non-white minority.</i><sup>25</sup></p>
	<i>Capacity-based_Climate</i>	<p><b>Climate:</b></p> <p><b>Policy relevance:</b> Policy efforts to reduce emissions such as the Regional Greenhouse Gas Initiative (RGGI)</p> <p><b>Method:</b> Plants with the highest CO<sub>2</sub> emission rates are retired first</p>
	<i>Generation-based_Cost</i>	<p><b>Generation-based retirement:</b></p>
	<i>Generation-based_EJ</i>	<p><b>Method:</b> Retire ~50% of total coal power generation in PA</p>
<i>Generation-based_Climate</i>		Same three priorities as above

## 2.2. Electricity Market Modeling (RPAM)

We use the RGGI + PJM Policy Analysis Model (RPAM) to examine how each coal retirement scenario induces changes in power market and plant-level emissions outcomes within PA and Rest of PJM region (see Supporting Information 1 (SI1) for detailed model description and validation).

RPAM is a multi-market equilibrium model that accounts for critical features of the wholesale power market operated by PJM Interconnection, preexisting state and federal policies, the supply of external renewable energy credits (RECs) from outside of PJM, and abatement and banking from the partially overlapping RGGI allowance market (see SI1: Section II for datasets used to calibrate and

estimate RPAM).<sup>4,26</sup> On the demand-side, there are five aggregate load zones connected by five aggregate transmission lines (SI1: Section II.A). On the supply-side, the model captures capacity and maintenance constrained supply from 845 representative electric generation units (EGUs) aggregated from 3,095 existing power plants in PJM (SI1: Section II.B). The model also predicts new capacity expansion for natural gas, wind, and solar on a state by load zone basis (SI1: Section II.C), considering anticipated annual profits net of annualized capital and financing costs. See SI1 Section II for datasets used to calibrate and estimate RPAM come from several dozen datasets (SI1: Section II) including from PJM Interconnection, S&P Global, EP, EIA, and Census. Subject to capacity, transmission, and policy/market clearing constraints, RPAM maximizes the sum of net benefits to PJM's wholesale customers (i.e., consumer surplus), total profits to PJM electricity producers (i.e., producer surplus) net of the costs of adding new capacity, total abatement costs from non-PJM RGGI states, and total net benefits to holders of RGGI banked allowances. This consideration of total welfare implications distinguishes the RPAM model from other electricity dispatch models that typically only considers the physical cost.<sup>18,20,21,27</sup>

RPAM is solved on an annual time-step from 2016 to 2019. This analysis focuses on 2019, including the Base Case that considers the observed generation fleet and six counterfactual scenarios that update the generation fleet with coal retirements in PA. RPAM reports plant-level emissions from existing power plants in 2019 (CO<sub>2</sub>, SO<sub>2</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, NH<sub>3</sub>, and VOC) (SI1: Section II.I). Emissions from new natural gas power plants added in each state-load zone are assumed to be released evenly across the corresponding sub-region. Emissions from new solar and wind are assumed to be zero.

### 2.3. Air Quality Modeling (ISRM)

Based on plant-level emissions from RPAM, we use the InMAP Source-Receptor Matrix (ISRM) to simulate the impacts on annual average ambient PM<sub>2.5</sub> concentrations. ISRM is derived from thousands of simulations of a reduced-form air quality model, InMAP, which uses meteorology and emissions data from 2005 and average population data spanning from 2008 to 2012 (SI2: Section II.A). ISRM quantifies the impact of one ton of precursor emissions from each individual source location on the ambient PM<sub>2.5</sub> concentration in each receptor location. ISRM assumes a linear relationship between changes in precursor emissions and PM<sub>2.5</sub> concentrations. Despite these simplifications, ISRM provides reasonable estimates for PM<sub>2.5</sub> pollution levels when compared to observational data<sup>28,29</sup> and has been used to assess pollution impacts in many different contexts.<sup>12,22,30</sup>

ISRM includes approximately 52,411 spatial grid cells across the contiguous United States, including roughly 2,297 grid cells in PA and 13,228 grid cells over the PJM region. The grid resolution increases with population density, ranging from 1km x 1km in densely populated urban areas to 48 km x 48 km in remote or rural areas. ISRM inputs are precursor annual emissions of NO<sub>x</sub>, SO<sub>2</sub>, NH<sub>3</sub>, primary PM<sub>2.5</sub>, and VOC for each grid cell, or the sum of plant-level emissions of these pollutants from RPAM for each grid cell. ISRM outputs are the grid-level simulated ambient concentrations of PM<sub>2.5</sub>, including primary and secondary PM<sub>2.5</sub>. Here we assume the pollutants are emitted at the ground level (<57 m), which could lead to overestimation of simulated PM<sub>2.5</sub> concentrations near plants underestimation of pollution levels in downwind regions.

The following equation describes the change in PM<sub>2.5</sub> concentration at receptor location  $b$  ( $\Delta C_b$ ) as a result of changes in emissions in location  $a$ :

$$\Delta C_b = \sum_p \sum_{a=1}^N \Delta E_{a,p} \cdot f_{(a,p)-b} \quad (1)$$

where  $p$  is the primary emitted pollutant (an element of  $P = \{\text{primary PM}_{2.5}, \text{NH}_3, \text{NO}_x, \text{SO}_2, \text{VOC}\}$ );  $\Delta E_{a,p}$  is the change in emissions for source grid cell  $a$  for pollutant type  $p$  emitted; and  $f_{(a,p)-b}$  is the relationship between annual total emissions in location  $a$  and annual average PM<sub>2.5</sub> in location  $b$ . Each InMAP simulation used to generate ISRM involves altering emissions of a specific pollutant from a single source by one ton. Thus, it generates a vector,  $f_{(a,p)}$ , representing impacts on all  $N$  receptors; the  $b^{\text{th}}$  component of this vector is denoted  $f_{(a,p)-b}$ . The total change in ambient PM<sub>2.5</sub> concentration ( $\mu\text{g}/\text{m}^3$ ) at location  $b$  is the aggregate impact from all precursor emissions and all locations.<sup>28</sup>

#### 2.4. Health Impact Assessment (BenMAP)

We use the U.S. EPA's Benefits Mapping and Analysis Program (BenMAP) model<sup>31</sup> to assess premature deaths associated with long-term exposure to ambient PM<sub>2.5</sub>.<sup>32</sup> BenMAP has been applied widely in health impact assessment.<sup>10,21,33-37</sup> BenMAP inputs include county and census tract averaged PM<sub>2.5</sub> concentrations calculated using the gridded concentrations from ISRM; outputs are annual total PM<sub>2.5</sub>-attributable deaths at the county and census tract levels. For our county-level analysis, we use gridded ISRM results to calculate population-weighted county-average PM<sub>2.5</sub> concentrations. If the ISRM grid size is smaller than a county, we calculate the population weighted average PM<sub>2.5</sub> concentrations for the county using multiple ISRM grids. For the geographic analysis in 3.4, we use ISRM results to calculate census-tract level PM<sub>2.5</sub> concentrations. If the census tract size is smaller than the ISRM grid, we use the same PM<sub>2.5</sub> concentration for all census tracts within one ISRM grid.

