# Analysis of the Public Health Impacts of the Regional Greenhouse Gas Initiative, 2009–2014

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January 2017

## Tables



## Figures

# Acronyms and Abbreviations

| | |
|---|---|
| BenMAP | Benefits Mapping and Analysis Program |
| CAA | Clean Air Act Amendments of 1990 |
| CAMD | Clean Air Markets Division |
| $CO_2$ | Carbon dioxide |
| COBRA | Co-Benefits Risk Assessment |
| EE | Energy efficiency |
| eGRID | Emissions and Generation Resources Integrated Database |
| EGU | Electric generating unit |
| EIA | Energy Information Administration |
| EPA | U.S. Environmental Protection Agency |
| ER | Emergency room |
| GHG | Greenhouse gas |
| Hg | Mercury |
| IPCC | Intergovernmental Panel on Climate Change |
| MAPS | Multi-Area Production Simulation |
| MW | Megawatt |
| MWh | Megawatt hours |
| NAAQS | National Ambient Air Quality Standards |
| NARSTO | North American Research Strategy for Tropospheric Ozone |
| NEI | National Emissions Inventory |
| NESCAUM | Northeast States for Coordinated Air Use Management |
| $NO_x$ | Nitrogen oxides |
| PM | Particulate matter |
| $PM_{2.5}$ | Fine particulate matter |
| RE | Renewable energy |
| RFF | Resources for the Future |
| RGGI | Regional Greenhouse Gas Initiative |
| S-R | Source-Receptor |
| $SO_2$ | Sulfur dioxide |
| TAG | Technical Advisory Group |
| WTP | Willingness-to-pay |
| ZEV | Zero emission vehicle |

## Acknowledgements

This report is an independent, retrospective study of the public health impacts of the Regional Greenhouse Gas Initiative (RGGI) over its first six years of implementation (2009-2014). Abt Associates relied on modeling results from two Analysis Group reports, *The Economic Impacts of the Regional Greenhouse Gas Initiative on Northeast and Mid-Atlantic States*, covering the 2009-2011 and 2012-2014 periods. Abt is grateful to Analysis Group for providing access to results of their dispatch modeling, which served as a foundation of our analysis of the impacts of RGGI on air emissions, air quality, and public health.

Abt would like to thank the Barr Foundation, Energy Foundation and the Merck Family Fund, with additional support from the Betterment Fund, Alexander Buck, Jr., The Devonshire Foundation, Thomas Haas at the New Hampshire Charitable Foundation and Daniel Hildreth, for their generous funding of this independent study as part of the RGGI Project Series.  The authors give special thanks to Laurie Burt (Laurie Burt, LLC), Project Coordinator of the RGGI Project Series, for serving as the project coordinator of this independently conducted report and providing key support.

In addition, Abt formed a Technical Advisory Group (TAG) to obtain feedback on our approach, methods, and interpretation of analytic results. We would like to thank the TAG members for sharing their time and expertise:

- **George (Tad) Aburn,** Air Director, Maryland Department of the Environment
- **Paul Hibbard,** Principal, Analysis Group
- **Dr. Patrick Kinney,** Professor of Environmental Health, Boston University
- **Dr. Paul Miller,** Deputy Director, Northeast States for Coordinated Air Use Management (NESCAUM)
- Additional anonymous contributors also provided informal input and review.

Michelle Manion of Abt Associates was the lead author of this report. Claire Zarakas, Stefanie Wnuck, Jacqueline Haskell, Anna Belova, David Cooley, Jonathan Dorn, Marissa Hoer, and Lisa Mayo of Abt Associates all made important contributions to this report.

The findings of this independent study are based solely on the analysis and judgment of Abt Associates and do not necessarily reflect the views of the TAG members, Laurie Burt, or our funders.

## About Abt Associates

Abt Associates is a mission-driven, global leader in research, evaluation, and program implementation in the fields of health, social and environmental policy, and international development. Known for its rigorous approach to solving complex challenges, Abt is regularly ranked as one of the top 20 global research firms and one of the top 40 international development innovators. The company has multiple offices in the United States and program offices in more than 40 countries.

Abt's experts in climate change, clean energy, and public health include economists, public health experts, epidemiologists, natural scientists, data scientists, attorneys, and others. In addition, Abt economists and public health experts support the U.S. Environmental Protection Agency's (EPA's) efforts to develop, maintain, and update the Benefits Mapping and Analysis Program (BenMAP) and the Co-Benefits Risk Assessment (COBRA) tools, both of which are utilized in this analysis.

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# Executive Summary

## Purpose of this Study

This independent study provides an analysis of the public health impacts of the Regional Greenhouse Gas Initiative (RGGI) over its first six years of implementation (2009 to 2014). RGGI is the nation's first regional regulatory program designed to reduce greenhouse gas (GHG) emissions from large electric power plants, and builds from a long and successful tradition in the Northeast states of using market-based programs to cost-effectively reduce air pollution. Since RGGI started in 2009, the program has raised nearly $3 billion to support the RGGI states' investments in energy efficiency, renewable generation, and other public benefit programs, and these states are on track to achieve reductions of GHG emissions of 45 percent below 2005 levels by 2020.

Because "criteria" air pollutants[1] are co-produced along with GHG emissions from fossil-fuel power plants, RGGI is also expected to drive reductions in these air pollutants and their adverse effects on human health. The objective of this independent study is to provide a *retrospective* analysis of the impacts of an existing GHG reduction program—RGGI—on air quality and public health.

Using publicly available, peer-reviewed air quality and public health models and historical data characterizing RGGI's actual performance during the program's first two compliance periods (covering 2009 to 2014), we addressed the following questions in this analysis:

- Did RGGI result in measurable changes in emissions of criteria air pollutants and air quality?
- If so, how did changes in air quality resulting from RGGI affect public health and to what degree?
- What were the spatial and temporal patterns to changes in air quality and public health due to RGGI implementation?
- Will health benefits from RGGI's first two compliance periods be replicated in the future?

## Key Results and Findings

**The RGGI program improved air quality throughout the Northeast states and created major benefits to public health and productivity, including avoiding hundreds of premature deaths and tens of thousands of lost work days.** RGGI's impact on electricity markets resulted in significant reductions in key air pollutants with adverse effects on human health. Over the first six years of the program, RGGI avoided hundreds of cases of premature deaths, heart attacks, hospitalizations, and emergency room (ER) visits; tens of thousands of lost work days, and hundreds of thousands of cases of restricted activity days due to poor air quality. Table 1 summarizes cumulative avoided health and productivity effects associated with RGGI's first two compliance periods.

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1 "Criteria air pollutants" refer to the six most common air pollutants in the United States: carbon monoxide (CO), lead, ground-level ozone ($O_3$), nitrogen oxides (NOx), particulate matter (PM), and sulfur dioxide ($SO_2$). The Clean Air Act requires EPA to set National Ambient Air Quality Standards (NAAQS), which are maximum allowable concentrations for these pollutants that are protective of public health.

**Table 1. Summary of Cumulative RGGI Health Benefits, 2009 to 2014**

<table>
<tr><td rowspan="6">Avoided Health Effects</td><th colspan="3">Avoided Mortality</th></tr>
<tr><td colspan="3">• 300–830 premature adult deaths</td></tr>
<tr><th colspan="3">Avoided Morbidity</th></tr>
<tr><td colspan="3">• 35–390 non-fatal heart attacks<br>• 420–510 cases of acute bronchitis<br>• 8,200–9,900 asthma exacerbations<br>• 13,000–16,000 respiratory symptoms</td></tr>
<tr><th colspan="3">Other</th></tr>
<tr><td colspan="3">• 180–220 hospital admissions<br>• 200–230 asthma ER visits<br>• 39,000–47,000 lost work days<br>• 240,000–280,000 days of minor restricted activity</td></tr>
<tr><td rowspan="2">Value of Avoided Health Effects</td><th>Low</th><th>Central</th><th>High</th></tr>
<tr><td>$3.0 billion</td><td>$5.7 billion</td><td>$8.3 billion</td></tr>
</table>

Source: Abt Associates analysis (2017).

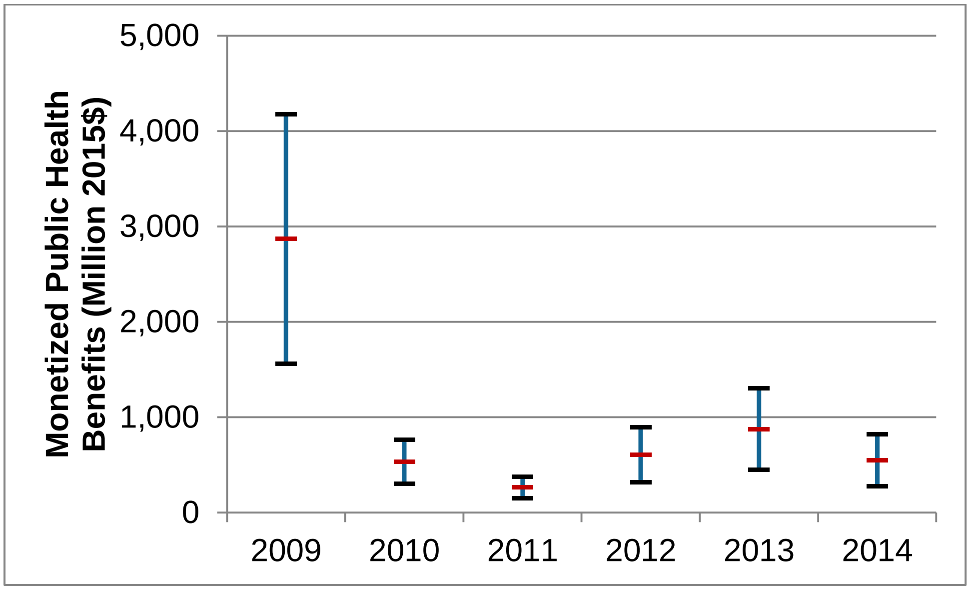
Notes: The total value of avoided health effects is the sum of health benefits in states participating in RGGI and in neighboring northeastern states, based on a 3 percent rate of discount. Values are in 2015 dollars.

**The economic value of RGGI's health and productivity benefits is estimated at a cumulative $5.7 billion ($3.0 billion low-end, $8.3 billion high-end).** Avoided cases of premature deaths due to reduced levels of fine particulate matter $PM_{2.5}$ account for the majority of RGGI's monetized health benefits. However, other important benefits to the region's economic productivity and quality-of-life include more than 39,000 avoided lost work days and at least 240,000 avoided days with restricted activities (e.g., exercising outdoors) due to poor air quality.

**Estimated benefits to health are positive in every state in the Northeast region (including RGGI and certain neighboring states)), and in almost every year of the study period.** States with the highest total monetized health benefits over RGGI's first six years include: Delaware, Maryland, New Jersey, New York, and Pennsylvania. Sizeable benefits also occur in Massachusetts, Connecticut, and New Hampshire. Benefits in Rhode Island, Vermont, and Maine are smaller in magnitude compared to those in states with larger populations, but are relatively consistent over the study period. Overall, health benefits estimated for the first compliance period are higher than for the second period.

**The largest annual improvements in air quality and health benefits from RGGI are in 2009 and 2013.** The largest single-year benefits in health due to RGGI occur in 2009 (shown in Figure 1). This result is consistent with RGGI's two observed effects on wholesale power markets: 1) changes in power prices to absorb $CO_2$ allowance costs, which results in shifting electricity dispatch from higher- to lower-carbon sources, and 2) investments in energy efficiency that reduce electricity demand, fossil fuel-based generation, and emissions. There is also some evidence that power plant owners, anticipating the requirements of the program, may have taken early action to reduce $CO_2$ emissions immediately before and after the start of the program in 2009. Energy efficiency investments were comparatively high in this year as well. The combination of higher prices and energy efficiency investments, together with early action, likely account for the largest single-year emission reductions and health benefits across the six year period. Similarly, higher benefits in 2013 most likely correspond to higher relative investments in energy efficiency and renewable energy in that year, and also reflect energy savings accruing from efficiency investments made in prior years.

