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Policy Analysis

Emissions and Health Implications of Pennsylvania's Entry into the Regional Greenhouse Gas Initiative

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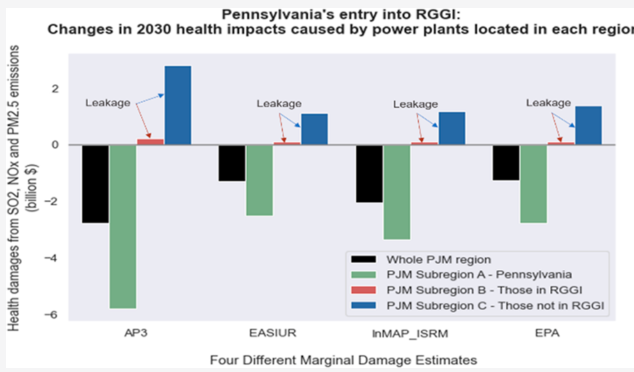
ABSTRACT: The Regional Greenhouse Gas Initiative (RGGI) is a cap-and-trade system targeting CO_2 emissions from the electricity sector in the northeastern United States. As a major power producer and carbon emitter, Pennsylvania plans to join RGGI in 2022, which will affect both the carbon market (i.e., RGGI) and the regional electricity market (i.e., PJM). Combining a PJM power system model with a reduced-form model of CO_2 emissions abatement from RGGI states that are not in PJM, we find the annual average emissions from power plants in Pennsylvania can be reduced by 40%, 79%, 68%, and 76% for CO_2, SO_2, NO_x, and $PM_{2.5}$, respectively, during 2022−2030. Then, based on a range of source-specific marginal damage estimates, we find the cumulative monetized health cobenefits to be 17.7 to 40.8 billion USD. However, the reduced emissions and health damages in Pennsylvania are slightly offset by increases in the other states in PJM that do not participate in RGGI. Our study hence highlights the potential cross-state leakage issue that warrants careful consideration in the policy design and implementation process.



KEYWORDS: *Air pollution, cobenefits, climate policy, electricity market, health damage, RGGI*

1. INTRODUCTION

The Regional Greenhouse Gas Initiative (RGGI) is the first market-based program in the U.S. to directly regulate greenhouse gas (GHG) emissions from power plants.[1] RGGI is a regional cap-and-trade system that places annual caps on power-sector CO_2 emissions, in which allowances are freely traded among power plants. Since the electricity sector is a major contributor to both CO_2 and air pollutants in this region,[2,3] by encouraging a shift toward low-carbon electricity sources, RGGI not only reduces CO_2 emissions but also brings health cobenefits from coreducing local air pollution.[4−7] To date, 11 states (New Jersey, Maryland, Delaware, Virginia, New York, Maine, New Hampshire, Vermont, Massachusetts, Connecticut, and Rhode Island) in the northeast and mid-Atlantic regions have voluntarily agreed to participate in the RGGI program (see a state map in Supplementary Figure S1; North Carolina, not shown on the map, has initiated a rulemaking process to join RGGI in July 2021).

Recently, Governor Tom Wolf used his executive authority to have the Commonwealth of Pennsylvania join RGGI. An executive order was issued in October 2019 that directed the Pennsylvania Department of Environmental Protection (DEP) to draft rules for Pennsylvania's entry into RGGI. The DEP's Environmental Quality Board has voted to adopt the final rule in July 2021, with Pennsylvania currently expected to begin participating in RGGI in early 2022.

As a large electricity producer and exporter,[8] Pennsylvania's anticipated entry into RGGI will not only affect the electricity generation activities within the state but also the flow of electricity throughout the regional wholesale electricity market in which it participates. Spanning all or parts of 13 states plus the District of Columbia (see Supplementary Figure S1 for a map), the regional electricity market is operated by the PJM Interconnection, a Regional Transmission Organization. Importantly, besides Pennsylvania, only four other states in the PJM market have previously joined RGGI (Virginia, New Jersey, Maryland, and Delaware). Modeling the interactions between the partially overlapping carbon market (i.e., RGGI) and electricity market (i.e., PJM) is hence critical to understanding the local and regional impacts as Pennsylvania joins RGGI.

In this study, we aim to quantify the impacts of Pennsylvania's entry into RGGI on regional CO_2 emissions and air quality-related health damages. Methodologically, our main contribution is to characterize the multimarket, multistate

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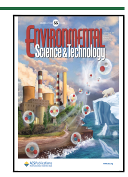