BenMAP uses the following log-linear health impact function to calculate changes in all-cause mortality attributable to ambient PM<sub>2.5</sub> exposure<sup>38</sup>, with detailed information in Table 2:

$$\Delta Y = (1 - e^{-\beta \cdot \Delta PM}) \cdot Y_0 \cdot Pop \quad (2)$$

**Table 2.** Summary of input data for the health impact assessment.

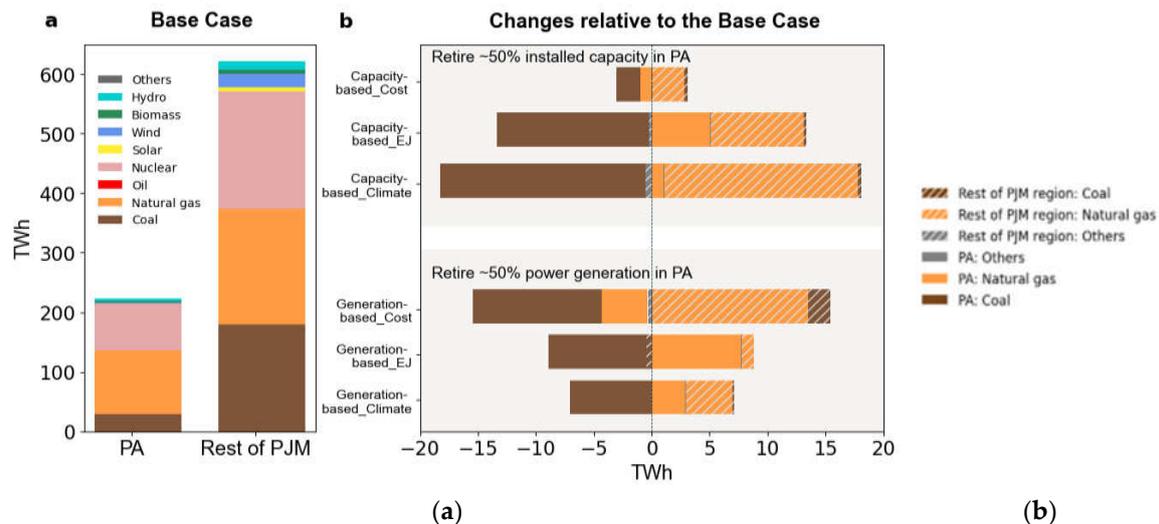
Variable*	Definition	Data Source
$Y_0$	All-cause baseline mortality rate for 2019	Center for Disease Control (CDC) WONDER database.
$Pop$	Population in 2019	2010 U.S. Census Bureau census block data with projection to 2019
$\beta$	Concentration-Response coefficient from epidemiological studies. Changes in mortality risk resulting from changes in PM <sub>2.5</sub> exposure level	The main results use the estimate from the American Cancer Society. <sup>39</sup> The sensitivity analyses use the estimates from Laden et al. 2006 <sup>40</sup> and Thurston et al. 2016. <sup>41</sup>
$\Delta PM$	Changes in PM <sub>2.5</sub> concentration in a coal retirement scenario relative to the <i>Base Case</i>	County or census-tract level PM <sub>2.5</sub> concentrations averaged from gridded concentrations simulated by ISRM

\* For more detailed information on these variables, see the BenMAP manual.<sup>38</sup> \*\* For additional information on sensitivity analyses using other concentration-response functions and  $\beta$  values, see SI2: Section IV.

### 3. Results

#### 3.1. Impacts on Electricity Generation

Coal-fired power plants account for 13% and 12% of total generation in PA and the rest of PJM, respectively in the *Base Case* (Figure 2a). Retiring coal-fired power plants in PA based on capacity or generation targets have different impacts on the power system. For the "Capacity-based" scenarios, declines in coal-fired electricity generation in PA vary substantially by 2.1 TWh, 13 TWh, and 18 TWh in the *Cost*, *EJ*, and *Climate* scenarios, respectively, relative to the *Base Case* (Figure 2b). This variation is primarily influenced by disparities in *Base Case* utilization rates. For instance, coal plants retired in the *Capacity-based\_Cost* scenario have lower utilization rates on average than the other two "Capacity-based" scenarios. However, reductions in coal-fired electricity generation are roughly the same across all "Generation-based" scenarios which implicitly control for variation in utilization rates.