**Figure 1. Annual Health Benefits due to RGGI, 2009 to 2014**

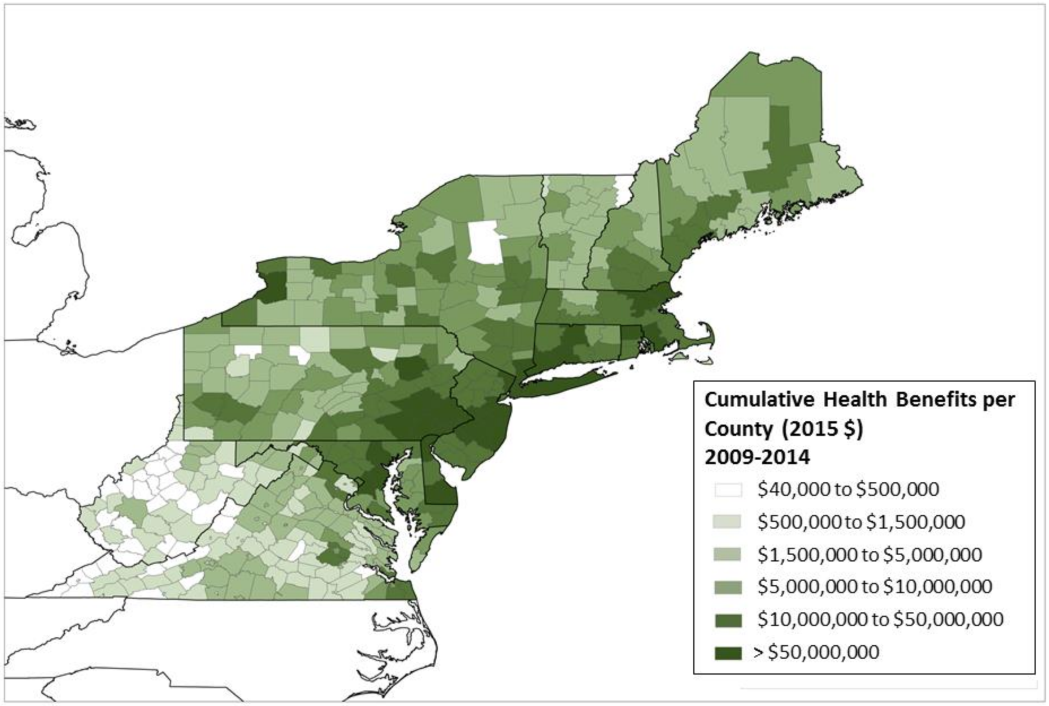



Source: Abt Associates analysis (2017).

Note: Value of annual health benefits is the sum of health benefits to RGGI states and neighboring northeastern states, based on a 3 percent rate of discount.

**Multiple states in the mid-Atlantic and New England regions experienced significant health benefits from RGGI-induced changes to air quality which originate in the RGGI states.** Due to regional transport of air pollutants, our modeling shows that states with densely populated areas located directly downwind of key coal-fired power plants experienced substantial health benefits, regardless of whether they participate in RGGI. As shown in Figure 2, Pennsylvania experienced the most significant benefits overall from RGGI due to reductions in emissions from Maryland's (and to a lesser extent Delaware's) large coal plants. The District of Columbia, Virginia and West Virginia also experienced modest health benefits from emissions reductions occurring in RGGI states. Similarly, emissions reductions due to RGGI from coal plants in western New York, Massachusetts, and New Hampshire create health benefits not only in those states, but also in Rhode Island, Vermont, and Maine.

**Figure 2. Cumulative Health Effects of RGGI, 2009 to 2014**




Source: Abt Associates analysis (2017).

**A small number of legacy coal plants, particularly in the mid-Atlantic RGGI states, account for the majority of RGGI's health benefits.** Coal-fired power plants have the highest emission rates of $SO_2$, which is the primary contributor to ambient $PM_{2.5}$ levels and risks to health. So, reductions in $SO_2$ emissions by coal plants account for the majority of health benefits. Of the RGGI states, Maryland has the most significant footprint of older coal-fired power plants and the largest inventory of $SO_2$ emissions. RGGI-induced changes in generation and emissions from five of Maryland's coal plants alone account for roughly 62 percent of $SO_2$ reductions in 2009, and 55 percent of cumulative $SO_2$ reductions from RGGI's first two compliance periods (2009 to 2014).

**If coal plants in RGGI states retire as planned in the near future, reductions of air pollutants and annual health benefits resulting from the RGGI program will likely level off. However, additional health benefits will occur as energy demand from other sectors—transportation and buildings—shifts onto a cleaner grid in RGGI and neighboring states.** As noted above, RGGI-induced changes at a relatively small number of coal plants drive a high proportion of RGGI's total reductions in key air pollutants and health benefits. However, a number of older coal-fired power plants in RGGI states driving many of the health benefits presented in this analysis are scheduled to retire within the next five years (e.g., Chalk Point in Maryland, Brayton Point in Massachusetts). As such, the fleet of power plants in RGGI states will on average be cleaner in the near future than the current fleet, so that future RGGI-induced reductions in generation are likely to result in less average annual health benefits going forward. However, states will be able to move energy use from other sectors, such as transportation and heating, to this cleaner grid. This process, known as "electrification," can further reduce air pollutants resulting in significant health benefits. For example, transitioning the light-duty vehicle fleet to about 65 percent zero-emission vehicles (ZEVs) by 2050 in eight northeastern states could result in emission reductions that generate nearly $12 billion in health benefits (American Lung Association of California 2016).

**RGGI-funded investments in energy efficiency strategically targeted to address daily air quality goals during high-electricity demand periods can generate additional health benefits.** The scope of this analysis addressed only annual changes in average $PM_{2.5}$ concentrations. However, air quality in a given location can be highly variable over the course of a year, and a single short-term exposure to high $PM_{2.5}$ concentrations can lead to more severe health outcomes than multiple exposures to low $PM_{2.5}$ concentrations. To the extent that RGGI states' future investments in energy efficiency programs can effectively target peak load on days with high electricity demand, RGGI can further reduce the number of low air quality days and thereby generate additional health benefits in the future.

**Estimates of RGGI's health benefits presented in this study are likely conservative, and also do not include the value of other co-benefits associated with reductions in air pollution, such as improved ecosystem services.** Health benefits resulting from energy savings associated with RGGI states' efficiency investments that persist beyond 2014 and from reductions in ozone were beyond the scope of this study, but could be significant. In addition, additional benefits to terrestrial and aquatic ecosystems resulting from reductions in sulfur and nitrogen deposition are not included in this analysis.

## Approach

The analytic approach used in this study for estimating RGGI's impact on emissions, air quality, and public health consisted of three sequential steps described below:

1. **Estimate annual changes in electric generation and emissions of air pollutants at power plants as a result of RGGI implementation from 2009 to 2014.**

   The RGGI program created changes to annual electricity generation, the mix of power plants (and fuels) dispatched to meet electric demand, and associated changes in emission profiles through its two direct effects on the electricity market: 1) Owners of large fossil-fuel power plants purchase $CO_2$ allowances to meet RGGI's emissions cap, and then build the costs of these purchases into wholesale power prices. In this way, purchases of $CO_2$ allowances result in shifts in power production from higher- to lower-carbon generation sources; and 2) Participating RGGI states' investments of proceeds from allowance auctions into energy efficiency measures and renewable generation result in reductions in overall electricity demand and increase the capacity for low- or zero-carbon electricity, respectively.

   We used results from electricity dispatch modeling to determine annual changes in generation (in megawatt-hours (MWh), at the plant level) due to the RGGI program and also for a counterfactual scenario representing the world without RGGI. Using EPA historical data on actual power plant-level emissions (and emissions rates), we then used the incremental difference in plant-level output due to RGGI, calculated associated changes in $SO_2$ and NOx emissions, and aggregated these emission changes at the county level. These results became the inputs to the air quality modeling conducted in the second step of this analysis.

2. **Estimate annual changes in air quality at the county level associated with changes in sulfur dioxide ($SO_2$) and $NO_x$ emissions from power plants, by year.**

   To estimate the air quality impacts of RGGI using annual county-level emission changes calculated under the first analytic step, we used EPA's Co-Benefits Risk Assessment (COBRA) model. COBRA is a free, screening-level tool that assists government agencies and others in assessing the benefits of clean energy and climate mitigation policies by estimating the effects of changes in air pollutant emissions on ambient air concentrations of fine particulate matter ($PM_{2.5}$). Using the estimated incremental change in county-level emissions of $NO_x$ and $SO_2$ due to RGGI that we calculated under Step 1, we performed a COBRA modeling run for each individual year from 2009 to 2014. Outputs from the COBRA modeling step consist of annual changes in ambient $PM_{2.5}$ levels in each county in RGGI and adjacent non-RGGI states, and become the inputs to the modeling of associated health impacts under Step 3.

3. **Assess public health impacts associated with changes in air quality due to RGGI implementation from 2009 to 2014.**

   To quantify and value the public health impacts associated with RGGI's first six years, we used EPA's BenMAP. The BenMAP model uses data describing population, background levels of health outcomes in populations, and economic values for health effects from literature to estimate the number and economic value of health impacts resulting from changes in air quality. We used the county-level changes in ambient $PM_{2.5}$ levels generated by COBRA as inputs to BenMAP. BenMAP then calculated annual health benefits from RGGI's relative effect on ambient $PM_{2.5}$ for 2009 to 2014.

In addition, we conducted sensitivity analysis to address uncertainties surrounding data, assumptions, and key modeling relationships. Specifically, we applied a sensitivity factor of 50 percent to discount estimates of health benefits for states not participating in the RGGI program, to account for a gap in information about changes in air emissions that may have occurred in these states as a result of RGGI. In addition, outputs from the BenMAP model also reflect uncertainties in the assumed relationship between reductions in exposures of human populations to key air pollutants and health outcomes, especially premature mortality. Finally, we did not quantify other benefits outside the scope of this analysis, such as health benefits associated with reductions in ozone and RGGI-induced energy savings occurring after 2014, or improved ecosystem health. As such, the benefits presented here can be considered a conservative representation of the co-benefits of the RGGI program to human health and ecosystems.

# Overview of Analysis

The northeastern U.S. states have a long track record of implementing market-based environmental programs to improve air and water quality. The first of these programs—the Acid Rain Program[2]—was established under Title IV of the 1990 Clean Air Act Amendments (CAA) and required power plants to reduce emissions of sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_x$), the primary contributors to acid rain formation. The Acid Rain Program also established a trading system that enabled regulated firms to exchange allowances or permits to meet emissions goals at the lowest possible total cost. The Acid Rain Program was an environmental success story: $SO_2$ emissions from electric power plants declined by more than one-third—from 15.9 million to 10.2 million tons—between 1990 and 2004 (U.S. EPA, 2016c), despite a 25 percent increase in electricity generation from coal-fired power plants over the same period (Schmalensee and Stavins, 2013). The program's cap of nearly 9 million tons of $SO_2$ emissions from the power sector was achieved by 2007, and declined further to 5 million tons by 2010.

Another important hallmark of the Acid Rain Program was that its environmental goals were achieved with low costs of implementation relative to net benefits. Electric utilities regulated under this program achieved the goals for emissions reductions at a significantly lower cost than was projected at the outset of the program. Costs projected before implementation of the Acid Rain Program were over $2.7 to $6.2 billion (U.S. EPA, 2011b). However, retrospective studies found that actual annual costs ranged from $0.5 billion to $2 billion, and total annual benefits ranged from $59 billion to $116 billion (Schmalensee and Stavins, 2013).

The Northeast region's second experience with implementing market-based trading to address air pollution from large power plants was the $NO_x$ Budget Program, which was initiated by 12 states in order to attain compliance with National Ambient Air Quality Standards (NAAQS) for ozone. The $NO_x$ Budget Program incorporated key "lessons learned" by regulators in state environmental agencies and utilities from implementing the Acid Rain Program and similar environmental trading programs. In particular, this program was the first time that a group of states worked together to establish their own multi-state program, in lieu of the U.S. Environmental Protection Agency (EPA) promulgating regulations to address summertime ozone exceedances in the region (Pew Center, 2003).[3] Another key feature of the $NO_x$ Budget Program was that the states developed a "model rule," a set of core requirements that each state needed to adopt to ensure a well-functioning program.[4]

The Regional Greenhouse Gas Initiative (RGGI) built from and further leveraged the northeastern states' hands-on experience with implementing multi-state, market-based programs. RGGI is the nation's first regional market-based regulatory program designed to reduce greenhouse gas (GHG) emissions from the electric sector. Beginning in 2003, Governor Pataki of New York invited environmental and public utility

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2 40 CFR Parts 72 through 78.