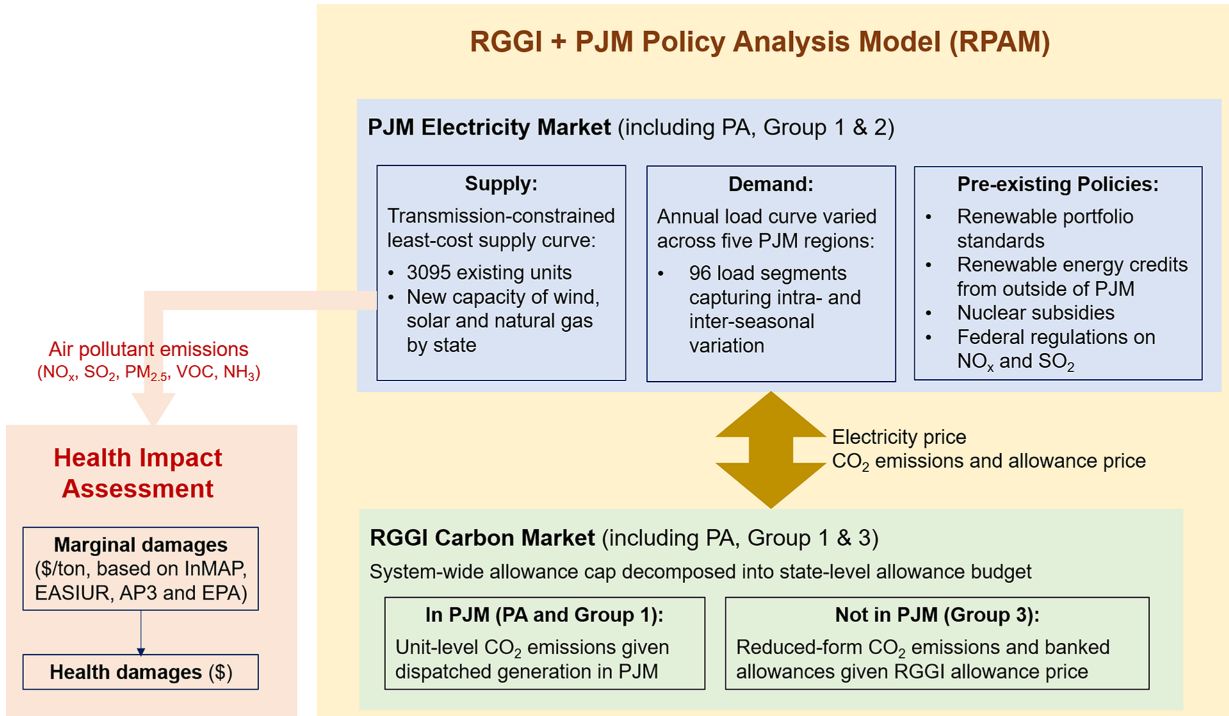

Figure 1. Flowchart of our modeling framework. The electricity market (PJM) and carbon market (RGGI) are modeled by the RGGI + PJM Policy Analysis Model (RPAM). A health impact assessment is conducted by multiplying the air pollutant emissions reported from RPAM with source-specific marginal damage estimates (including the estimate used by the EPA[10,11] and those derived from reduced-complexity models, InMAP,[12] EASIUR,[13] and AP3[14,15]).

Table 1. Three Groups of States Modeled in RPAM That Will Be Affected by Pennsylvania's Entry into RGGI through the Linkages in the Electricity Market (PJM), the Carbon Market (RGGI), or Both[a]

		Electricity market	
		PJM	Non-PJM
Carbon market	RGGI	**Group 1:** New Jersey, Maryland, Delaware, and Virginia (starting in 2021)	**Group 3:** New York (*under New York Independent System Operator*), Maine, New Hampshire, Vermont, Massachusetts, Connecticut, and Rhode Island (*under New England Independent System Operator*)
	Non-RGGI	**Group 2:** Washington, DC, Ohio, West Virginia, and part of Kentucky, Michigan, Illinois, Indiana, North Carolina, and Tennessee	Not included in the study

[a]For the PJM regions (i.e., Groups 1 and 2), we model power system decisions and associated air quality-related health impacts in detail. For non-PJM RGGI regions (Group 3), we model the aggregate power sector CO_2 emissions to ensure RGGI CO_2 emissions caps are met.

dynamics in the partially overlapping RGGI carbon and PJM electricity markets. To this end, we first use a multimarket model (RGGI+PJM Policy Analysis Model, RPAM[9]) to simulate the linkages between the PJM electricity market and the RGGI carbon market. Based on the model projected air pollutant emissions for the PJM region, we then utilize various source-specific marginal damage estimates (i.e., monetized health damages of *emitting* one unit of air pollutant emissions) to monetize the health damages. Figure 1 summarizes our modeling framework.

2. METHODS

2.1. RPAM Model. *2.1.1. Modeling Strategies for Different Types of States and Regions.* We consider three groups of states/regions that may be affected by Pennsylvania's entry into RGGI (Table 1; more details in Supplementary Figure S1):

- Group 1 (RGGI and PJM): PJM states/regions that participate in RGGI;
- Group 2 (PJM, not RGGI): PJM states/regions that do not participate in RGGI, and
- Group 3 (RGGI, not PJM): States outside PJM but are part of RGGI.

For the regions within PJM (Groups 1 and 2), RPAM uses a power dispatch model with new capacity expansion to simulate the generation, load, and transmission activities and report the emissions of CO_2 and air pollutants from each electricity generation unit. For Group 3 regions that are outside PJM, RPAM uses a reduced-form model to simulate CO_2 emissions abatement and allowance banking, in order to keep the sum of Groups 1 and 3 CO_2 emissions, net of banked allowances, lower than or equal to the RGGI cap. Intuitively, if Pennsylvania joins RGGI, other PJM states that are not subject to RGGI (Group 2) may increase their electricity production and, subsequently, their emissions of CO_2 and other air pollutants. This potential leakage from Group 1 to Group 2 states within PJM is a central focus of our analysis. Since the electricity sector in the Group 3 regions is not directly connected with Pennsylvania, the reallocation of

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electricity generation activities and the leakage issue is less of a concern. Our evaluation of the air quality-related health impacts hence focuses on the PJM regions (Groups 1 and 2).