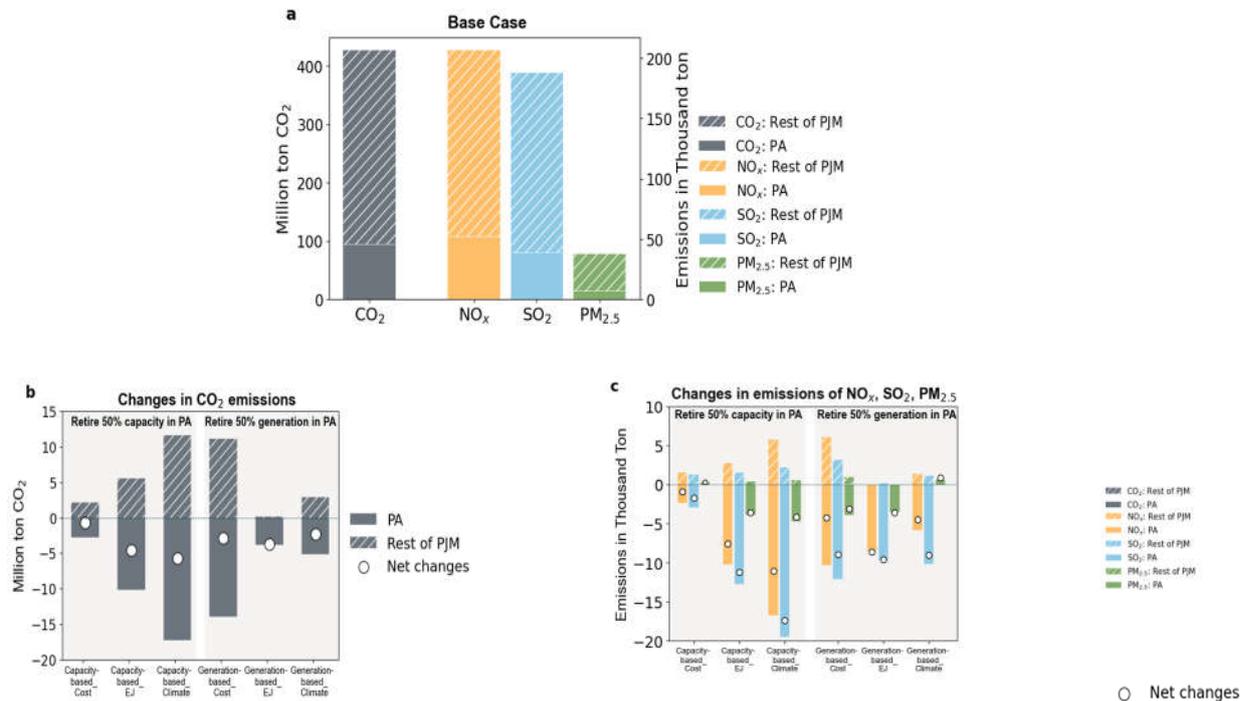


**Figure 2. Electricity generation (TWh) by fuel source.** Panel (a) depicts *Base Case* electricity generation in PA and Rest of PJM. Panel (b) reports changes in generation relative to the *Base Case* for the six scenarios in PA and Rest of PJM by power plant source (Coal, Natural Gas, and Others). “Others” in Panel (b) refers to generation from all non-coal or natural gas sources.

Coal power plant retirements in PA drive changes in the transmission constrained dispatch of power both within and between PA and Rest of PJM. These changes are driven by: (i) the amount of coal generation displaced by retirements; (ii) the marginal costs and available capacities of remaining units; and (iii) the location of retired generation and associated transmission constraints. Generally, our results are similar to findings in previous studies<sup>42</sup> that coal retirements in PA lead to an increase in dispatch from natural gas plants, because dispatching existing plants is cheaper than installing new capacity to make up for foregone generation and natural gas plants are dispatched more often due to their cost advantage (Figure 2b). However, the scale and location of additional generation may be affected by changes in transmission congestion. For instance, in the *Generation-based\_Cost* scenario, natural gas-based generation in PA also declines slightly.

### 3.2. Impacts on Emissions of CO<sub>2</sub> and Other Air Pollutants

Our main results focus on emissions of CO<sub>2</sub>, due to its climate impacts, and of SO<sub>2</sub>, NO<sub>x</sub>, and PM<sub>2.5</sub> because prior studies found these three pollutants to be the most important precursors from the power sector, contributing to 81%, 12%, and 6% of ambient PM<sub>2.5</sub>, respectively at the national level.<sup>28</sup> (SI2: Figure B.2 provides results for NH<sub>3</sub> and VOC, which contribute 0.2% and 0.1% to ambient PM<sub>2.5</sub>, respectively). In the *Base Case*, we estimate annual total CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub>, and PM<sub>2.5</sub> emissions from all power plants in the PJM region to be 426 million tons, 206 thousand tons, 187 thousand tons, and 38 thousand tons, respectively, of which 17 to 25% are from PA plants (Figure 3a).

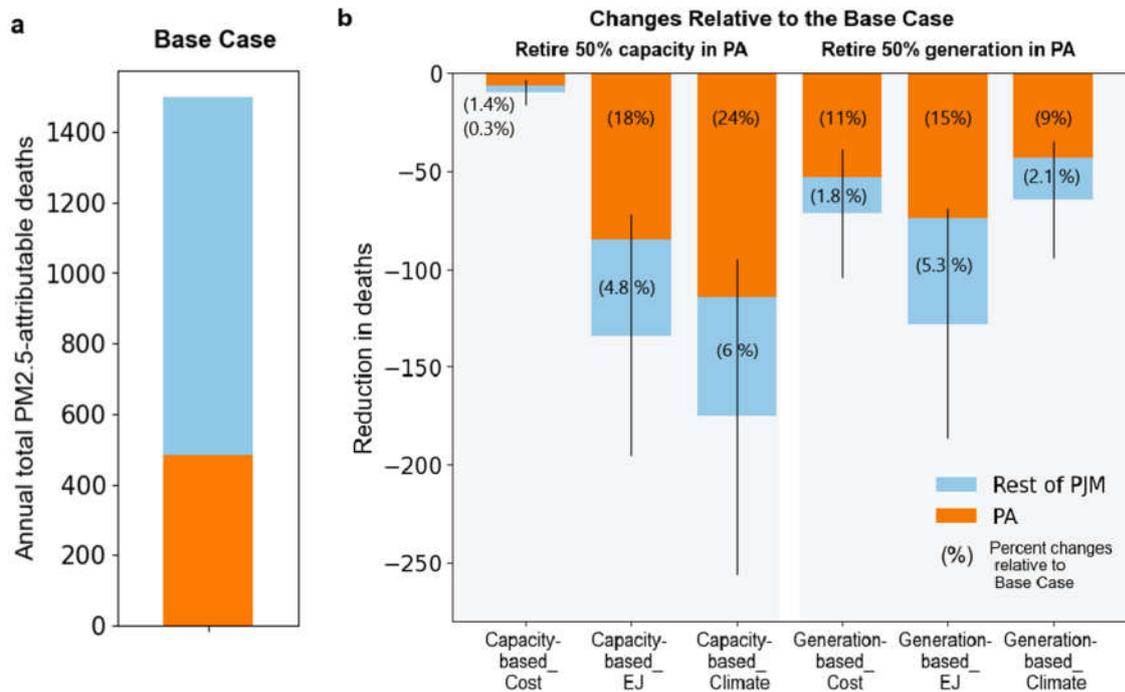


**Figure 3.** Annual total emissions of CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub>, and PM<sub>2.5</sub> from all power plants located in PA and Rest of PJM. Panel (a) reports emissions under the *Base Case*; Panels (b) and (c) show the changes in CO<sub>2</sub> and criteria air pollutants in each of the six retirement scenarios relative to the *Base Case*. The white circles show the net change across the whole PJM region. Results for NH<sub>3</sub> and VOC are reported in SI2: Figure B.2.

Although all six scenarios reduce CO<sub>2</sub> and air pollutant emissions in aggregate across PJM relative to the *Base Case*, the spatial distribution of emissions changes varies considerably across scenarios (Figure 3b and Figure 3c). As noted above, changes in the spatial pattern of precursor emissions follow from changes in power generation which, in turn, through ISRM, correspond to changes in the spatial pattern of receptor emissions. Reductions in coal power generation in PA largely explain observed declines in emissions there. For example, the *Capacity-based\_Climate* scenario leads to the largest reduction in coal-fired electricity generation and thus emissions in PA of 18% for CO<sub>2</sub>, 50% for SO<sub>2</sub>, 32% for NO<sub>x</sub>, and 75% for PM<sub>2.5</sub>. Changes in power generation in Rest of PJM also largely explain changes in emissions there. For example, we find almost no emissions increase in Rest of PJM in the *Generation-based\_EJ* scenario (Figure 3b and Figure 3c) consistent with the negligible change in generation there (Figure 2b). However, in the *Capacity-based\_Cost* scenario, we find small increases in CO<sub>2</sub> (0.6%), NO<sub>x</sub> (0.9%), SO<sub>2</sub> (0.8%), and PM<sub>2.5</sub> (0.6%) emissions due to more substantial increases in natural gas generation in Rest of PJM (Figure 2b).