3 The first example of a local regulator establishing a cap-and-trade program for meeting air quality goals was the RECLAIM program established by South Coast Air Quality Management District to reduce emissions of criteria air pollutants in the Los Angeles County basin.

4 The "model rule" was created by a task force that included representatives from all states in the Ozone Transport Commission and EPA.

staff from 10 northeastern states[5] to begin working together on the scope and design of a regional system to reduce carbon dioxide ($CO_2$) emissions from power plants. The program's scope includes new and existing fossil-fuel electric generating units (EGUs) with capacity of 25 megawatts (MW) or more.[6] In late 2008, the 10 RGGI states held the first allowance auctions in preparation for RGGI's January 2009 start date. As of this writing, the RGGI program has an eight-year track record (i.e., January 2009–December 2016) and the following achievements:

- Raised nearly $3 billion in auction proceeds for participating state investments in energy efficiency (EE), renewable energy (RE), and other public benefit programs;
- Is on track for reducing GHG emissions 45 percent below 2005 levels by 2020;[7]
- Generated net savings in consumers' electricity and energy bills through substantial investments in demand-side efficiency;
- Performed over 30 quarterly allowance auctions in a well-functioning marketplace.

For these reasons, RGGI has been held up as a blueprint for other programs and certainly helped to inform the EPA's proposal for the Clean Power Plan, a national-level GHG program for the electric power sector. However, the direct results of the RGGI program are only a part of the story—its influence in the northeastern United States extends beyond reductions in GHG emissions.

## 1.1 Objectives of Analysis

While the RGGI states' objectives for the program were primarily focused on reducing GHG emissions, increasing the role of renewable energy, and reducing imports of fossil fuels, RGGI and similar clean energy programs also have other, less direct effects on the economy, the environment, and public health. A broader evaluation of the full suite of RGGI's impacts will provide policymakers and the public with a more complete picture of the program's effectiveness.

Analysis Group conducted the first set of studies that analyzed other impacts of RGGI beyond its primary goal of reducing GHG emissions from large power plants. In 2011 and 2015, after RGGI's first three-year compliance periods ended, Analysis Group performed retrospective analysis of RGGI's impact on electricity markets, costs to power producers, impacts on electricity bills of consumers and businesses, and impacts on economic output of the RGGI states. Both of these studies demonstrated that RGGI implementation created positive and substantial benefits to the regional economy over the six years since its inception. This positive economic story resulted in part because the RGGI states opted to invest nearly all of the proceeds received from RGGI allowance auctions back into the economy. The RGGI states did

5 At the outset of the program, Connecticut, Delaware, Massachusetts, Maryland, Maine, New Hampshire, New Jersey, New York, Rhode Island, and Vermont all participated in RGGI. New Jersey left the RGGI program in 2011; nine states currently participate in the RGGI program.

6 Owners of new and existing power plants regulated under RGGI must acquire a tradeable allowance for each short ton of $CO_2$ emitted. Owners of EGUs retire their allowances at the end of a three-year "control period" (also "compliance period").

7 New Jersey left the RGGI program in late 2011, and the emissions cap and goals were readjusted accordingly.

this through expansion of energy efficiency programs, new renewable power projects, assistance to low-income consumers of energy bills, and other programs designed to reduce GHG emissions.

Because Analysis Group's studies of RGGI economic impacts were retrospective, they used historical, real-world data on actual program performance and market outcomes to generate insights into net economic benefits of the program. Retrospective studies like these can provide especially useful inputs to RGGI's regular three-year program review process, during which policymakers in the RGGI states consider adjustments to fine-tune the program's effectiveness and net benefits.

The relationship between programs that improve air quality and public health is well-established: in numerous studies of the costs and benefits of CAA, EPA estimated that improved air quality results in public health benefits that exceed the costs of achieving air quality targets by a 30:1 ratio (U.S. EPA 2011c). Most of the economic value of CAA benefits (about 85 percent) are attributable to health benefits; specifically, reductions in premature deaths associated with reductions in ambient particulate matter (U.S. EPA 2011c). In 2020 alone, EPA estimates that the CAA will prevent over 230,000 early deaths.

Because air pollutants with adverse effects on human health are often co-produced with $CO_2$ when electric power is generated from fossil-fuel power plants, RGGI and similar GHG programs for the power sector are expected to drive some reductions in levels of these air pollutants. Numerous studies have explored the impact of *future* policies and programs aimed at reducing GHG emissions on air pollution and public health. To date, however, few studies have investigated public health impacts of *existing* GHG reduction programs such as RGGI.

To better understand the impacts of RGGI on public health, Abt Associates conducted an independent study of the program's effect on emissions and air quality during the first two compliance periods—2009 to 2014. The objective of our study is to apply credible, widely accepted tools, methods, and publicly available data to answer the following questions:

- Did the first six years of RGGI's implementation result in measurable changes in emissions of criteria air pollutants and air quality?
- If so, how did changes in air quality resulting from RGGI's implementation affect public health and to what degree?
- What spatial and temporal patterns are evident in changes in air quality and health outcomes resulting from RGGI?
- Will health benefits from RGGI's first two compliance periods be replicated in the future?

## 1.2 Scope of Analysis

**Retrospective analysis**. Many policy analyses are *prospective*, that is, they project incremental impacts that are anticipated to occur in the future as a result of policy, relative to a baseline or counterfactual case representing the world without the policy. However, our analysis is *retrospective*, i.e., it looks backward at incremental outcomes and impacts that occurred from 2009 to 2014 as a result of RGGI. Our analysis benefits from having actual historical data for many variables used in the analysis. Specifically, we used EPA datasets to describe actual annual $NO_x$ and $SO_2$ emissions, annual generation levels, and emission rates at the individual plant level for all power plants located in the RGGI states. In addition, we rely upon results from electricity market dispatch modeling runs conducted by Analysis Group in 2011 and 2015; these modeling runs also incorporated actual historical data for fuel prices, costs of emissions allowances, power plant retirements and additions, and other electricity market factors (e.g., transmission constraints).[8]

**Scope.** Below we provide additional detail on the scope of this analysis and how the analytic scope may influence results.

*Timeframe:* The timeframe addressed by this analysis encompasses the entirety of RGGI's first two compliance periods, i.e., 2009 to 2011, and 2012 to 2014, respectively. This is a somewhat limited picture of the incremental impacts of RGGI in one respect: proceeds invested by the states into energy efficiency programs during the 2009 to 2014 timeframe will continue to generate energy savings *after* 2014, because the incremental energy savings from high-efficiency devices funded through these programs typically persist for 10 to 15 years after installation. Our omission of these additional energy savings in this analysis was due to data and modeling limitations.[9] As such, our estimates likely *underestimate* reduced emissions associated with avoided electricity generation due to RGGI, and thus underestimate health benefits.

*Air quality modeling:* To estimate changes in air quality associated with RGGI implementation, we use EPA's Co–Benefits Risk Assessment model (COBRA) (U.S. EPA, 2015c). COBRA includes a reduced-form air quality model that estimates the effect of emission changes on formation of fine particulate matter (referred to as $PM_{2.5}$).[10] COBRA does not estimate changes in ozone, another air pollutant with adverse health effects. Thus, this analysis does not estimate benefits associated with ozone reductions, although they are expected to occur. Changes in levels of ambient particulate matter, however, are typically the largest factor driving human health benefits.[11] Therefore, we expect COBRA to capture a large share of RGGI's impacts on health in the region, although our estimates will be conservative.

*Geographic scope:* The geographic scope of this analysis includes changes in electricity market outcomes and associated emissions changes occurring in states participating in the RGGI program. Because changes in emissions that take place within RGGI states will affect air quality and public health in "downwind" states, we also report results for states within the region affected by the program but not currently participating in RGGI.

*Other benefit categories:* There are additional benefits associated with reducing emissions of $CO_2$ and other air pollutants that are outside of the scope of this study. First, this study does not cover the potential health benefits of mitigating climate change, such as fewer heat-related illnesses or cases of vector-borne disease.

The scope of this study also excludes reductions in regional haze, largely caused by $PM_{2.5}$ pollutants scattering the sunlight, which impairs visibility and also contributes to harmful respiratory impacts. EPA

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8 Descriptions of these dispatch models and results from Analysis Group's use of them in their analyses of RGGI's regional economic impacts can be found in Analysis Group (2011, 2015).

9 Additional detail on tools and methods used for air quality modeling is provided in Section 2.

10 Fine particulate matter is less than 2.5 micrometers in diameter.

11 Anenberg et al. (2010) estimated that in North America annual mortalities due to anthropogenic $PM_{2.5}$ are approximately three to four times greater than annual mortalities due to anthropogenic ozone.

requires reductions in haze through the Regional Haze Rule to improve visibility in federally protected national parks and wilderness areas (U.S. EPA, 1999).

Benefits to ecosystems and natural resources represent a final category of benefits not captured in this analysis. RGGI-related reductions in the deposition of sulfur and nitrogen compounds in the environment, which have adverse effects on terrestrial and aquatic ecosystems, would improve the health of these ecosystems (Miller, 2011). These environmental impacts can also affect human livelihoods and public health.

This remainder of this report is organized as follows:

- **Section 2:** This section provides additional context for changes in air quality and public health as co-benefits of climate mitigation and clean energy policies.
- **Section 3:** This section describes the analytic approach, data, and methods used to estimate changes in emissions, air quality, and public health associated with RGGI implementation from 2009 to 2014.
- **Section 4:** This section provides results of the analysis and discussion of key findings, policy implications, and uncertainties.
- **Appendices:** The appendices include additional background and technical detail describing the air quality and public health modeling tools used in this analysis. Detailed state-level results are available in Appendix E, which is available for download as a separate document. .

# 2. Co-Benefits of Climate Mitigation and Clean Energy Programs

In addition to reducing GHG emissions, climate mitigation and clean energy programs such as RGGI can create an array of other public benefits—often referred to as "co-benefits"—in the energy system, the environment, and the economy.[12] These co-benefits can figure importantly in the analysis of total benefits and overall policy effectiveness. For example, the Intergovernmental Panel on Climate Change (IPCC) finds that the near-term public health co-benefits from climate mitigation may offset a significant portion of total mitigation costs (IPCC, 2013).

Table 2 lists key categories of co-benefits resulting from climate and clean energy policies, which are described below:

- **Energy system co-benefits** result from investments that improve the overall performance and efficiency of electricity grid operations. Energy system co-benefits include reduction in electricity losses over transmission lines (typically up to 10 percent), and alleviating load at times of peak demand. In addition, a more efficient system featuring a higher level of distributed generation resources (in contrast to large centralized power plants connected by long-distance transmission lines) can increase the resilience of the grid to severe storms while also enhancing reliability.
- **Economic co-benefits** associated with a more efficient and decentralized electricity grid include: direct savings on energy bills by consumers and businesses; reductions in high costs of serving peak load; and reducing imports of fossil fuels and thereby retaining more capital in the region. Regional employment and economic development can benefit directly from the growth of clean energy industries. In 2016, the 9 RGGI states plus New Jersey ranked in the top 20 states in the United States for total capital investments in energy efficiency, renewables, clean technology ventures, and policies supporting energy efficiency and clean technology (Clean Edge 2016). In Massachusetts for example, clean energy employment grew more than eight times faster than the overall growth rate across all Massachusetts industries from 2011 to 2013 (Massachusetts Clean Energy Center, 2013).
- **Public health co-benefits** result from improvements to environmental endpoints—airsheds and watersheds—as pollutant loadings to air and water are reduced via lower energy demand and shifting of energy generation to cleaner sources. Emissions of fine particulate matter, which can be emitted directly from sources or formed secondarily through atmospheric chemical processes, can cause premature death, heart attacks, and strokes, as well as harmful effects on the respiratory system, including asthma attacks. This category of co-benefit is the primary focus of this report; however, as noted below, reductions in emissions of mercury (Hg) and ozone-forming $NO_x$ can also result from policies targeting GHGs and are also beneficial to human health.
- **Environmental co-benefits** of climate and clean energy programs arise from reducing total energy demand and shifting generation to cleaner, more efficient sources of generation. Key environmental benefits from clean energy include reductions in emissions of air pollutants and their precursors (e.g.,

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[12] These positive outcomes are often referred to as "co-benefits" because they are additional to the direct program objective of reducing carbon emissions and increasing efficiency and renewable energy. While this list of co-benefits associated with climate mitigation and clean energy programs is fairly comprehensive, more in-depth information can be found in the following sources: U.S. EPA (2011a) and Regulatory Assistance Project (2014).

particulate matter (PM), $NO_x$, $SO_2$, ozone, air toxics, and Hg), which results in reduced formation and deposition of these pollutants.