2.1.2. Model Overview. RPAM[9] simulates the capacity investment, electricity generation, load, and electricity flow decisions in the PJM wholesale electricity market as well as the impacts of the RGGI CO_2 allowance market on participating states (see the modeling domain depicted in Supplementary Figure S1). Subject to constraints at the unit and system levels, the model maximizes the sum of PJM consumers' surplus, i.e., total benefit to PJM's customers, PJM producers' surplus, i.e., total profit to PJM electricity producers, total benefits to non-PJM RGGI states by adjusting their CO_2 emissions from electricity subject to state-level emission budgets, and total benefit to holders of RGGI banked allowances. Note that PJM producers' surplus includes profits from investments in new units and electricity generation from both new and existing units. For the PJM electricity market, RPAM includes the following: (1) electricity supply: transmission-constrained supply curve of 845 representative units for existing capacity (aggregated from 3,095 units) and an endogenous supply of new capacity; (2) electricity demand: annual price-elastic demand curves that vary across five PJM regions with virtual bidding, and (3) pre-existing policies affecting the PJM power system, e.g., nuclear subsidies, Renewable/Alternative Energy Portfolio Standards, alternative/renewable energy credits from outside of PJM, the federal Acid Rain Program, and the annual SO_2 and NO_x programs established by the Cross-State Air Pollution Rule. Operating on an annual time step, RPAM can add natural gas combined cycle (NGCC), wind, and solar capacity in each state at carefully calibrated capital costs (more in the SI). It allows for the electricity markets to be cleared in 96 load segments consisting of representative hours of the year. RPAM also considers annual plant retirement schedules until the end of 2021.

For the RGGI carbon market, RPAM captures the following: (1) system-wide allowance cap that is decomposed into state-level allowance budgets; (2) unit-level CO_2 emissions for PJM states that are also in RGGI (Group 1, plus PA in some cases); (3) reduced-form CO_2 emissions and banked allowances for RGGI member states that are not in PJM (Group 3); and (4) the endogenous carbon price of RGGI allowance at which the sum of covered power plants within RGGI, net of banked allowances, is less than or equal to the annual RGGI cap. Notably, the PJM and RGGI markets are connected through the regional CO_2 allowance cap: the CO_2 emissions from all electricity generation units in the RGGI member states, including those within PJM (Group 1 states) and outside PJM (Group 3 states), should meet the aggregate allowance cap.

For the PJM region, the model also reports the annual emissions at the plant level, including CO_2, SO_2, NO_x, $PM_{2.5}$, ammonia (NH_3), and volatile organic compounds (VOCs). CO_2, SO_2, and NO_x emissions are calculated based on marginal emissions rates using the best available estimates from three data sets (CEMS,[16] EPA's eGrid,[17] and S&P Global's PJM Summary Capacity[18]); $PM_{2.5}$, NH_3, and VOC emissions are calculated following the United States Environmental Protection Agency (EPA)'s Integrated Planning Model (IPM)[19] and Flat File Generation Methodology.[20] The emissions of these air pollutants will be used for health damage quantification in the following steps.

RPAM is calibrated for 2016 and 2017 data and validated for 2018 based on generation mix, new capacity investments, locational marginal prices, and CO_2 emissions (for more information see Landry et al., 2020[21]). Compared to other capacity planning models of national scope such as IPM,[19] we find RPAM performs better in predicting transmission congestion, imports and exports of electricity between PJM regions, as well as regional generation by fuel type.

2.2. Scenario Design. We design three scenarios (Table 2): ***1) Base Case***: Pennsylvania will not join RGGI, but the states already in RGGI or have announced a timeline to join will be subject to the RGGI rule; ***2) RGGI Case***: Pennsylvania will join RGGI in 2022; and ***3) RGGI + No AEPS Case***: Pennsylvania will join RGGI in 2022 but terminates its Alternative Energy Portfolio Standard[22] (AEPS) in the same year.

Table 2. Scenario Design[a]

	Action by PA	CO_2 allowance[21,23−26] PA	Regional
Base Case	Not joining RGGI	N/A	2022: 90.1 MMT 2026: 92.8 MMT 2030: 79.6 MMT
RGGI Case	Joining RGGI in 2022	2022: 70.8 MMT 2026: 61.7 MMT 2030: 52.7 MMT	2022: 160.9 MMT 2026: 154.5 MMT 2030: 132.3 MMT
RGGI + No AEPS Case	1) Joining RGGI in 2022 2) Terminating the Alternative Energy Portfolio Standard (AEPS) in 2022	Same as *RGGI Case*	Same as *RGGI Case*

[a]In all scenarios, we assume New Jersey joined RGGI in 2020 and Virginia will join in 2021. We assume unlimited banking is possible and consider pre-existing state and federal policies. The allowance budget for PA is designed based upon projections of Pennsylvania's future 2022 emissions.

The difference between the *RGGI Case* and *Base Case* captures the key effects of Pennsylvania's entry into RGGI. The *RGGI + No AEPS Case* examines how the interactions between low-carbon policies will influence power system dynamics and the resulting health impacts. AEPS requires that 18% of the electricity supplied by Pennsylvania's electric distribution companies and electric generation suppliers comes from alternative energy resources by 2021, which can be complied with by procuring Alternative Energy Credits (AECs) from qualified alternative energy resource facilities. While the Commonwealth is on track to achieve this target, how this legislation will evolve beyond 2021 remains uncertain.

2.3. Marginal Damage Estimates. Based on unit-level air pollutant emissions for PJM reported by RPAM, we quantify the health damages using four different types of marginal damage estimates (EPA, AP3, EASIUR, and InMAP-ISRM). The marginal damage estimates measure the aggregate health damages attributable to one ton of emissions released from a specific source location. Although these source-based estimates do not disentangle where the impacts will occur, except for the EPA estimate, the other three estimates are derived from reduced-complexity models, which provide location-varying estimates depending on where the emissions originate from.