### 3.3. Impacts on Ambient PM<sub>2.5</sub> Concentrations and PM<sub>2.5</sub>-Attributable Deaths

In the *Base Case*, power sector emissions from all electricity generation in PJM result in an annual PM<sub>2.5</sub> concentration of up to 5.9 µg/m<sup>3</sup> across PJM counties, which is associated with 1,500 PM<sub>2.5</sub>-attributable deaths annually (95% confidence interval: 1,400 to 1,600) (Figure 4a). The low concentration level results from estimating the effects only from power sector emissions, while other sectors, such as transportation and residential, contribute additional pollution in this region.<sup>10,42,43</sup>



**Figure 4.** Annual total PM<sub>2.5</sub>-attributable deaths from power sector emissions in the *Base Case* (Panel a) and the changes in the six coal retirement scenarios relative to the *Base Case* in PA and Rest of PJM (Panel b). Here we use the concentration-response coefficients from Krewski et al., 2009.<sup>39</sup> Error bars represent the estimates based on the 95% confidence interval of the concentration-response coefficients for the total deaths throughout the whole PJM region.

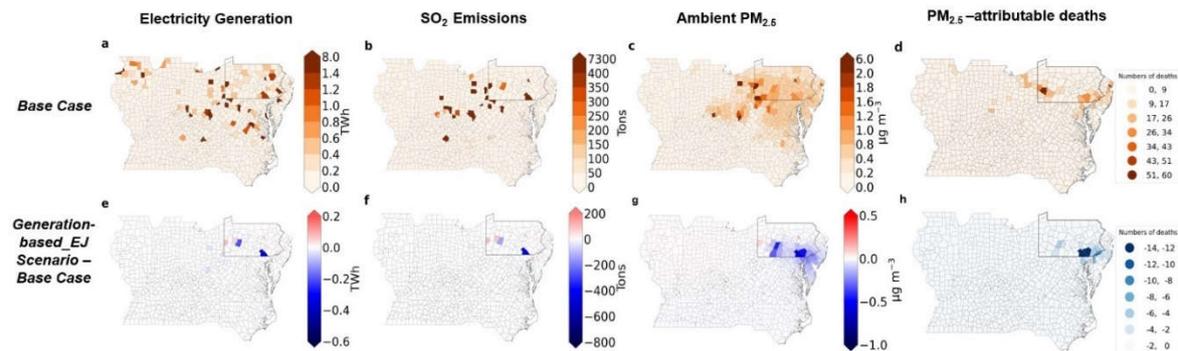
Although changes in precursor emissions are negative in some counties and positive in others depending on the scenario, almost all counties experience a reduction in ambient PM<sub>2.5</sub> concentrations and associated deaths relative to the *Base Case* (see SI2, Table B.2 for population-weighted annual average PM<sub>2.5</sub>-concentrations by scenario). This is because retired coal plants are often more polluting than the generation that replaces them (such as natural gas), causing precursor emissions to fall in aggregate across PJM. Despite spatial variation in precursor emissions from retired and replacement generation predicted by RPAM and corresponding spatial variation in receptor emissions arising from air pollution formation and transport via ISRM, the aggregate decline in precursor emissions dominates, leading to lower ambient PM<sub>2.5</sub> concentrations and associated deaths for most counties in the southeast of PA.

Nonetheless, these complex linkages, together with differences in socio-demographics that characterize pollution exposure across counties, cumulatively determine the magnitude and distribution of avoided PM<sub>2.5</sub>-attributable deaths (see SI2: Table C.3 for absolute changes in PM<sub>2.5</sub>-attributable deaths relative to the *Base Case*). Of the six scenarios, *Capacity-based\_Climate* reduces PM<sub>2.5</sub> concentrations and associated deaths the most: by 114 in PA (95% CI: 61 to 121) or 24% relative to the *Base Case*. Rest of PJM also observes a reduction of 61 PM<sub>2.5</sub>-attributable deaths (95% CI: 45 to 90) or 6% relative to the *Base Case* (Figure 4b).

### 3.4. Insights on Geographic Distribution and Environmental Justice Communities

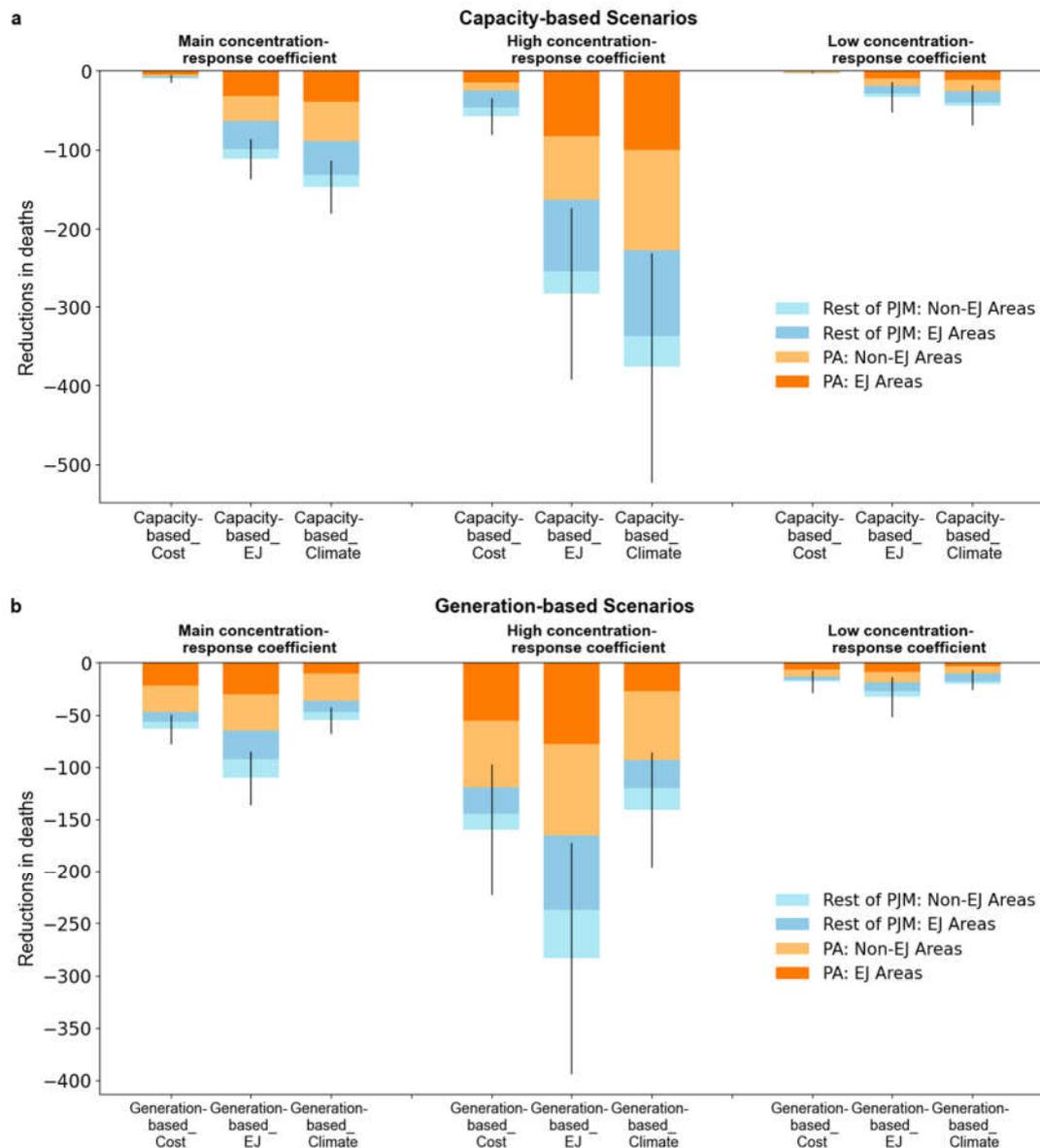
We find important spatial variation across the PJM region regarding the patterns of electricity generation, air pollutant emissions, ambient concentrations of PM<sub>2.5</sub>, and PM<sub>2.5</sub>-attributable deaths. Here, we focus on the results for the *Generation-based\_EJ* scenario (Figure 5), with results for the other scenarios provided in SI2: Figures C.3-D.4. Under this scenario, the majority of health benefits in Rest of PJM occur in PA's southern neighbors Delaware, Maryland, and New Jersey. Thus, regional