Ozone is formed by emissions of nitrogen oxides reacting in the presence of sunlight with volatile organic compounds in the air. Ozone's effects on human health include increased frequency of asthma attacks, shortness of breath, aggravated lung disease, damage to lungs through long-term exposure, additional hospitalizations and emergency room (ER) visits, and premature deaths. Coal-fired power plants and other stationary sources (e.g., incinerators) can also release mercury into the air. Airborne mercury emissions then settle into terrestrial and aquatic ecosystems and can be converted to methylmercury, a harmful neurotoxin. Methylmercury enters into the food chain, where it builds up ("bio-accumulates") in fish through their diet. As a result, the most common source of human exposure to methylmercury occurs through fish consumption.

**Table 2. Benefits of Climate Mitigation and Clean Energy Policies**

| | Energy System | Economic | Public Health | Environmental |
|---|---|---|---|---|
| **Direct benefits** | Reduced electricity load and peak demand<br><br>Increase in distributed generation<br><br>Reductions in imports of fossil fuels | Energy savings from energy efficiency investments<br><br>Increased economic activity for energy efficiency and renewable energy sectors | **Improved air quality from co-reductions in emissions of criteria air pollutants** | Reductions in $CO_2$ emissions and impacts of climate change<br><br>Reductions of nitrogen, sulfur, mercury, and other air toxics in air and watersheds |
| **Indirect benefits** | Fuel diversification<br><br>Increased energy security<br><br>Improved grid resilience and reliability | Job creation in clean energy and energy efficiency sectors | Fewer incidences of respiratory and cardiovascular diseases and premature deaths from improved air quality<br><br>Improved water quality | Improved terrestrial and aquatic ecosystem health<br><br>Improved visibility<br><br>Potential reductions in water intake by power plants |

Sources: IPCC (2014); U.S. EPA (2011a); Union of Concerned Scientists (2013).

## 2.1 Regional Economic Impacts of RGGI

The RGGI program had a net positive impact on the regional economy of the Northeast over the initial six years of program implementation. This outcome reflects key policy decisions made regarding the sale of nearly $2 billion of $CO_2$ allowances to owners of fossil-fuel power plants. The decision by RGGI states to auction nearly all emission allowances, rather than distributing allowances directly to regulated entities for free, is a unique and defining feature of the RGGI program.[13] As a result of this key design feature, the states were able to use proceeds collected from allowance auctions during the 2009 to 2014 period for

[13] Emission allowances were allocated freely to regulated utilities under both the Acid Rain and $NO_x$ Budget Programs.

public benefit purposes. Each state determined how to deploy its share of RGGI proceeds based on its own legislative and public policy priorities.[14] During the first two compliance periods of RGGI, states participating in the program invested a substantial portion of auction proceeds into energy efficiency programs, renewable energy generation, and other GHG reduction programs. By investing proceeds into programs that themselves generate additional reductions in GHG emissions and energy demand, the RGGI states essentially leveraged revenues from proceeds to amplify the magnitude of GHG emissions reductions achieved, beyond those that would have been achieved solely from placing a cost on the right to emit $CO_2$.

Analysis Group's empirical review of the RGGI states' strategic investments of proceeds from RGGI auctions into efficiency and clean energy programs showed that these programs generated economic benefits to consumers and business, and an increase in output and employment in the region. Using six years of actual data gathered from RGGI's first two compliance periods, Analysis Group conducted consecutive analyses (in 2011 and 2015, respectively) that tracked individual RGGI states' investments of proceeds on an annual basis, and then estimated direct and indirect impacts of the program on the regional economy. In its calculations, Analysis Group accounted for the effects of the RGGI program on power system dispatch, net energy costs to consumers, revenues to electric generators, and overall state economic performance (Analysis Group, 2011, 2015).

Both the 2011 and 2015 Analysis Group studies arrived at similar conclusions: RGGI states' investments of auction proceeds into energy efficiency, renewable energy, climate mitigation activities, and direct rebates resulted in positive impacts on the region's economic value-added and employment. Analysis Group found that in the period 2009–2011, economic value-added in the RGGI states totaled $1.6 billion, and found similarly that economic value added in the period 2012–2014 was $1.3 billion. These benefits were found to be due in part to the states' combined investments in energy efficiency and clean energy in both compliance periods (Analysis Group, 2011, 2015). Additional economic value-added translated to an average of $31 per capita in the region for the 2012 to 2014 compliance period alone (Analysis Group, 2015). In addition, employment in the RGGI states increased by more than 16,000 job-years in the period 2009–2011, and 14,000 job-years from 2012 to 2014. Table 3 summarizes these key findings from Analysis Group's studies.

### Table 3. Summary of RGGI Economic Benefits, 2009 to 2014

| Type of Economic Impact | First Compliance Period (2009-2011)[1] | Second Compliance Period (2012-2014)[2] |
|---|---|---|
| Total value-added to RGGI states | $1.6 billion | $1.3 billion |
| Net job creation[3] | 16,000 job-years | 14,200 job-years |

Source: Analysis Group (2011, 2015).

1. Reported in 2011 dollars, on a net present value basis using a discount rate of 3 percent.

[14] The 2005 Memorandum of Understanding and the 2008 revised Model Rule designate a minimum of 25 percent of each state's allowance proceeds to go to a "consumer benefit or strategic energy purpose." In practice, states are vastly exceeding the required minimums for public benefit or energy purposes. Allowances are apportioned through state allowance budgets, which are largely based on historical power plant emissions in each state and an agreed-upon formula. The allotment of allowances then determines the magnitude of each state's proceeds from the allowance auction.

2. Reported in 2015 dollars, on a net present value basis using a discount rate of 3 percent and reflects adjustments for inflation.
3. A job-year is defined as providing full-time job for one year.

Analysis Group's studies confirm that investments in energy efficiency acted as an important economic multiplier. Adopting energy efficiency measures reduces the total demand for electricity generation, and reduces wholesale electricity prices through impacts on system dispatch. Consumers who reduce their electricity use by becoming more efficient save on monthly energy bills. On a macroeconomic scale, reduced demand through energy efficiency and expansion of renewables lowers the total amount paid to fossil-fuel generators located outside of the RGGI region. Overall, higher per-kilowatt costs passed on to electricity consumers to cover the costs of $CO_2$ allowance purchases in the short term are offset by energy bill savings resulting from RGGI proceeds investments within the region (Analysis Group, 2015).

In the next section, we provide additional context for this evaluation of RGGI's impact on air quality and public health.

## 2.2 Impacts of Climate and Clean Energy Programs on Air Quality and Public Health

Policies and programs that reduce GHG emissions from electric power plants and other fossil-fuel stationary sources (e.g., industrial boilers) can also achieve important public health benefits. Fossil-fuel power plants emit not only $CO_2$ but also other air pollutants with proven adverse effects on human health, including fine particulate matter ($PM_{2.5}$), $NO_x$, $SO_2$, Hg, and air toxics.

Power plant emissions of $NO_x$, $SO_2$, and other pollutants impact air quality at the local level to varying degrees, depending on characteristics of the source,[15]spatial distribution of emissions, and local meteorological conditions that dictate the formation of pollutants with adverse health effects. The burning of fossil fuels releases $SO_2$, which contributes to the formation of acid rain and $PM_{2.5}$ and can cause impact human respiratory and cardiovascular systems. $NO_x$ emissions also form $PM_{2.5}$ and ground-level ozone, thereby exacerbating negative impacts of this air pollutant. Fine particulate matter composed of airborne solid particles and liquid droplets carries a mixture of soot, smoke, toxic metals, and many other harmful chemical pollutants; inhaling the fine particulate matter can lead to severe health effects. By entering the lungs and even the bloodstream, these air pollutants can cause or aggravate respiratory conditions and cardiovascular diseases and can lead to premature death.

Below we describe results of recent prospective analyses of the impacts of national- and regional-level climate mitigation and clean energy policies on air quality and public health.

**Findings from Recent Studies**

A number of recent studies have demonstrated the link between policies aimed at reducing GHG emissions, associated changes in levels of air pollutants, and resulting impacts on human health. Generally, these studies rely upon a multi-step analytic approach that is similar to the process employed

15 For example, the height of the emissions stack affects dispersion and formation of air pollutants, particularly through wind patterns that contribute to interstate transport of air pollutants. While tall stacks may be designed to limit negative air quality impacts on the local community, the overall pollution does not diminish, it is only transported downwind.

in this analysis (described in Section 3). The first step is to estimate the impact of a proposed policy on emissions of criteria air pollutants. Then, air quality models are applied to estimate how changes in emissions of air pollutants resulting from the policy modify levels of air pollution in specific geographic locations. Finally, a public health model is used to estimate changes in public health outcomes associated with air quality changes to specific geographic locations and populations, and the associated economic value of health impacts.

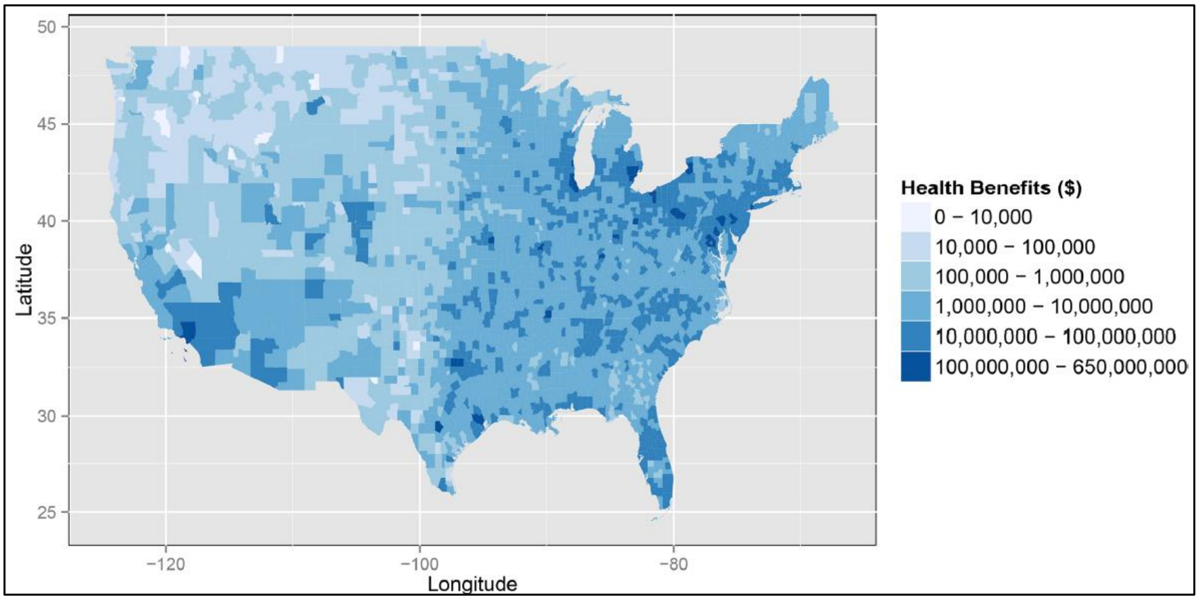
Based on an analysis of three national-level climate mitigation policies (for the electric sector, transportation sector, and an economy-wide trading system, respectively), a 2014 study by concluded that the health benefits associated with reduced $PM_{2.5}$ and ozone could offset some or all of the near-term costs of these policies (Thompson et al. 2014). Estimated public health benefits offset costs of mitigation by a range of 26 to 1,000 percent, with the economy-wide trading system offering the greatest flexibility and the largest potential net-benefits to health. Emission reductions occurring through a clean energy standard generated a median of nearly $40 billion in net benefits, accounting for nearly 120 percent of costs.