A wide range of factors can affect the marginal damage from one unit of air pollutant emissions. For instance, one ton of SO_2 emitted from a power plant near population centers will have higher marginal damages in aggregate. To derive the source-specific marginal damages, the four estimates use different baseline emissions, spatial resolution, and atmospheric chemistry and transport models (major assumptions are summarized in Supplementary Table S2-1). As such, each of the four estimates has strengths and weakness, with regard to how well they capture different types of pollutants, the location of emitting sources, the amount of wind transport, and the size and vulnerability of exposed populations. For instance, while the EPA estimate reports one national average estimate for each of the 17 different sectors, the other three approaches report one estimate for all sectors but at much finer spatial resolution (i.e., more than 50,000 grid cells for InMAP-ISRM and at the county level for AP3 and EASIUR). In addition, while InMAP-ISRM and AP3 report the marginal damages for five pollutants (SO_2, NO_x, $PM_{2.5}$, NH_3, and VOCs), the EPA estimate includes only three (SO_2, NO_x, and $PM_{2.5}$). A thorough literature review is included in Supplementary Section 2.1.

2.4. Health Impact Assessment. Within PJM, for each pollutant (p), we quantify the aggregate health damages due to the source emissions from each power plant (i), by multiplying the amount of emissions with the corresponding marginal damage estimates ($MD_{i,p}$).

Based on plant-level damages, we then sum up the total health damages caused by the emissions released from all power plants located in each county, state, and the entire PJM region (see Supplementary Figure S2-1). Specifically,

$$D_p = \sum_{i}^{N} (MD_{i,p} \times E_{i,p})$$

where i represents each individual power plant, N is the number of power plants located in a specified region (e.g, county, state, or PJM region), $MD_{i,p}$ is the marginal damage estimate, and $E_{i,p}$ is the emissions of pollutant p from power plant i. We report the economic value of the health damages in 2016 dollars.

Since the spatial resolution and sector specification vary across different marginal damage estimates, we apply $MD_{i,p}$ using consistent assumptions. Specifically, for the EPA measure, we use the marginal damage estimate for electricity sector emissions (among 17 available sectors) and apply the same $MD_{i,p}$ to all power plants throughout the PJM region. For EASIUR and AP3, depending on which county the power plants are located in, we use county-specific $MD_{i,p}$ from low stack-height emissions (i.e., defined as <150 m for EASIUR and <250 m for AP3). For InMAP-ISRM, for each of the 52411 grid cells, we apply marginal damages for emissions from the ground level (57−379 m), considering the national average stack height of 172 ft (52.4 m).[11] While the RPAM model reports the location for most power plants, for those plants without specific location information (i.e., unmapped units and projected new additions), we use national average marginal damages under all four approaches. (See Supplementary Figure S2-1 for an example of our calculation.)

3. RESULTS AND DISCUSSION

3.1. Electricity Market Outcomes. The electricity sector in Pennsylvania and the overall PJM region is currently dominated by natural gas, coal, and nuclear generation (Figure 2). In 2020, generation from these three types of power plants

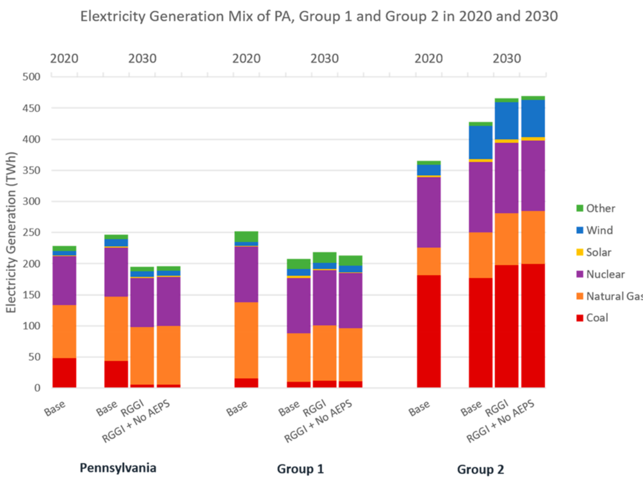

Figure 2. Electricity generation in Pennsylvania (left), Group 1 (middle), and Group 2 (right) by fuel type in the base year (2020) and the three scenarios in 2030 (unit: TWh). Each stacked bar represents the electricity generation mix by fuel type (i.e., coal, natural gas, nuclear, solar, wind, and others). Group 1 includes other PJM regions that participate in RGGI; Group 2 includes other PJM regions that do not participate in RGGI.

contributed, respectively, to 37.3%, 21.0%, and 34.5% of total generation in Pennsylvania and 27.1%, 31.9%, and 32.8% of total generation in non-Pennsylvania PJM regions (i.e., Group 1 and 2 states combined). By the end of 2030, the dominance of these three technologies will largely persist under the *Base Case.* While more wind and solar capacity will be added in the coming decades, the share of renewable resources in total generation mix remains small in the PJM region (e.g., less than 13% as predicted by RPAM).

With Pennsylvania's entry into RGGI, by 2030, coal power generation is projected to fall dramatically in Pennsylvania (38.0 TWh lower in the *RGGI Case* than *Base Case)*, while that in Group 2 (non-RGGI PJM regions) increases by 20.4 TWh. Group 1 states (i.e., both in RGGI and PJM) are not affected much.