impacts are still largely determined by close proximity to PA coal plant closures (see SI2: Figure G.7 for an expanded air quality assessment that also includes states outside PJM).



**Figure 5. Geographical distribution of impacts.** The first row provides results for the *Base Case*; The second row shows the changes in the *Generation-based\_EJ* scenario relative to the *Base Case*. From left to right, the four columns depict county-level annual total electricity generation, annual total SO<sub>2</sub> emissions from power generation, simulated county-level annual average ambient PM<sub>2.5</sub> concentrations, and annual total PM<sub>2.5</sub>-attributable deaths. SI2: Figures C.3 and D.4 provide results for other five scenarios, and SI2: Figures E.5 and F.6 report results for NO<sub>x</sub> and Primary PM<sub>2.5</sub> emissions for each of the six scenarios.

To further understand the potential equity implications of PA coal plant closures, we compare the health effects in EJ Areas and non-EJ Areas. Since the PA Department of Environmental Protection defines EJ Areas based on census tracts, we perform a health impact assessment at the census tract level using gridded PM<sub>2.5</sub> concentrations from ISRM. This analysis is limited by the fact that some census tracts are smaller than ISRM grids and so is unable to identify exposure disparities across different census tracts in such circumstances. At the same time, we also consider sensitivity in concentration-response coefficients ( $\beta$ ) which are one of the largest sources of uncertainty in health assessment<sup>44-46</sup> (see Figure 6). We find the two *EJ* scenarios provide more benefits to PA EJ Areas relative to other scenarios, highlighting the immediate advantage of retirement strategies designed to reduce *in situ* exposure to vulnerable populations. However, we also find that these two scenarios have the potential to provide substantial health benefits to EJ Areas in Rest of PJM (extending PA's EJA definition to Rest of PJM). Although these scenarios do not consider constraints to "safeguard" EJ Areas in Rest of PJM from experiencing worse exposure outcomes, they demonstrate potential equity co-benefits from coal plant retirements in PA to downwind EJ Areas in Rest of PJM. Higher or lower  $\beta$ , may amplify or attenuate these changes but they do not absolve them, nor affect the proportion of avoided deaths in EJ Areas in PA and Rest of PJM, respectively.



**Figure 6.** Reduction in deaths at the census tract-level from power sector emissions using different concentration-response coefficients. (Panel a) shows reduction in deaths “Capacity-based” scenarios and (Panel b) shows “Generation-based” scenarios. Premature deaths estimated based on the concentration-response coefficients in Krewski et al. 2009 (main concentration)<sup>39</sup>, Laden et al. 2006 (high concentration)<sup>40</sup>, and Thurston et al. 2016 (low concentration).<sup>41</sup> We categorize census tracts based on their location (PA vs. Rest of PJM) and if they are EJ Areas or non-EJ Areas. Error bars show the 95% confidence interval of the concentration-response coefficients.

## 4. Discussion

### 4.1. Directions for Future Work

Our study examines the distributional air quality and health effects of coal power plant retirements in PA. In conducting this analysis, we also identify four important areas for future work. First, how can modeling frameworks be improved to assess finer-scale decisions, impacts and disparities? While our analysis focuses on annual aggregate impacts due to the time step of RPAM, a finer temporal resolution would be useful to understand power dispatch and transmission decisions, short-term pollution events, and acute health impacts such as morbidity and hospital admissions. Further, our current approach involves a one-way coupling from energy to air quality and then to

health. Thus, our model takes pre-designed scenarios that do not optimize the energy system to achieve health or equity objectives. Future research that optimizes scenario design based on health (or other priorities) may provide valuable policy insights. Second, how will coal retirement decisions interact with other trends in electricity and end-use sectors to collectively shape air quality and health outcomes? While we focus only on coal retirements in PA, increased renewable penetration and accelerated adoption of electric vehicles, heat pumps, and other energy efficient durable goods may significantly alter future electricity and energy consumption with difficult-to-predict impacts on air quality and health. Third, how do varying sources of uncertainty influence environmental impact assessment? Uncertainties exist in the energy system (policy implementation, behavioral response, future technology choices, etc.)<sup>47-49</sup>, air quality modelling (chemical and physical transport processes, spatial distribution of different groups, etc.),<sup>50-52</sup> and health impact assessment (baseline health conditions, health attributes of different groups, etc.)<sup>53,54</sup>. Finally, in SI2 we monetize air quality and health impacts (see Table F.6 and Table G.7) and changes in operational costs across PJM (see Table E.5 for relevant RPAM costs). Extending this analysis to conduct a comprehensive equity and cost-benefit assessment that includes climate damages, sunk capital costs, and broader economy-wide socioeconomic impacts of coal retirement may be a useful direction for future research.