A 2015 study compared three national-level climate policies to determine which policy achieved the largest public health co-benefits, based on estimated changes in $PM_{2.5}$ and ozone (Driscoll et al., 2015). The authors found that limiting carbon emissions from power plants, while providing flexible compliance mechanisms and emphasizing energy efficiency investments, resulted in greater health co-benefits than a carbon tax of requiring heat-rate improvements at coal-fired plants. The energy efficiency investment scenario resulted in an estimated 3,500 premature deaths avoided nationally (with a range of 780 to 6,100) through changes in $PM_{2.5}$ and ozone. The study found that air quality improvements are maximized by shifting electric generation from coal plants to lower-carbon emitting sources and investing in demand-side efficiency measures.

A more recent study of a moderately stringent, highly flexible national policy scenario modeled after the final Clean Power Plan (EPA's proposed rule for power plants' GHG emissions nationally) estimates that public health benefits will exceed implementation costs by $12 billion per year in 2020 (Buonocore et al. 2016). The value of health benefits in RGGI states ranged from $10,000 to $100 million per county (see Figure 3). Under this scenario, the study estimates a total of $880 million in public health benefits in the New England states. Among New Jersey, Delaware, Maryland, and Virginia (a non-RGGI state[16]), the study estimates a total of $3 billion in public health benefits. For New York alone, the study estimates a total of $1.6 billion in health benefits.

[16] Throughout this report, we use the term "non-RGGI" to refer to states in the Northeast U.S. that are not participating in the RGGI program.

**Figure 3. Total Annual Health Benefits in 2020 by County for Moderately Stringent, Highly Flexible Carbon Standards**




Source: Buonocore et al. (2016).

Notably, the authors modeled investments in energy efficiency measures beginning in 2013 and increasing until 2025. Associated benefits from energy efficiency accrue years after initial investments are made; therefore, a comparison of costs in 2020 to benefits in 2020 does not take into account total benefits expected when the modeled regulation reaches its full effect in 2030. The authors conclude that not only are health benefits realized in the near term, they are also expected to extend past 2020 (Buonocore et al. 2016).

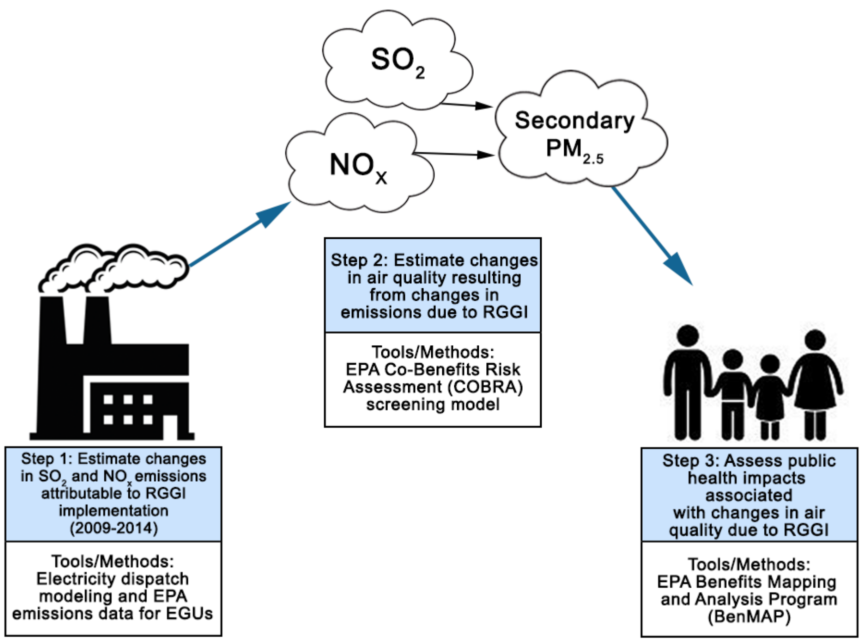
Despite the diversity and complexity of climate and energy scenarios modeled in these studies, they point to a consistent conclusion: there is potential for public health benefits to meet or exceed costs of mitigating GHG emissions by a significant degree. As Thompson et al. (2014) and Buonocore et al. (2016) both observe, estimates of overall net benefits are more sensitive to estimates of mitigation costs than to public health and other benefits.

# 3. Analytic Approach

We used a three-step analytic process to estimate the impacts on air quality and public health resulting from implementation of the RGGI program from 2009 to 2014. As shown in Figure 4, each of these steps relies upon a specific modeling tool (or tools) and datasets to estimate the incremental impacts of RGGI on the following variables: generation (in megawatt-hours (MWh)) by power plants, air pollution emissions, air quality, and public health.

This analysis was highly sequential—results from each analytic step were inputs to the next modeling tool in this process. At each stage of the analysis, we reviewed draft results at a highly disaggregated level and performed quality control before using results as an input to the next analytic step. In many cases, draft results were benchmarked to results from similar analyses and studies as another cross-check.

**Figure 4. Overview of Analytic Steps and Tools**




Source: Abt Associates analysis (2017).

### Step 1: Estimate annual changes in electric generation and emissions of air pollutants at power plants as a result of RGGI implementation from 2009 to 2014.

To determine annual changes in emissions of air pollutants from electric power plants associated with RGGI implementation, we first estimated changes in electricity generation in participating RGGI states. For this step, we relied upon results from electricity dispatch modeling performed by Analysis Group in support of their studies of RGGI's regional economic impacts. These dispatch modeling runs were used to calculate incremental differences in electricity market outcomes between an "RGGI" scenario, and a counterfactual "No RGGI" scenario. Specifically, the difference in results of these two scenarios is the incremental change in annual generation levels (in MWh) for power plants located in the RGGI states (including plants not regulated under RGGI).[17]

We then used actual, annual plant-level emissions and pollution control data from EPA to calculate changes in $NO_x$ and $SO_2$ emissions associated with changes in generation at the power plant level due to RGGI.[18] Changes in plant-level $NO_x$ and $SO_2$ emissions were aggregated at the county level for each year from 2009 to 2014, and then became the key inputs to the air quality modeling conducted in Step 2.

**Step 2: Estimate annual changes in air quality at the county level associated with changes in $SO_2$ and $NO_x$ emissions from power plants, by year.**

For this step in the analysis, we used the COBRA model, developed by EPA to conduct screening-level analyses of the effect of changes in emissions on air quality. We ran COBRA using inputs of annual changes in $SO_2$ and $NO_x$ emissions aggregated for each county in all RGGI participating states derived under Step 1 of the analysis.

COBRA's air quality model simulates chemical reactions in the atmosphere that transform $NO_x$ and $SO_2$ into components of particulate matter. In the northeastern United States, these components constitute the majority of $PM_{2.5}$ resultant from power plant emissions and make up more than half of all ambient $PM_{2.5}$ (NARSTO, 2004). As noted earlier, as a simplified air quality model, COBRA does not model formation of ozone, although this is a major pollutant in the Northeast.

COBRA's outputs are changes in annual ambient $PM_{2.5}$ at the county level, which are the inputs to public health modeling conducted under Step 3.

**Step 3: Assess public health impacts associated with changes in air quality due to RGGI implementation from 2009 to 2014.**

We used the Benefits Mapping and Analysis Program (BenMAP) to translate county-level changes in annual ambient $PM_{2.5}$ from Step 2 into county-level changes in the frequency of various adverse health events among a population, referred to as incidences. BenMAP uses inputs of air quality changes, population, and baseline health incidences (i.e., the background frequency of a health impact in a population) to estimate the public health changes resulting from changes in air quality. BenMAP then estimates the economic value of health incidences avoided based on a synthesis of multiple economic valuation studies.

## 3.1 Estimating Changes in Emissions due to RGGI

Estimating changes in emissions due to RGGI requires isolating RGGI's incremental effect on the electricity market from that of the many other factors affecting the complex electric power system. Variations in weather and economic growth can influence electricity demand. And before RGGI's

[17] The scope of results from the dispatch modeling runs used in this analysis reflected changes in generation by power plants located in RGGI states, but did not include changes in other states and provinces adjacent to or with interconnection to RGGI. Results from dispatch modeling were also available for Pennsylvania but were not validated for plant additions, retirements, and other changes that occurred during the timeframe of this analysis.

[18] While power plants also emit other pollutants that affect air quality and health (such as mercury and air toxics), these pollutants' effects on air quality are not captured in the air quality modeling tool applied in this analysis.

inception in January 2009, major transformations in the market for natural gas, which is a key fuel used in electricity production, were underway. Advancements in shale gas extraction methods significantly increased the supply of domestic natural gas and resulted in substantial decreases in natural gas prices beginning in 2008.[19] Also in this timeframe, effects of the 2009 recession dampened demand for electricity.

In 2010, RGGI Inc. commissioned a study[20] to examine the role of factors that contributed to a 33 percent decrease in $CO_2$ emissions from the electric power sector across RGGI states, from 2005 to 2009 (RGGI Inc., 2010).[21] As shown in Figure 5, the study found that fuel-switching from oil and coal to lower-cost natural gas accounted for nearly one-third of the decline in $CO_2$ emissions from 2005 to 2009. An additional 25 percent of emissions reductions were due to weather, whereas the economic recession was responsible for a small fraction (about 4 percent) of emission reductions. Changes in available generation capacity (i.e., reduced coal capacity and increased nuclear, wind, and hydropower capacity) together accounted for nearly 21 percent of the reduction in emissions.

Finally, energy efficiency and customer-sited renewable generation accounted for approximately 12 percent of emissions reductions over this timeframe. While the study was not an analysis of the effect of the RGGI program, it showed that fuel-switching to natural gas and weather variations were more significant factors in the rapid decline of $CO_2$ emissions over the 2005 to 2009 timeframe than economic conditions or changes in the mix of available generation capacity.

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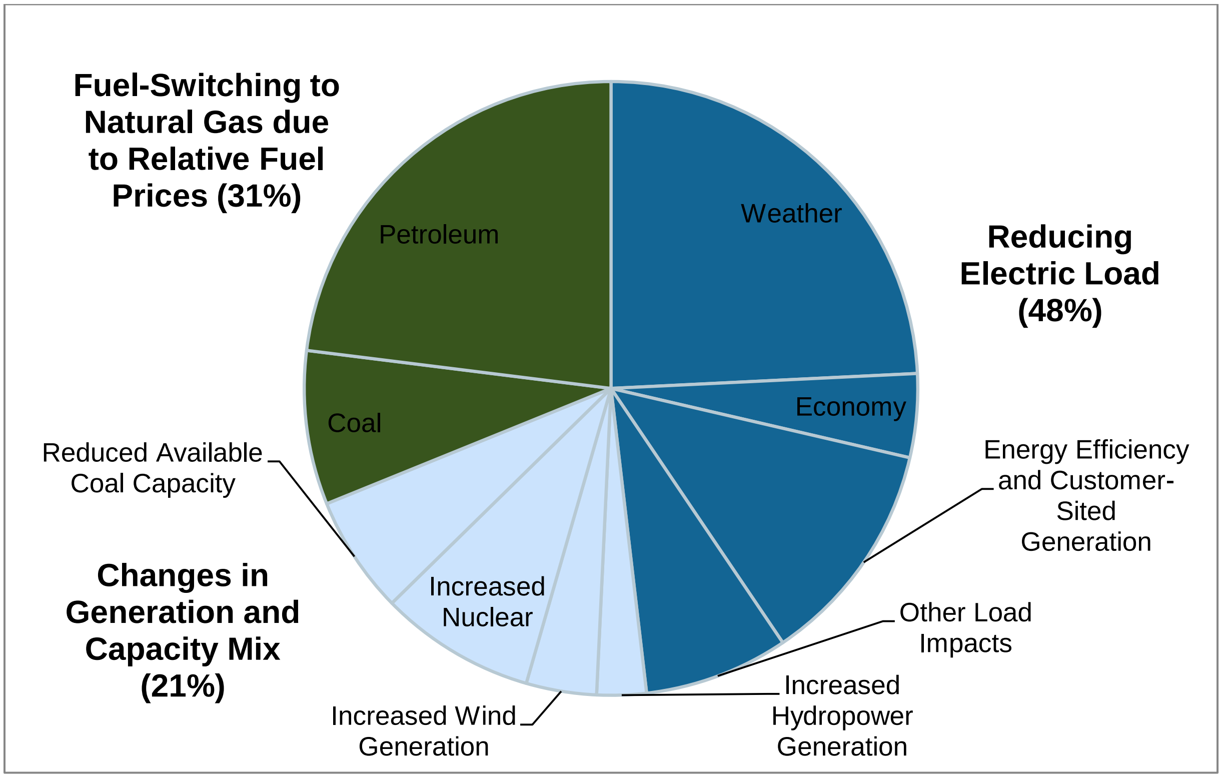
19 The Henry Hub price for natural gas fell by nearly 70 percent between 2008 and 2015 (EIA, 2016).