These countervailing effects in Pennsylvania and Group 2 regions are due to the market operations and cross-state linkages in the PJM electricity market. Even when Pennsylvania joins RGGI, over half of the power generated in PJM will still come from states that do not participate in RGGI. These Group 2 states are not subject to RGGI CO_2 emissions cap, and thus their plants do not face a carbon price.[9] As such, coal and natural gas power plants in Pennsylvania become more expensive to operate, causing them to shift up PJM's dispatch curve, which, in turn, reduces the amount of time they are dispatched. Since coal units are more carbon-intensive than natural gas units, costs rise higher for coal, leading to a greater reduction in coal power generation. In the meantime, fossil-based power plants in Group 2 states become more cost-competitive in the absence of a carbon price. Their generation goes up, which creates a pathway for leakage.

3.2. CO_2 and Air Pollutant Emissions. We report the emissions in 2020 and 2030 as a benchmark for present-day emissions and the end-year of model simulation, respectively. We also report two intermediate years of great policy

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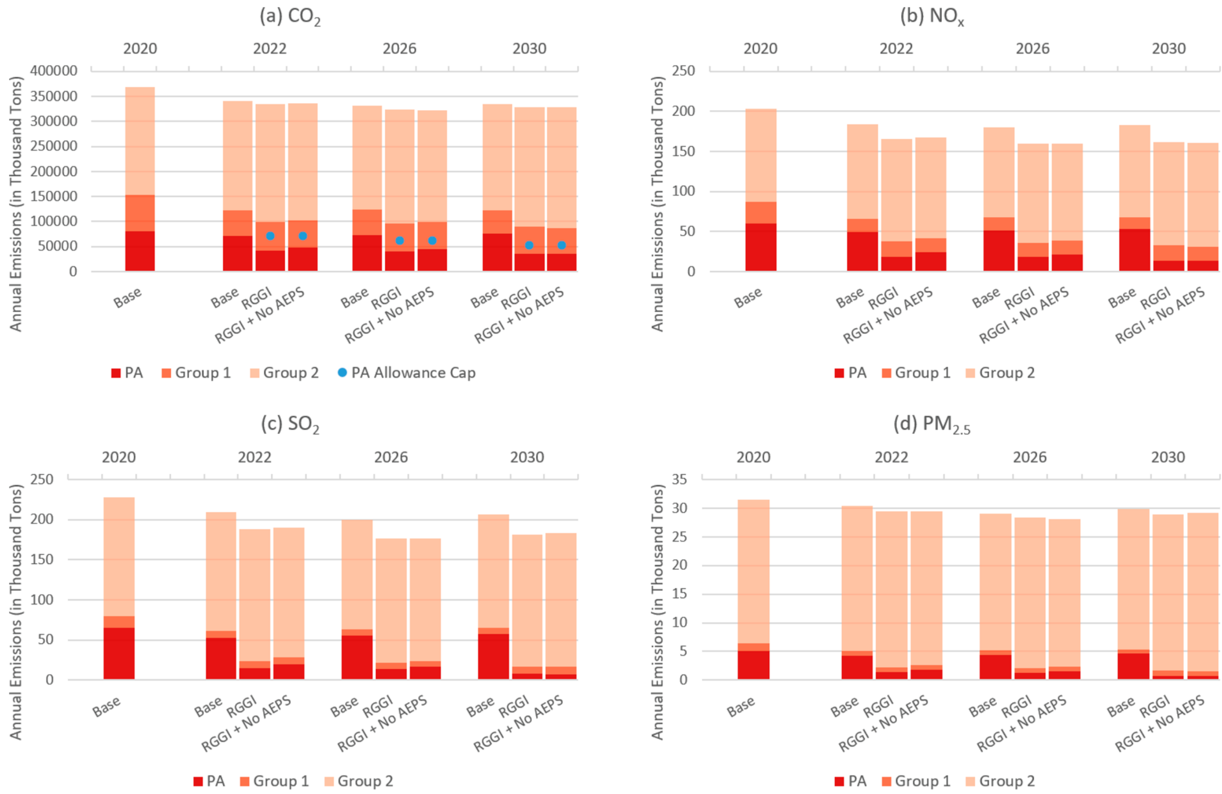

Figure 3. Annual emissions of (a) CO_2, (b) NO_x, (c) SO_2, and (d) $PM_{2.5}$ from the power plants located in Pennsylvania (dark red bars), Group 1 (orange bars), and Group 2 (light orange bars) (unit: thousand ton). The emissions of NH_3 and VOCs are presented in Supplementary Figures S3-1 and S3-2. Group 1 includes the PJM regions that participate in RGGI; Group 2 includes the PJM regions that do not participate in RGGI. Leakage rates for each pollutant are shown in Supplementary Table S3-3.

relevance: 2022—the year Pennsylvania becomes a member of the RGGI, and 2026—the year after the third banking adjustment finishes and the combined RGGI cap is relatively less stringent than 2025. We focus on CO_2 and three major air pollutants (NO_x, SO_2, $PM_{2.5}$) in the main text, with NH_3 and VOC results included in Supplementary Figures S3-1 and S3-2.

In the *Base Case* (i.e., Pennsylvania not joining RGGI), the CO_2 emissions released from the power plants in Pennsylvania largely remain unchanged from 2020 to 2030. In comparison, the air pollutant emissions are projected to decrease over the same time frame. This is a combined effect of three factors: a) an increase in projected electricity demand that drives up electricity production and associated emissions; b) changes in generation mix that reduces the emissions (i.e., an increasing share of natural gas and renewable power plants), and c) lower air pollutants emission intensity of new natural-gas power plants that are equipped with end-of-pipe controls. While the CO_2 emissions are affected only by the first two factors, which have competing influences on each other, the air pollutant emissions are further reduced due to the third factor.