#### 4.2. Policy Implications

The results from our analysis have important policy implications. At the regional level, regional transmission organizations (RTOs) have historically affected retirement decisions through capacity and energy market design and reliability rules. For example, PJM affects plant retirements primarily through identification of “Reliability Must Run” units—those for which deactivation is delayed to “preserve reliability”.<sup>55</sup> At the national level, the Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC) affect retirements through rate regulation and analyses of the reliability implications of rapid coal and nuclear plant retirements. Federal and RTO rules that delay cost-based deactivations delay coal power plant retirements, constraining emissions and health benefits achieved under *Cost* scenarios and blocking potential benefits from *EJ* and *Climate* scenarios. New rules should consider factors beyond reliability, such as EJ and health impacts of delayed deactivation, and prioritize reliability solutions that would enhance these impacts.

At the state level, PA policy affects coal power plant retirements in many ways, including approving the siting of new high-voltage transmission lines.<sup>56</sup> As we find that retirements targeting EJ Areas in PA provide the greatest health benefits to those areas, impediments to new transmission infrastructure may delay these benefits. Further, heightened review requirements for new projects may delay the closure of coal plants and corresponding benefits to EJ Areas. More broadly, PA’s energy transition will affect the spatial and temporal pattern of health benefits, including to EJ Areas. PA’s entry into RGGI could lead to retirements similar to those in the *Climate* scenarios, despite the November 2023 Commonwealth Court decision that currently blocks PA’s entry.<sup>57</sup> If PA successfully appeals this decision and enters RGGI, it may also wish to consider allowance auction revenue recycling schemes that address the disparate impacts of such retirements across PA and, possibly, Rest of PJM.

#### 4.3. Conclusion

Market and environmental shifts in U.S. electricity production demand a careful analysis of transitions in key states like PA and across grid regions like PJM Interconnection. Using energy systems and health impact modeling, this study explores the consequences of retiring coal-fired power plants in PA and PJM. Natural gas often replaces coal, reducing overall air pollution. Spatial analysis highlights air quality variations, emphasizing the need for pre-retirement impact assessments. Prioritizing plant closures near population centers or EJ Areas maximizes health benefits (when retired generation is held constant), presenting an opportunity for low-carbon energy transitions to improve environmental and health outcomes for historically disadvantaged communities.

**Supplementary Materials:** The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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## References

1. Linn, J.; McCormack, K. The Roles of Energy Markets and Environmental Regulation in Reducing Coal-fired Plant Profits and Electricity Sector Emissions. *The RAND Journal of Economics* **2019**, *50* (4), 733–767. <https://doi.org/10.1111/1756-2171.12294>.
2. *Electricity explained* - U.S. Energy Information Administration (EIA). <https://www.eia.gov/energyexplained/electricity/> (accessed 2023-06-09).
3. U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. <https://www.eia.gov/state/analysis.php?sid=PA#55> (accessed 2023-06-22).
4. An T. Pham, and Seth A. Blumsack. *Understanding The Direct and Strategic Effects Voluntary Entry into Regional Cap and Trade Systems*. RGGI\_Manuscript.pdf. Google Docs. [https://drive.google.com/file/d/1SgLfBHHYmPg2Tx9ukB82\\_SQ6ODTYOv\\_X/view?usp=sharing&usp=embed\\_facebook](https://drive.google.com/file/d/1SgLfBHHYmPg2Tx9ukB82_SQ6ODTYOv_X/view?usp=sharing&usp=embed_facebook) (accessed 2023-06-09).
5. Blumsack, S. Prospects for Pennsylvania in the Regional Greenhouse Gas Initiative Working Paper, December 2020. **2020**.
6. *Coal and the environment* - U.S. Energy Information Administration (EIA). <https://www.eia.gov/energyexplained/coal/coal-and-the-environment.php> (accessed 2023-06-09).
7. Filonchyk, M.; Peterson, M. P. An Integrated Analysis of Air Pollution from US Coal-Fired Power Plants. *Geoscience Frontiers* **2023**, *14* (2), 101498. <https://doi.org/10.1016/j.gsf.2022.101498>.
8. Mayfield, E. N. Phasing out Coal Power Plants Based on Cumulative Air Pollution Impact and Equity Objectives in Net Zero Energy System Transitions. *Environ. Res.: Infrastruct. Sustain.* **2022**, *2* (2), 021004. <https://doi.org/10.1088/2634-4505/ac70f6>.
9. Fan, M.; Wang, Y. The Impact of PM<sub>2.5</sub> on Mortality in Older Adults: Evidence from Retirement of Coal-Fired Power Plants in the United States. *Environ Health* **2020**, *19* (1), 28. <https://doi.org/10.1186/s12940-020-00573-2>.
10. Fann, N.; Fulcher, C. M.; Baker, K. The Recent and Future Health Burden of Air Pollution Apportioned Across U.S. Sectors. *Environ. Sci. Technol.* **2013**, *47* (8), 3580–3589. <https://doi.org/10.1021/es304831q>.
11. Fann, N.; Fulcher, C. M.; Hubbell, B. J. The Influence of Location, Source, and Emission Type in Estimates of the Human Health Benefits of Reducing a Ton of Air Pollution. *Air Qual Atmos Health* **2009**, *2* (3), 169–176. <https://doi.org/10.1007/s11869-009-0044-0>.
12. Thind, M. P. S.; Tessum, C. W.; Azevedo, I. L.; Marshall, J. D. Fine Particulate Air Pollution from Electricity Generation in the US: Health Impacts by Race, Income, and Geography. *Environ. Sci. Technol.* **2019**, *53* (23), 14010–14019. <https://doi.org/10.1021/acs.est.9b02527>.
13. Martenies, S. E.; Akherati, A.; Jathar, S.; Magzamen, S. Health and Environmental Justice Implications of Retiring Two Coal-Fired Power Plants in the Southern Front Range Region of Colorado. *GeoHealth* **2019**, *3* (9), 266–283. <https://doi.org/10.1029/2019GH000206>.
14. Henneman, L. R. F.; Rasel, M. M.; Choirat, C.; Anenberg, S. C.; Zigler, C. Inequitable Exposures to U.S. Coal Power Plant-Related PM<sub>2.5</sub>: 22 Years and Counting. *Environ Health Perspect* **2023**, *131* (3), 037005. <https://doi.org/10.1289/EHP11605>.
15. Polonik, P.; Rieke, K.; Reese, S.; Burney, J. Air Quality Equity in US Climate Policy. *Proc. Natl. Acad. Sci. U.S.A.* **2023**, *120* (26), e2217124120. <https://doi.org/10.1073/pnas.2217124120>.
16. Goforth, T.; Nock, D. Air Pollution Disparities and Equality Assessments of US National Decarbonization Strategies. *Nat Commun* **2022**, *13* (1), 7488. <https://doi.org/10.1038/s41467-022-35098-4>.
17. Dimanchev, E. G.; Paltsev, S.; Yuan, M.; Rothenberg, D.; Tessum, C. W.; Marshall, J. D.; Selin, N. E. Health Co-Benefits of Sub-National Renewable Energy Policy in the US. *Environ. Res. Lett.* **2019**, *14* (8), 085012. <https://doi.org/10.1088/1748-9326/ab31d9>.
18. Deetjen, T. A.; Azevedo, I. L. Climate and Health Benefits of Rapid Coal-to-Gas Fuel Switching in the U.S. Power Sector Offset Methane Leakage and Production Cost Increases. *Environ. Sci. Technol.* **2020**, *54* (18), 11494–11505. <https://doi.org/10.1021/acs.est.9b06499>.