20 This study was conducted for RGGI Inc. in 2010 by the New York State Energy Research and Development Authority.

21 Note that the timeframe of the RGGI Inc. study preceded RGGI program implementation and was focused on changes in emissions that pre-dated RGGI.

**Figure 5. Factors Influencing $CO_2$ Emission Reductions in RGGI States, 2005-2009**




Source: RGGI Inc. (2010).

Note: Connecticut, Delaware, Maryland, Massachusetts, Maine, New Hampshire, New Jersey, New York, Rhode Island, and Vermont are included in this analysis.

A more recent study focused specifically on RGGI's role in reducing regional $CO_2$ emissions during the first compliance period (2009 to 2011) (Murray and Maniloff 2015). Using econometric modeling, the study isolated the incremental effect of RGGI on emissions from that of other factors, including lower natural gas prices, the 2009 economic recession, and other environmental and energy programs, including states' minimum requirements for renewable energy generation (known as Renewable Portfolio Standards). Accounting for these factors, the study found that $CO_2$ emissions would have been 24 percent higher in the region over the first compliance period if the RGGI program did not exist (Murray and Maniloff 2015).[22]

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[22] The study compared changes in $CO_2$ emissions from the electric sector from 1990-2008 to the 2009-2012 period and found that without low natural gas prices, the RGGI program, the recession, or state renewable goals, $CO_2$ emissions would have been 52 percent higher across the region. The same counterfactual scenario applied nationally found total $CO_2$ emissions would have only been 11 percent higher from 2009 to 2012. As such, the study concluded that nearly half of the actual $CO_2$ emissions reductions in RGGI states during this time period can be attributed to RGGI program implementation. The Murray and Maniloff study did not distinguish between the impact of RGGI's $CO_2$ allowance price from the effects of RGGI states' investments in energy efficiency and renewable energy on emissions, but noted that both are key aspects of RGGI's effect on generation and emissions.

For this analysis, we relied upon results from dispatch modeling of RGGI's first two compliance periods conducted by Analysis Group. These modeling runs estimated RGGI's incremental effect on overall electricity demand, the mix of generation sources and dispatch from power plants in the RGGI states, independent of changes in other variables over the 2009 to 2014 timeframe. These modeling runs provide an estimate of RGGI's incremental effect on the electricity market by simulating a "RGGI" scenario and a "No RGGI" counterfactual scenario. Modeling of the RGGI scenario depicted the two primary direct effects of the program on the wholesale power market, as described below:

- **Costs of $CO_2$ allowance purchases:** Owners of large fossil-fuel power plants purchase $CO_2$ allowances to meet RGGI's cap on emissions, and then build the costs of these purchases into the price at which they are willing to supply power to the wholesale market.[23] In this way, the cost of $CO_2$ allowances affects prices for power in many hours, which in turn can alter marginal generation (i.e., the last generator dispatched to meet hourly demand) from higher- to lower-carbon generation sources.
- **Investments of RGGI proceeds into energy efficiency (EE) and additional renewable generation (RE):** States' investments of RGGI proceeds into energy efficiency measures result in reductions in overall electricity demand and changes in the shape of annual electricity demand profiles.[24] Although much smaller than states' investments in energy efficiency, investments of RGGI proceeds in customer-sited renewables increase the capacity for low- or zero-carbon electricity. Demand-side efficiency investments and an increase in renewable capacity together shift demand for fossil-based electricity downward, resulting in changes to the mix of generation sources dispatched and associated emissions.

The No RGGI scenario is a counterfactual case of power market outcomes absent these two effects of RGGI. In this counterfactual scenario, all other variables affecting power markets except for RGGI (i.e., fuel prices, transmission constraints, $NO_x$ and $SO_2$ allowance prices, state renewable energy requirements, plant retirements and additions) were held constant to the RGGI scenario. The difference between these two scenarios (i.e., RGGI and No RGGI) represents RGGI's incremental effect on the power system; specifically, changes in hourly generation by power plants located in RGGI states.

Because this analysis is retrospective, we had access to actual historical data depicting annual generation and emissions at individual power plants under RGGI. However, our retrospective approach also presented some analytical challenges in cases where results for the modeled RGGI scenario differ from

23 New England and many mid-Atlantic states have competitive markets for electric power, which means that prices bid into the market by power plant owners should be close to the marginal costs of producing the last unit needed to meet hourly electricity demand.

24 Different energy efficiency programs tend to reduce hourly electricity demand in different ways, and thus affect the "shape" of customer demand over the course of the year in addition to reducing the total aggregate demand across the year. For example, energy efficiency programs that focus on replacing older, inefficient air conditioning units with newer, more efficient models generate reductions in electricity demand almost exclusively in summer daytime hours, when electricity demand peaks across the Northeast region. An air conditioning energy efficiency program thus alters the "shape" of electricity demand by generating reductions only in summer daytime hours. This, in turn, disproportionately reduces generation from the most expensive, least efficient, and most polluting generating resources during the highest-load hours of the year.

actual RGGI data. Such differences are typical because dispatch models simulate economically optimized outcomes that do not perfectly align with power producers' actual, real-world decisions.

To calibrate dispatch modeling results to actual, "real-world" outcomes, we based our analysis on the *relative* incremental effect of RGGI simulated by the dispatch modeling. Using actual data for RGGI, we constructed a new No RGGI scenario by applying the *percent difference* between emissions levels from the modeled results for the RGGI and No RGGI scenarios to actual emissions levels under RGGI. The difference between the RGGI emissions inventory and the No RGGI emissions estimate is the incremental change in emissions due to RGGI. These emissions changes then become the inputs to Step 2 of the analysis described below.

Appendix A includes descriptions of specific calculations and datasets used in our analysis of incremental emissions changes due to RGGI.

## 3.2 Air Quality Modeling

EPA developed the COBRA model to conduct screening-level analyses of the effect of emissions changes on air quality. COBRA models the ambient air quality changes that result from criteria pollutant emissions using a simplified air dispersion model, which quantifies the relationships between emissions from each source and air quality (average annual $PM_{2.5}$) in each county. As described earlier, the choice to apply the COBRA air quality modeling tool for this analysis results in a somewhat more limited picture of actual changes in air quality than could be developed with a more detailed air quality modeling tool.[25] To reiterate, COBRA estimates how changes in emissions of primary $PM_{2.5}$, $SO_2$, and $NO_x$ result in changes in ambient levels of $PM_{2.5}$, but COBRA does not model changes in ozone formation.

We used the COBRA model in order to estimate changes in air quality due to RGGI implementation. To run the COBRA model, we input estimated annual changes in $SO_2$ and $NO_x$ emissions derived under Step 1 of the analysis, aggregated at the county level, for all counties in RGGI participating states. We input these into COBRA for each modeling year 2009 through 2014 and then performed a COBRA run for each of these years. Outputs from each of these COBRA runs are changes in annual levels of ambient $PM_{2.5}$ for each county, and are expressed in micrograms per cubic meter ($\mu g/m^3$). Annual county-level changes in ambient $PM_{2.5}$ then became the inputs to Step 3, modeling of public health impacts.

The scope of our analysis of air quality excludes the effect of energy savings associated with RGGI states' investments in energy efficiency made in the 2009 to 2014 timeframe that persist past 2014. To include the effect of these energy savings on air quality and health would require a projection of emissions inventories for all sectors to support additional COBRA modeling runs for each year subsequent to 2014. Because projections for future baseline emissions are currently unavailable for this timeframe, however, the impact of these energy savings was excluded from this analysis.[26]

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[25] For example, the Community Multiscale Air Quality and CAMx models are often used to conduct cost-benefit studies of major proposed regulations—these models are capable of very detailed atmospheric modeling to estimate how emissions form ambient levels of ozone and ambient fine particles at very granular geographic levels.

[26] Specifically, the only annual emissions projection currently available from EPA is for the year 2025.

COBRA and underlying assumptions and data sources used for this step are described in more detail in Appendix B.

## 3.3 Public Health Modeling

To estimate the public health benefits resulting from RGGI, we used EPA's BenMAP, Version 4.0.67.[27] BenMAP uses data describing population, frequency of baseline health outcomes, and economic values to estimate the number and economic value of health impacts resulting from changes in air quality.

Abt Associates designed and implemented the original BenMAP model for EPA, which was the first publicly available model for valuing the health impacts of changes in air quality. EPA's current version of BenMAP[28] is being deployed around the world by government agencies and others for generating estimates of public health improvements resulting from reductions in air pollutants.

We used the county-level estimates of RGGI's effect on $PM_{2.5}$ relative to observed ambient $PM_{2.5}$, generated by COBRA under Step 2, as inputs to BenMAP. BenMAP used these estimated changes in ambient $PM_{2.5}$ to calculate the health benefits resulting from RGGI for 2009-2014.

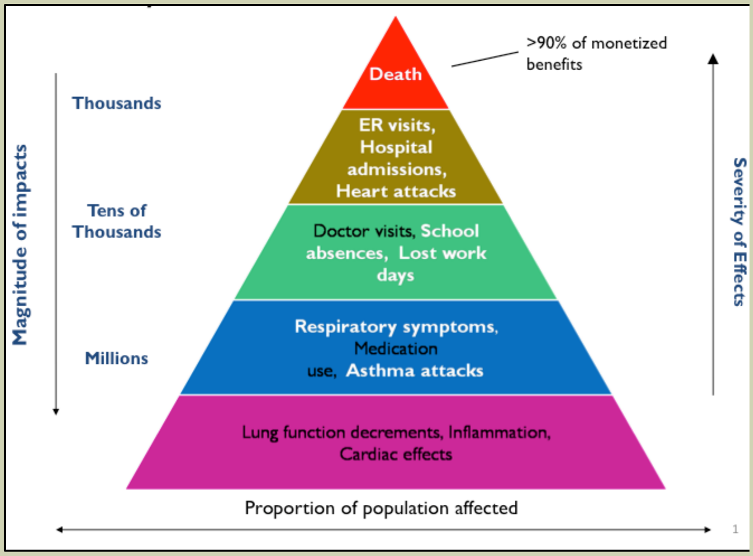
BenMAP and underlying assumptions and data sources used for this step are described in more detail in Appendix C.

27 COBRA also has functionality to estimate health benefits, but we selected BenMAP over COBRA for this step of the analysis because BenMAP allows us to capture changes in baseline population, incidence, and valuation over the entire study timeframe. While COBRA is an appropriate tool for estimating ambient air quality, the fact that its datasets are tied to a specific calendar year limits its representation of how air quality affects public health over time.

28 This version is known as BenMAP-Community Edition.

## How Does BenMAP Value Health Benefits?

**Effects of Air Pollution on Health**




Source: U.S. EPA (2016a).

As a society we value a clean, safe environment and a healthy population. Without an explicit value tied to a public good such as clean air,[1] it is challenging to evaluate the costs, benefits, and overall effectiveness of policies and programs that enhance or protect public goods. To estimate the value of public goods that are not traded in markets, economists rely upon a range of methods. One approach to quantifying the value of programs that benefit human health is to calculate the value of avoiding the "cost of illness," such as medical expenses and lost productivity. Another method is based on the value that individuals are willing to pay to avoid illness or reduce the risk of premature death.