With Pennsylvania joining RGGI, we observe significant reductions in emissions of both CO_2 and air pollutants that are released from Pennsylvania's power plants. For instance, comparing the *RGGI Case* to the *Base Case*, the 2030 emissions from Pennsylvania's power plants are 51.8%, 85.5%, 74.0%, and 83.6% lower for CO_2, SO_2, NO_x, and $PM_{2.5}$, respectively. This occurs for two reasons. First, fossil-based generators in Pennsylvania now face a carbon price, which discourages production from these units. Second, Pennsylvania's participation expands the number of power plants covered under RGGI and therefore alters the marginal costs of abating CO_2 emissions. Since it is cheaper for Pennsylvania's generators to reduce their CO_2 emissions than it is for other generators in RGGI (i.e., Group 3 states), Pennsylvania reduces more than its RGGI allowance budget (i.e., comparing the blue dots to the dark red bars in Figure 3a).

If Pennsylvania terminates its Alternative Energy Portfolio Standard while joining RGGI in 2022, the expected reductions in CO_2 and air pollutant emissions will be a little smaller, due to a slightly lower share of zero-emitting renewables in the generation mix in the *RGGI + No AEPS Case* as compared to the *RGGI Case.*

However, the reductions in emissions of CO_2 and air pollutants within Pennsylvania are accompanied by an increase in emissions in the rest of the PJM states that are not subject to the RGGI rule (i.e., Group 2). Comparing the *RGGI Case* to the *Base Case*, the 2030 CO_2 and SO_2 emissions in Pennsylvania reduce by 39.1 million tons and 49,549 tons, respectively, while those from the Group 2 regions increase by 26.2 million tons and 22,332 tons. This underscores that leakage can be a critical concern: while Pennsylvania decreases its fossil-based power generation and associated emissions as the Commonwealth participates in RGGI, other PJM states are not bound by the RGGI carbon price and may utilize their fossil units more intensively (due to lower generation costs). It leads to an increase in emissions of CO_2 and air pollutants in those regions (see a similar finding from a prior study).[27] To further illustrate these regional differences, county-level results will be discussed later in Section 3.3.2.

3.3. Health Impacts from Joining RGGI.

3.3.1. Aggregate Health Impacts. For Pennsylvania and Group 2 regions,

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regardless of years, scenarios, or regions, we find that SO_2 emissions always dominate the total health damages from power generation activities, followed by NO_x and/or $PM_{2.5}$ emissions (see Supplementary Figure S5-1). This pattern is due to the fact that a) in the power sector, fossil plants are a major source of SO_2 emissions,[12,28] and b) the atmospheric chemistry and physical reactions in this region are effective in turning SO_2 emissions into secondary particulate matter in the air,[29] causing high exposure of ambient $PM_{2.5}$ in Pennsylvania and Group 2 regions. For Group 1 states, we find NH_3 to be the major contributor to the health damages. Such results are dominated by a few northeastern counties in the Greater Philadelphia Area and New Jersey. These counties not only have higher NH_3 emissions. The NH_3 emissions from these counties also lead to greater marginal damages, as shown in location-specific estimates in InMAP-ISRM and AP3, due to a range of demographic and meteorological factors. (See more in Supplementary Section 2.)

Since all four marginal damage estimates report SO_2, NO_x, and $PM_{2.5}$ and these pollutants contribute to a majority of the health damages, below we show the aggregate health damages from these three types of emissions (more discussion in Section 3.4.2).

Under the *Base Case*, we estimate the total health damages caused by the air pollutant emissions released from Pennsylvania's power plants to be \$3.5−7.9 billion in 2020, \$2.9−6.4 billion in 2022, \$3.0−6.7 billion in 2026, and \$3.1−7.0 billion in 2030 (the range covers the results using four different marginal damage estimates). With Pennsylvania joining RGGI in 2022, comparing the *RGGI Case* to the *Base Case*, the total health damages caused by Pennsylvania's power plants decrease by \$1.9−4.4 billion in 2022 (67−70% reduction), \$2.1−4.9 billion in 2026 (71−74% reduction), and \$2.5−5.8 billion in 2030 (81−84% reduction). Terminating the Alternative Energy Portfolio Standard lowers the health cobenefits from joining the RGGI, though the magnitude of such a penalty is relatively small (i.e., only slightly higher health damages in the *RGGI + No AEPS Case* than in the *RGGI Case*). Prior analysis found that most of the health damages from power plants in Pennsylvania will occur within the state boundary.[30] It hence suggests significant local health cobenefits if the Commonwealth participates in RGGI.

However, the leakage issue leads to a redistribution of health impacts between Pennsylvania and the other PJM states that are not in RGGI. The reduced health damages caused by Pennsylvania's power plants are accompanied by increased damages from the generators in Group 2 states (Figure 4). The total health damages caused by the power plants in Group 2 regions will increase by \$0.8−1.8 billion in 2022 (9.2−9.8% increase), \$0.9−2.2 billion in 2026 (12.0−13.2% increase), and \$1.1−2.8 billion in 2030 (14.0−15.9% increase).

Despite substantial variations in absolute health damages across four different marginal damage estimates, the percent reductions in health damages due to Pennsylvania's participation in RGGI are similar (see Supplementary Figure S5-2). Comparing the *RGGI Case* to the *Base Case*, total 2030 health damages caused by all PJM power plants reduce by 9−17% across the four marginal damage estimates. The ranges for the percent reductions are even smaller for the health damages from each individual pollutant, with 12−16% for NO_x, 12−19% for SO_2, and 3−10% for $PM_{2.5}$. Note that AP3 often yields the largest health damages (or cobenefits) due to the greater marginal damage estimates for almost all types of pollutants (e.g., SO_2, NO_x, and $PM_{2.5}$).