19. Bin Thaneya, A.; Horvath, A. Exploring Regional Fine Particulate Matter (PM<sub>2.5</sub>) Exposure Reduction Pathways Using an Optimal Power Flow Model: The Case of the Illinois Power Grid. *Environ. Sci. Technol.* **2023**, *57* (21), 7989–8001. <https://doi.org/10.1021/acs.est.2c08698>.
20. Sergi, B. J.; Adams, P. J.; Muller, N. Z.; Robinson, A. L.; Davis, S. J.; Marshall, J. D.; Azevedo, I. L. Optimizing Emissions Reductions from the U.S. Power Sector for Climate and Health Benefits. *Environ. Sci. Technol.* **2020**, *54* (12), 7513–7523. <https://doi.org/10.1021/acs.est.9b06936>.
21. Luo, Q.; Copeland, B.; Garcia-Menendez, F.; Johnson, J. X. Diverse Pathways for Power Sector Decarbonization in Texas Yield Health Cobenefits but Fail to Alleviate Air Pollution Exposure Inequities. *Environ. Sci. Technol.* **2022**, *56* (18), 13274–13283. <https://doi.org/10.1021/acs.est.2c00881>.
22. Yang, H.; Pham, A. T.; Landry, J. R.; Blumsack, S. A.; Peng, W. Emissions and Health Implications of Pennsylvania's Entry into the Regional Greenhouse Gas Initiative. *Environ. Sci. Technol.* **2021**, *55* (18), 12153–12161. <https://doi.org/10.1021/acs.est.1c02797>.
23. Hernandez-Cortes, D.; Meng, K. C. Do Environmental Markets Cause Environmental Injustice? Evidence from California's Carbon Market. *Journal of Public Economics* **2023**, *217*, 104786. <https://doi.org/10.1016/j.jpubeco.2022.104786>.
24. Peng, W.; Ou, Y. Integrating Air Quality and Health Considerations into Power Sector Decarbonization Strategies. *Environ. Res. Lett.* **2022**, *17* (8), 081002. <https://doi.org/10.1088/1748-9326/ac8361>.
25. PA Environmental Justice Areas. Department of Environmental Protection. <https://www.dep.pa.gov/443/PublicParticipation/OfficeofEnvironmentalJustice/Pages/PA-Environmental-Justice-Areas.aspx> (accessed 2023-06-15).
26. Welcome | RGGI, Inc. <https://www.rggi.org/> (accessed 2023-06-22).
27. Kerl, P. Y.; Zhang, W.; Moreno-Cruz, J. B.; Nenes, A.; Realff, M. J.; Russell, A. G.; Sokol, J.; Thomas, V. M. New Approach for Optimal Electricity Planning and Dispatching with Hourly Time-Scale Air Quality and Health Considerations. *Proceedings of the National Academy of Sciences* **2015**, *112* (35), 10884–10889. <https://doi.org/10.1073/pnas.1413143112>.
28. Goodkind, A. L.; Tessum, C. W.; Coggins, J. S.; Hill, J. D.; Marshall, J. D. Fine-Scale Damage Estimates of Particulate Matter Air Pollution Reveal Opportunities for Location-Specific Mitigation of Emissions. *Proc. Natl. Acad. Sci. U.S.A.* **2019**, *116* (18), 8775–8780. <https://doi.org/10.1073/pnas.1816102116>.
29. Wang, Y.; Apte, J. S.; Hill, J. D.; Ivey, C. E.; Patterson, R. F.; Robinson, A. L.; Tessum, C. W.; Marshall, J. D. Location-Specific Strategies for Eliminating US National Racial-Ethnic PM<sub>2.5</sub> Exposure Inequality. *Proc. Natl. Acad. Sci. U.S.A.* **2022**, *119* (44), e2205548119. <https://doi.org/10.1073/pnas.2205548119>.
30. Bin Thaneya, A.; S Apte, J.; Horvath, A. A Human Exposure-Based Traffic Assignment Model for Minimizing Fine Particulate Matter (PM<sub>2.5</sub>) Intake from on-Road Vehicle Emissions. *Environ. Res. Lett.* **2022**, *17* (7), 074034. <https://doi.org/10.1088/1748-9326/ac78f6>.
31. US EPA, O. *Environmental Benefits Mapping and Analysis Program - Community Edition (BenMAP-CE)*. <https://www.epa.gov/benmap> (accessed 2023-06-15).
32. Sacks, J. D.; Lloyd, J. M.; Zhu, Y.; Anderton, J.; Jang, C. J.; Hubbell, B.; Fann, N. The Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE): A Tool to Estimate the Health and Economic Benefits of Reducing Air Pollution. *Environmental Modelling & Software* **2018**, *104*, 118–129. <https://doi.org/10.1016/j.envsoft.2018.02.009>.
33. Mirzaei, A.; Tahriri, H.; Khorsandi, B. Comparison between AirQ+ and BenMAP-CE in Estimating the Health Benefits of PM<sub>2.5</sub> Reduction. *Air Qual Atmos Health* **2021**, *14* (6), 807–815. <https://doi.org/10.1007/s11869-021-00980-5>.
34. Yang, P.; Zhang, Y.; Wang, K.; Doraiswamy, P.; Cho, S.-H. Health Impacts and Cost-Benefit Analyses of Surface O<sub>3</sub> and PM<sub>2.5</sub> over the U.S. under Future Climate and Emission Scenarios. *Environmental Research* **2019**, *178*, 108687. <https://doi.org/10.1016/j.envres.2019.108687>.
35. Fann, N.; Rislely, D. The Public Health Context for PM<sub>2.5</sub> and Ozone Air Quality Trends. *Air Qual Atmos Health* **2013**, *6* (1), 1–11. <https://doi.org/10.1007/s11869-010-0125-0>.
36. Pungler, E. M.; West, J. J. The Effect of Grid Resolution on Estimates of the Burden of Ozone and Fine Particulate Matter on Premature Mortality in the USA. *Air Qual Atmos Health* **2013**, *6* (3), 563–573. <https://doi.org/10.1007/s11869-013-0197-8>.
37. Li, Y.; Henze, D. K.; Jack, D.; Kinney, P. L. The Influence of Air Quality Model Resolution on Health Impact Assessment for Fine Particulate Matter and Its Components. *Air Qual Atmos Health* **2016**, *9* (1), 51–68. <https://doi.org/10.1007/s11869-015-0321-z>.