To estimate a value for health benefits resulting from a reduction in air pollution, BenMAP estimates the value of total avoided health costs. BenMAP links air quality changes to public health outcomes by applying empirical relationships derived from epidemiological studies between air pollutants and 12 categories of human health effects (described in detail in U.S. EPA, 2015a). The economic value of improving air quality increases with the number of avoided premature deaths and illnesses, though the value of different avoided health effects can vary widely. For example, the economic, or "monetized" value for an avoided case of adult mortality is over $9 million, compared to the monetized value of an avoided case of respiratory symptoms ($22-$36); see Appendix C for a table of avoided health effects and their economic values.

As the "pyramid of effects" in the accompanying figure illustrates, the majority of monetized health benefits from reductions in air pollutants arise from a small number of avoided premature deaths (U.S. EPA, 2016a). The value of an avoided premature death is an estimate of how much people are willing to pay for small reductions in the risks of premature death (U.S. EPA, 2016b). This concept of avoided risk is commonly expressed as the "value per statistical life" (VSL), and is a commonly used value in economic and regulatory analysis of environmental and public health policies. It is important to note that the VSL concept represents the sum of many small risk reductions that are then aggregated, and does not represent the monetary value of an individual life.

# 4. Results and Discussion

In this section of the report, we discuss results from each analytic step used to determine RGGI's impact on public health. We then provide an overview of key findings, policy implications, and uncertainties for these results.

## 4.1 Changes in Generation due to RGGI

We calculated changes in electricity generation due to RGGI first on an absolute basis (in MWh per year), and then expressed them as a percentage relative to generation that would have occurred in the No RGGI scenario. These percentages are based on generation changes in RGGI-participating states only. Table 4 shows that the RGGI program resulted in a net reduction in electricity generation in every year of the first two compliance periods.[29]

### Table 4. Annual Change in Generation due to RGGI

| | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
|---|---|---|---|---|---|---|
| Generation change in RGGI States | -5.8% | -2.9% | -2.0% | -3.4% | -7.0% | -6.9% |

Source: Abt Associates analysis (2017).

Reductions in annual generation ranged from a low of 2.0 percent in 2011 to a high of 7.0 percent in 2013. Changes in generation as a result of RGGI were lowest overall in 2010 and 2011. The most significant RGGI-induced changes in generation occurred in 2009, 2013, and 2014.

In competitive electricity markets, changes in any number of variables, including fuel prices, weather, and plant and system operational changes, can cause variations in the level of electricity dispatched by a given power plant (or group of plants) from year to year. In this analysis, however, our modeling results account for all of these factors and thereby isolate the incremental effect of RGGI on electricity markets and dispatch. Thus, we interpret RGGI-induced changes in generation to be a result of the combination of (1) RGGI states' investments in energy efficiency and renewable energy and (2) the effect of $CO_2$ allowance prices on electricity dispatch. Our analysis does not quantify the individual contributions of these elements of the RGGI program to RGGI's overall net effect.

In addition to allowance prices and states' investments in EE and RE, the "announcement effect" is another factor that may have influenced the market response to RGGI. This effect describes the response by power plants owners to RGGI states' announcements of their intentions to join the RGGI system. If a plant owner believes an announcement to be credible, the prospect of future carbon prices can spur them to invest in lower-carbon generation options before the policy starts.[30] A 2015 study found that the

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29 Note that this analysis reflects modeling results only for those states that participated in RGGI at some point during the first two compliance periods. New Jersey participated in RGGI's first compliance period from 2009 to 2011, but did not participate in RGGI's second compliance period from 2012 to 2014. We modeled generation changes in New Jersey for 2009 to 2011, and assumed no generation changes from 2012 to 2014.

30 Alternatively, if firm or plant owners do not view a policy announcement as credible, they might wait until a program takes effect to act. Murray and Maniloff (2015) noted literature which finds that the announcement effect was significant for policies addressing other air pollutants.

announcement of the RGGI program likely had a statistically significant effect on $CO_2$ emissions before and shortly after RGGI's start date (i.e., late 2008 and early 2009)—this suggests that owners of power plants in RGGI states did find states' policy announcements to be credible and took early actions to reduce $CO_2$ emissions (Murray and Maniloff 2015). The anticipation of pending $CO_2$ emissions limits may have affected plant owners' demand for $CO_2$ allowances and generation bids in 2009, the first year of the program.

Note that these results do not reflect changes in generation that may have occurred at power plants located in states or Canadian provinces (e.g., Quebec) adjacent (and with interconnection) to RGGI states, but not participating in RGGI. It is possible that changes in the marginal costs of electricity dispatch associated with pass-through of the cost of $CO_2$ allowance purchases by plant owners in RGGI states resulted in increases in electricity dispatch in non-RGGI states and provinces outside RGGI to some degree. Modeling by Resources for the Future (RFF) in 2004 projected that under RGGI, generation and $CO_2$ emissions in non-RGGI states would increase due to RGGI. Specifically, RFF estimated that that for every 100 tons of $CO_2$ reductions within the RGGI region, non-RGGI states and provinces adjacent to the RGGI region could emit an additional 37 tons of $CO_2$, a dynamic known as "leakage" (RFF, 2004).

RGGI Inc. (2013) examined patterns in generation in neighboring states over the first three years of RGGI implementation, and did not find conclusive evidence of substantial leakage to generators in non-RGGI states:[31] $CO_2$ emissions from non-RGGI electricity generators did not appreciably increase during 2009 to 2011 relative to a base period of 2006 to 2008, and total electric generation from all non-RGGI electric generation sources serving load in the RGGI region increased by only 1.2 percent, or 3.3 million MWh, over the same timeframe. A later RGGI Inc. study (2016) found that generation from all generators in non-RGGI states increased by nearly 12 percent in 2012 to 2014 compared to the 2006 to 2008 base period. However, neither RGGI Inc. study estimated RGGI's incremental effect on changes in generation in non-RGGI states and provinces relative to a counterfactual scenario, and thus are inconclusive with respect to the program's incremental impact on $CO_2$ emissions from these jurisdictions.

To account for the uncertainty in RGGI's effect on generation and emissions from fossil-fuel generators located in neighboring non-RGGI states and provinces, we applied a sensitivity factor that discounts benefits in non-RGGI states by 50 percent to represent a low-end estimate. Our high-end estimate of our range of estimates assumes 100 percent of benefits for non-RGGI states were realized.

## 4.2 Changes in Criteria Pollutant Emissions due to RGGI

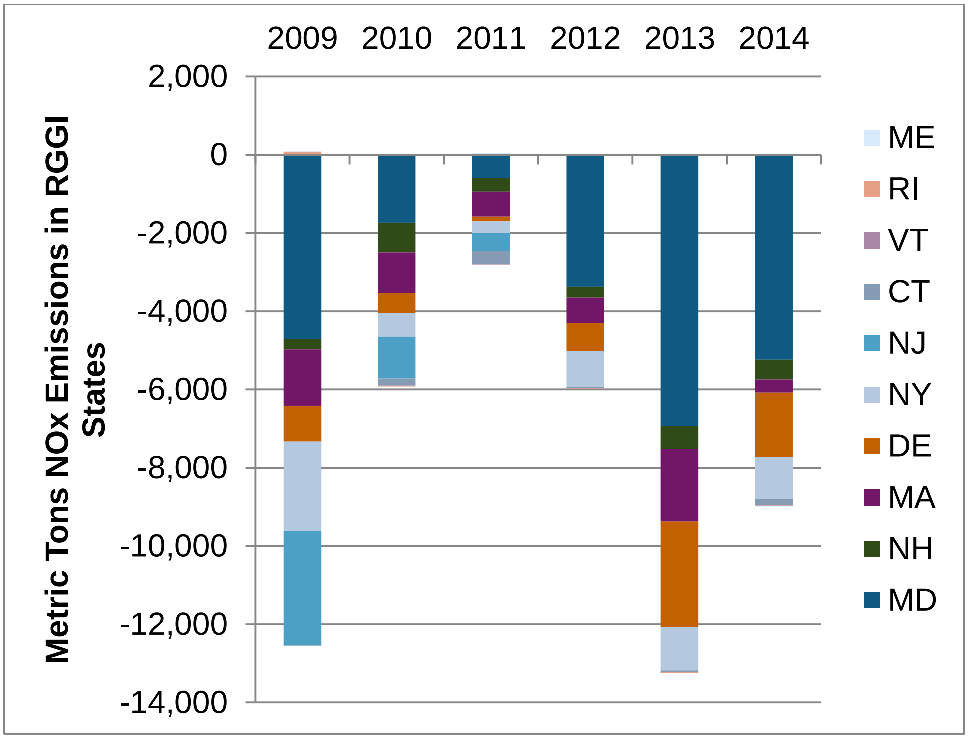
As described earlier, this analysis tracks changes in emissions of $SO_2$ and $NO_x$ resulting from RGGI implementation. Annual changes in levels of these pollutants are the primary inputs to modeling of RGGI's impacts on air quality and public health.

Results of this analysis show that RGGI resulted in net reductions of both pollutants in each year of RGGI's first two compliance periods. Figure 6 shows that the largest reductions in $NO_x$ emissions due to

31 Note that RGGI Inc.'s monitoring reports are based only on comparisons of empirical data for generation and $CO_2$ emissions since RGGI's start in 2009 to similar data before the program began, and do not include modeling of a counterfactual No RGGI scenario. As such, RGGI Inc. notes that it cannot say conclusively what the likely magnitude of changes in generation and $CO_2$ emissions from neighboring non-RGGI states would have been in the absence of the RGGI program.

RGGI also coincide with years with the most significant declines in generation—2009, 2013, and 2014. In 2009, $NO_x$ reductions from Maryland plants accounted for about one-third of total reductions, with plants in New York and New Jersey also accounting for significant $NO_x$ reductions. In 2013 and 2014, reductions from plants located in Maryland and Delaware accounted for most of the reductions in total $NO_x$ emissions. Decreases in $NO_x$ emissions due to RGGI were at their lowest levels in 2010, 2011, and 2012.

**Figure 6. Changes in $NO_x$ Emissions due to RGGI**

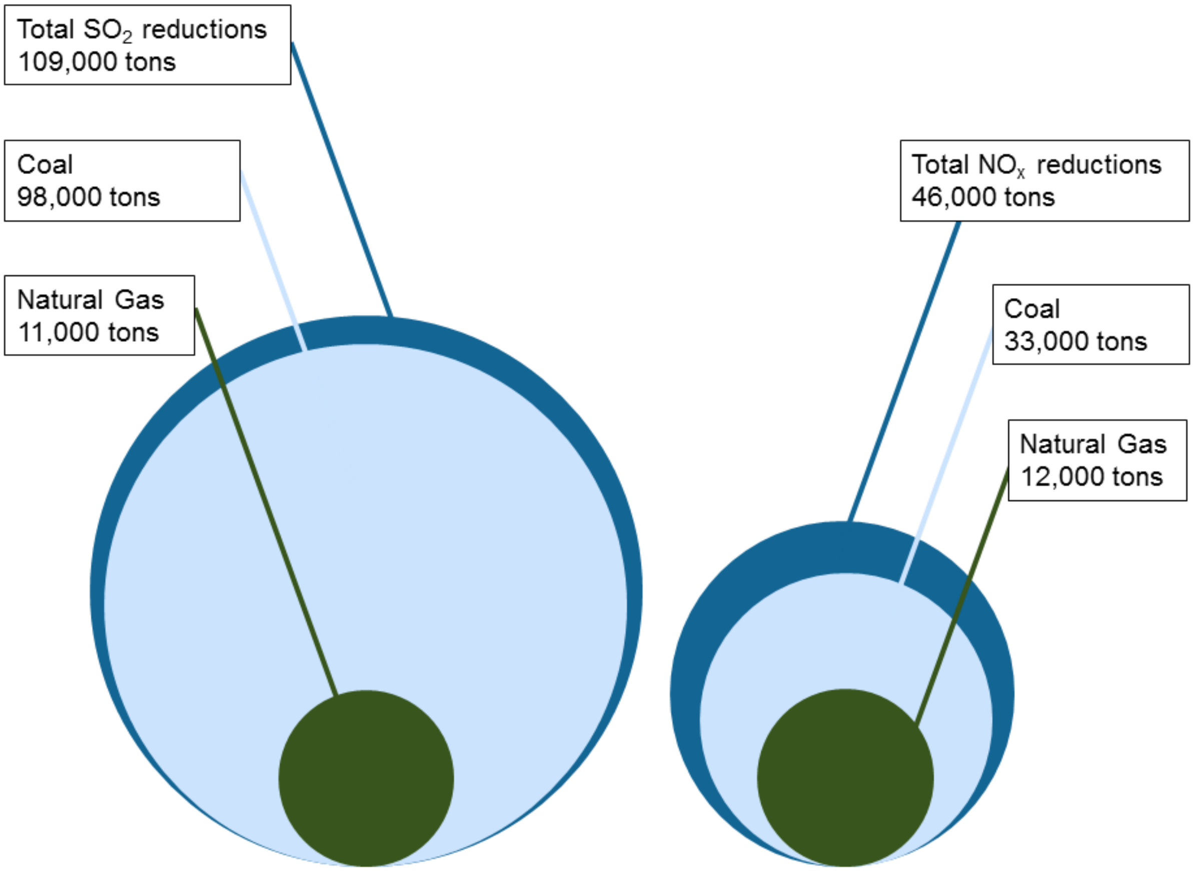



Source: Abt Associates analysis (2017).