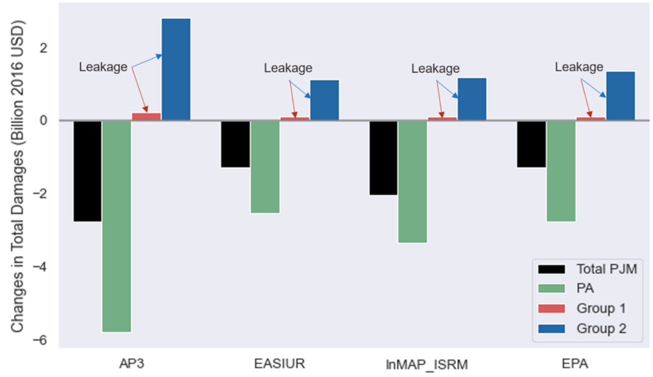

Figure 4. Changes in projected health damages in 2030 due to Pennsylvania's entry into RGGI. Comparing the *RGGI Case* to the *Base Case*, here we show the total health damages caused by the power plants located in the entire PJM region (black bars) and in three subregions, including Pennsylvania (green bars), Group 1 (in RGGI; red bars), and Group 2 regions (not in RGGI; blue bars). Positive bars correspond to absolute increases in total health damages (i.e., health co-harms due to cross-region leakage; see Supplementary Tables S5-2-4 for leakage rates), and negative bars represent absolute reductions (i.e., health cobenefits). AP3, EASIUR, InMAP-ISRM, and EPA are four different types of marginal damage estimates used in this study. Here we sum up the damages from SO_2, NO_x, and $PM_{2.5}$ emissions. The unit is billion 2016 USD.

3.3.2. Spatial Distribution. To demonstrate the spatial patterns for health impacts in more detail, we show the health damages caused by the emissions released from the power plants in each county (Figure 5, using AP3 as an example; other marginal damage estimates see Supplementary Section 4).

While the health damages caused by local power plants are expected to go down in many counties in Pennsylvania (shown as blue colors in Figure 5b and 5c), a couple of counties in Group 2 states (i.e., not in RGGI) will significantly increase their coal power generation, causing much greater health damages (shown as orange colors in Figures 5b and 5c). The changes in Group 1 states (PJM states that are also in RGGI) are negligible.

Although the marginal damage approach in this study cannot further attribute the damages based on where the human exposure actually occurs, our results imply that the pathway for cross-state leakage created in the electricity market may result in uneven air pollution exposure and health outcomes across different PJM states. A detailed, geographically explicit evaluation of health impacts is therefore an important direction of future research (see more discussion in Section 3.4.2).

3.4. Discussion. *3.4.1. Comparing with the Cobenefit Assessment from Pennsylvania's Department of Environmental Protection (DEP).* Here, we compare our air quality cobenefits estimates with the assessment from the Pennsylvania DEP[31] (assuming a 3% discount rate; see more in Supplementary Tables S5-2 and -3).

The DEP estimated that by joining RGGI, Pennsylvania can avoid 66,700 and 112,700 short tons of cumulative SO_2 and NO_x emissions by 2030, respectively, leading to \$2.42 and \$0.37 billion of cumulative avoided health damages from 2019 through 2030. In comparison, despite the shorter time horizon

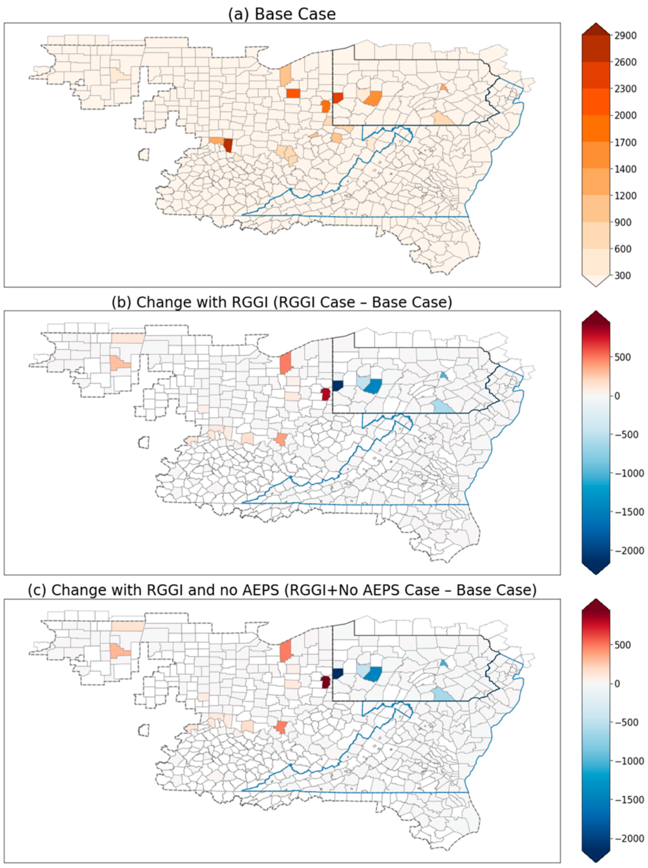

Figure 5. Health damages caused by the power plants located in each county in 2030 (unit: million 2016 USD). Here, we use the results from county-level marginal damage from AP3 as an example. The total annual health damages are the sum of the damages from SO_2, NO_x, and $PM_{2.5}$ emitted from the power plants located in the respective regions. Panels (a)−(c) show the results in the *Base Case* and the differences in the *RGGI* and *RGGI + No AEPS case* as compared to the *Base Case*. In panels (b) and (c), the orange/blue colors indicate an increase/decrease from the *Base Case*. The maps show the entire PJM regions, and we highlight Pennsylvania using the black boundaries, Group 1 using blue boundaries, and Group 2 using dashed gray lines. The results presented here are based on the *source* location of emissions (i.e., where power plants locate), not the *receptor* location of health impacts (i.e., where human exposure occurs).

we consider (2022−2030 in ours), we estimate a much greater scale of avoided air pollutant emissions (i.e., 396,000 and 312,000 tons of avoided SO_2 and NO_x emissions), which turns into larger cobenefits in economic terms (i.e., \$10.5−28.6 billion from avoided SO_2 and \$1.7−6.7 billion from avoided NO_x emissions).