38. US EPA, O. *BenMAP-CE Manual and Appendices*. <https://www.epa.gov/benmap/benmap-ce-manual-and-appendices> (accessed 2023-06-15).
39. Krewski, D.; Jerrett, M.; Burnett, R. T.; Ma, R.; Shi, Y.; Turner, M. C.; Iii, C. A. P.; Thurston, G.; Calle, E. E.; Thun, M. J. Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality. **2009**.
40. Laden, F.; Schwartz, J.; Speizer, F. E.; Dockery, D. W. Reduction in Fine Particulate Air Pollution and Mortality: Extended Follow-up of the Harvard Six Cities Study. *Am J Respir Crit Care Med* **2006**, *173* (6), 667–672. <https://doi.org/10.1164/rccm.200503-443OC>.
41. Thurston, G. D.; Ahn, J.; Cromar, K. R.; Shao, Y.; Reynolds, H. R.; Jerrett, M.; Lim, C. C.; Shanley, R.; Park, Y.; Hayes, R. B. Ambient Particulate Matter Air Pollution Exposure and Mortality in the NIH-AARP Diet and Health Cohort. *Environ Health Perspect* **2016**, *124* (4), 484–490. <https://doi.org/10.1289/ehp.1509676>.
42. Russell, M. C.; Belle, J. H.; Liu, Y. The Impact of Three Recent Coal-Fired Power Plant Closings on Pittsburgh Air Quality: A Natural Experiment. *Journal of the Air & Waste Management Association* **2017**, *67* (1), 3–16. <https://doi.org/10.1080/10962247.2016.1170738>.
43. Tessum, C. W.; Apte, J. S.; Goodkind, A. L.; Muller, N. Z.; Mullins, K. A.; Paoella, D. A.; Polasky, S.; Springer, N. P.; Thakrar, S. K.; Marshall, J. D.; Hill, J. D. Inequity in Consumption of Goods and Services Adds to Racial–Ethnic Disparities in Air Pollution Exposure. *Proc. Natl. Acad. Sci. U.S.A.* **2019**, *116* (13), 6001–6006. <https://doi.org/10.1073/pnas.1818859116>.
44. Kodros, J. K.; Carter, E.; Brauer, M.; Volckens, J.; Bilsback, K. R.; L'Orange, C.; Johnson, M.; Pierce, J. R. Quantifying the Contribution to Uncertainty in Mortality Attributed to Household, Ambient, and Joint Exposure to PM<sub>2.5</sub> From Residential Solid Fuel Use. *GeoHealth* **2018**, *2* (1), 25–39. <https://doi.org/10.1002/2017GH000115>.
45. Burnett, R.; Cohen, A. Relative Risk Functions for Estimating Excess Mortality Attributable to Outdoor PM<sub>2.5</sub> Air Pollution: Evolution and State-of-the-Art. *Atmosphere* **2020**, *11* (6), 589. <https://doi.org/10.3390/atmos11060589>.
46. Burnett, R. T.; Pope, C. A.; Ezzati, M.; Olives, C.; Lim, S. S.; Mehta, S.; Shin, H. H.; Singh, G.; Hubbell, B.; Brauer, M.; Anderson, H. R.; Smith, K. R.; Balmes, J. R.; Bruce, N. G.; Kan, H.; Laden, F.; Prüss-Ustün, A.; Turner, M. C.; Gapstur, S. M.; Diver, W. R.; Cohen, A. An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure. *Environ Health Perspect* **2014**, *122* (4), 397–403. <https://doi.org/10.1289/ehp.1307049>.
47. Bridges, A.; Felder, F. A.; McKelvey, K.; Niyogi, I. Uncertainty in Energy Planning: Estimating the Health Impacts of Air Pollution from Fossil Fuel Electricity Generation. *Energy Research & Social Science* **2015**, *6*, 74–77. <https://doi.org/10.1016/j.erss.2014.12.002>.
48. Bistline, J. E. Electric Sector Capacity Planning under Uncertainty: Climate Policy and Natural Gas in the US. *Energy Economics* **2015**, *51*, 236–251. <https://doi.org/10.1016/j.eneco.2015.07.008>.
49. Bistline, J. E. Natural Gas, Uncertainty, and Climate Policy in the US Electric Power Sector. *Energy Policy* **2014**, *74*, 433–442. <https://doi.org/10.1016/j.enpol.2014.08.017>.
50. Molitor, J.; Jerrett, M.; Chang, C.-C.; Molitor, N.-T.; Gauderman, J.; Berhane, K.; McConnell, R.; Lurmann, F.; Wu, J.; Winer, A.; Thomas, D. Assessing Uncertainty in Spatial Exposure Models for Air Pollution Health Effects Assessment. *Environmental Health Perspectives* **2007**, *115* (8), 1147–1153. <https://doi.org/10.1289/ehp.9849>.
51. Özkaynak, H.; Frey, H. C.; Burke, J.; Pinder, R. W. Analysis of Coupled Model Uncertainties in Source-to-Dose Modeling of Human Exposures to Ambient Air Pollution: A PM<sub>2.5</sub> Case Study. *Atmospheric Environment* **2009**, *43* (9), 1641–1649. <https://doi.org/10.1016/j.atmosenv.2008.12.008>.
52. Gerharz, L. E.; Klemm, O.; Broich, A. V.; Pebesma, E. Spatio-Temporal Modelling of Individual Exposure to Air Pollution and Its Uncertainty. *Atmospheric Environment* **2013**, *64*, 56–65. <https://doi.org/10.1016/j.atmosenv.2012.09.069>.
53. Mesa-Frias, M.; Chalabi, Z.; Vanni, T.; Foss, A. M. Uncertainty in Environmental Health Impact Assessment: Quantitative Methods and Perspectives. *International Journal of Environmental Health Research* **2013**, *23* (1), 16–30. <https://doi.org/10.1080/09603123.2012.678002>.
54. Briggs, D. J.; Sabel, C. E.; Lee, K. Uncertainty in Epidemiology and Health Risk and Impact Assessment. *Environ Geochem Health* **2009**, *31* (2), 189–203. <https://doi.org/10.1007/s10653-008-9214-5>.
55. *PJM - Ensuring a Reliable Energy Transition*. <https://www.pjm.com/about-pjm/ensuring-a-reliable-energy-transition> (accessed 2023-12-12).

56. Transmission\_Lines.Pdf. [https://www.puc.pa.gov/general/consumer\\_ed/pdf/Transmission\\_Lines.pdf](https://www.puc.pa.gov/general/consumer_ed/pdf/Transmission_Lines.pdf) (accessed 2023-12-12).
57. Ziadeh, R.; DeLiberato, V. C. IN THE COMMONWEALTH COURT OF PENNSYLVANIA.

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