The differences in avoided emissions are primarily because the DEP's analysis suggests a much more rapid rate of coal-plant retirement in the absence of RGGI than does the RPAM model.[9] There is substantial uncertainty surrounding coal plant retirement decisions over the next decade in Pennsylvania, including price signals from the PJM markets as well as future regulatory and market uncertainty that will affect plant investment and operational costs. The scenarios reflected in our RPAM model and in the DEP's model collectively represent a range of potential outcomes on how quickly coal plants in Pennsylvania will retire. The carbon emissions reductions and air quality improvements attributable specifically to RGGI are going to be sensitive to the specific coal-plant retirement scenario reflected in one model versus another. Indeed, modeling coal retirement in more detail is an ongoing effort of our team.

Besides the differences in avoided emissions, to monetize the health damages, different marginal damage estimates are adopted in our and the DEP's analysis. The DEP uses varying benefit-per-ton values over time (i.e., the 2020 BPT values of \$33,383 and \$3,089 for NO_x and SO_2 for 2019−2022, the 2025 values of \$36,663 and \$3,316 for 2023−2027, and the 2030 values of \$39,538 and \$3,521 for 2028−2030). Assuming a linear relationship between marginal changes in emissions and resulting health impacts, the marginal damage estimates (i.e., the monetized health damages of *emitting* one unit of air pollutant emissions) are equivalent to benefit-per-ton estimates that were used in other studies[12,28,32−34] (i.e., the monetized health benefits of *avoiding* one ton of pollutant emissions). Therefore, depending on years and the source of marginal damage estimates, our marginal damage or BPT values are higher than the DEP's in some circumstances but lower in others.

It is worth noting that using the RPAM model, we also project the cumulative cost of Pennsylvania joining RGGI to be over \$972 million for Pennsylvania between 2022 and 2030.[9] The potential health cobenefits will likely be higher than the costs by 1−2 orders of magnitude in both the DEP and our study. These tangible, local health benefits provide strong justification for the Commonwealth to join RGGI.

3.4.2. Limitations and Directions for Future Research. To shed light on uneven regional impacts issues driven by leakage concerns, future work needs to identify major processes and uncertainties that determine the magnitude and distribution of health impacts. One key limitation of our marginal damage approach is that we can only attribute the health damages by emissions sources but not by emissions impacts on human exposure and health. By carefully simulating the emission, transport, and chemical processes using fine-resolution air pollution modeling, future work should further assess the regional distribution of the health impacts and inform decision-making on environmental justice.[12,35,36] Key factors that are worth further attention include the characterization of atmospheric chemistry processes (e.g., the interactions of emissions from the power sector and nonpower sectors to form secondary particulate matter), the transport of air pollution to downwind regions, the characteristics of the exposed population, as well as the concentration−response relationships that quantify the increases in health risk from air pollution exposure.

In addition, given the uncertainty in future coal plant retirements, it is also imperative to improve our understanding and modeling capabilities for coal plant retirement decisions (see more in Section 3.4.1).

3.4.3. Conclusion and Policy Implications. In this study, we find that Pennsylvania's participation in RGGI can significantly avoid air pollutant emissions released from the power plants located within the Commonwealth. These avoided emissions will lead to significant health cobenefits: the net present value of the cumulative health cobenefits is estimated to be \$17.7−40.8 billion from 2022 to 2030. Our analysis hence confirms that climate policies, if carefully designed, can generate substantial air quality and health cobenefits.[32,34,37−44] A wide range of factors can affect expected health cobenefits. For instance, dynamics in the electricity market will determine upstream drivers in energy

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activities and emissions, such as the types of power plants that will enter or exit the market and where power production (and associated emissions) will take place given transmission constraints. Many factors can further affect the downstream exposure levels and health impacts, such as the formation and transport of air pollution and the size of the exposed population. Incorporating these key factors is important in providing a reliable assessment of the expected health impacts from this policy decision.

However, we also find the decrease in health damages caused by Pennsylvania's power plants is accompanied by an increase in health damages from power plants in other PJM states that are not part of RGGI. Because these states are not bound by the carbon emissions cap under RGGI, power generation activities relocate from Pennsylvania to these non-RGGI states, leading to the leakage issue. Since local emissions affect local health the most, our results suggest potential health co-harms in these other PJM states, highlighting the need for coordinated policymaking to avoid unintended negative impacts outside Pennsylvania.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c02797.

> Additional information on RGGI + PJM Policy Analysis Model (RPAM), summary of marginal damage (MD) estimates used in this study, spatial distribution of MD from three models for all pollutants, emissions by pollutant and changes in emissions across scenarios, spatial distribution of total health damages for each MD estimate, and undiscounted and discounted annual total health damages (PDF)

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Notes

The authors declare no competing financial interest.

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