Due to the high sulfur content of coal, emission rates of $SO_2$ are significantly higher for coal-fired power plants than for natural gas plants. Therefore, reductions in generation by coal-fired plants as a result of RGGI dominate total $SO_2$ reductions. As shown in Figure 7, coal plants account for 90 percent of reductions in $SO_2$ emissions resulting from RGGI. However, $NO_x$ emission rates for coal- and natural-gas fired generation are much more comparable, especially when coal units are controlled for $NO_x$.[32] As such, RGGI-induced reductions in $NO_x$ emissions can occur from a decline in generation by either coal-fired or natural gas-fired units. As shown in Figure 7, coal plants account for 73 percent of total RGGI-induced $NO_x$ reductions from 2009 to 2014, while natural gas plants account for 26 percent of total $NO_x$ reductions due to RGGI in the same timeframe.

32 See Figure 18 in Appendix D for a comparison of $NO_x$ and $SO_2$ emission rates across generation technologies and fuel types.

**Figure 7. Changes in $SO_2$ and $NO_x$ Emissions due to RGGI from 2009-2014, by Fuel Type**




Source: Abt Associates analysis (2017).

Figure 8 shows that RGGI results in a decline in $SO_2$ emissions relative to the No RGGI baseline in every year of RGGI's first two compliance periods. RGGI had by far the greatest impact on $SO_2$ emissions in 2009, when $SO_2$ emissions fell by more than 76,000 metric tons. This single-year decline also accounts for nearly half of total reductions in $SO_2$ emission reductions over the full 2009 to 2014 timeframe. Moreover, the majority of $SO_2$ emission reductions in 2009 occurred in Maryland, which has the largest capacity of coal-fired power plants in all RGGI states. In response to Maryland's Healthy Air Act of 2006, $SO_2$ controls were installed at five of Maryland's coal plants in late 2009.[33] As a result of these controls, the $SO_2$ emissions rate (tons of $SO_2$ per MWh) declined by nearly an order of magnitude at some of these plants. This explains why absolute $SO_2$ reductions in Maryland are much smaller for all years after 2009, even in years such as 2013 and 2014 when RGGI resulted in meaningful decreases in generation from these plants.

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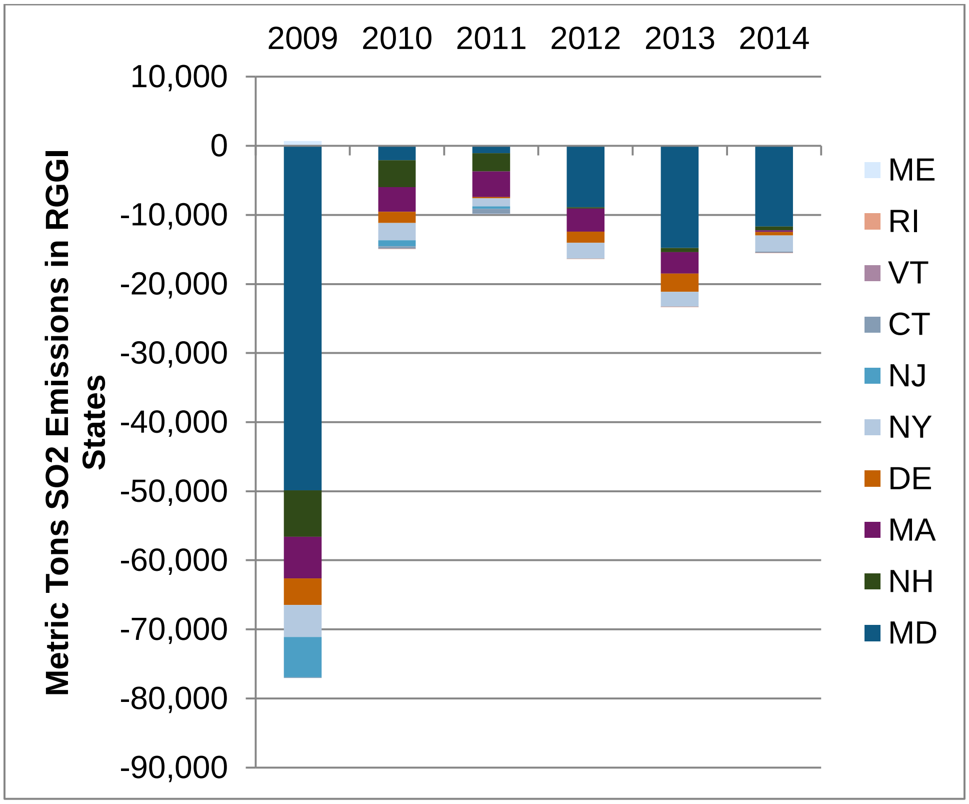
33 Controls for $SO_2$ were installed in the last two months of 2009 on the following Maryland coal plants (units): Brandon Shores (1 unit); AES Warrior Run (1 unit); Morgantown (2 units); Dickerson (3 units); and Chalk Point (2 units).

**Figure 8. Changes in $SO_2$ Emissions due to RGGI**




Source: Abt Associates analysis (2017).

### Accounting for State Power Plant Regulations: Maryland's Healthy Air Act

With seven large power plants and more than 4,600 MW of capacity fired by coal, at the time of RGGI's start in 2009, Maryland had the largest inventory of criteria pollutant emissions from power plants of all states in the RGGI region. In 2006, Maryland passed the Healthy Air Act (HAA) in 2006 to achieve Clean Air Act goals for $NO_x$, $SO_2$, and Hg emissions from large power plants. Owners of Maryland coal-fired power plants installed a significant number of controls for these pollutants shortly after HAA took effect. Most of these controls, which included flue gas desulfurizers, baghouses, injection systems, and scrubbers, were installed on MD coal units within four years after HAA took effect. These controls were highly effective—between 2009 and 2010, $SO_2$ emissions fell by more than 80 percent, and $NO_x$ emissions declined by more than 60 percent from 2007 to 2009 (Maryland Department of the Environment, 2015).

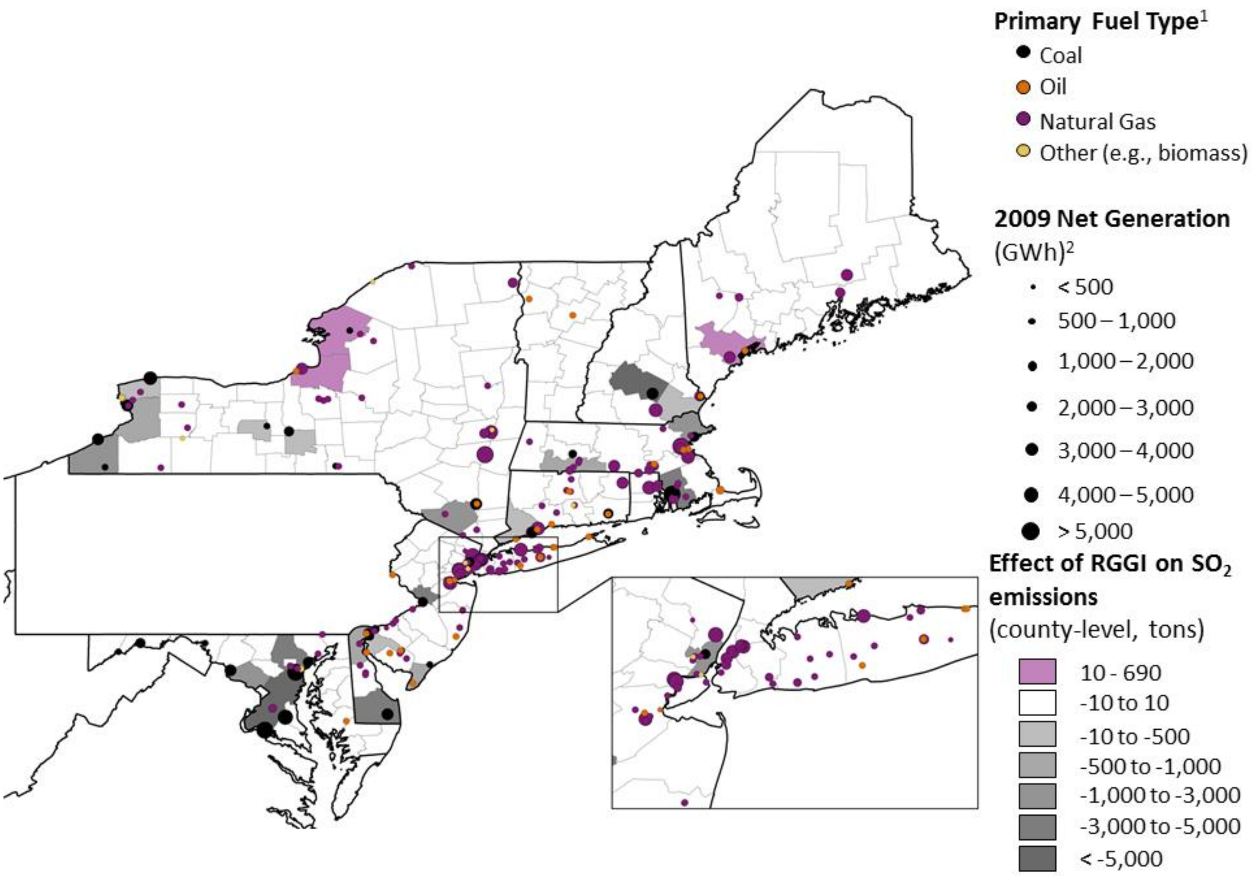
Given the importance of $SO_2$ emissions from Maryland's coal-fired power plants to this analysis, we sought additional input from Maryland Department of Environment staff to make sure that our emissions inventories for 2009 and 2010 accurately reflected total emissions for Maryland's power plants. We also pulled plant-specific data on control installations from EPA to ensure that our plant-specific emission factors for $SO_2$ and $NO_x$ reflected changes made in response to the HAA. As a result, we are confident that results from this analysis reflect incremental emissions reductions in Maryland that are attributed to RGGI rather than to Maryland's HAA. We also confirmed that annual emission factors for other coal plants outside Maryland accounted for installations of pollution controls.

In addition to reductions from Maryland, RGGI has also resulted in $SO_2$ reductions from individual legacy coal plants[34] located in Delaware, New England, and New York, as shown in Figure 9. However, because these coal plants are generally more geographically isolated than Maryland's coal plants,[35] the impacts of $SO_2$ emissions reductions from these individual plants on air quality in surrounding downwind counties is more easily observable in air quality results. For the most part, the single largest county-level reductions in $SO_2$ emissions in 2009 occurred in or immediately adjacent to a county with a large coal-fired plant; however, a few oil-fired plants also played a role in changes in $SO_2$ emissions. In a few counties, $SO_2$ emissions actually increased to a small degree due to an increase in generation by a local oil- or coal-fired plant. However, each of these counties still experienced net improvements in air quality.

[34] Legacy in this context refers to older coal plants, built in the 1950s to 1970s to serve baseload power needs and whose original capital costs are fully amortized.

[35] Five of Maryland's coal plants are clustered relatively close together in Anne Arundel, Charles, and Prince Georges counties.

**Figure 9. RGGI-Regulated Plants and 2009 $SO_2$ Reductions**




Source: Abt Associates analysis (2017).

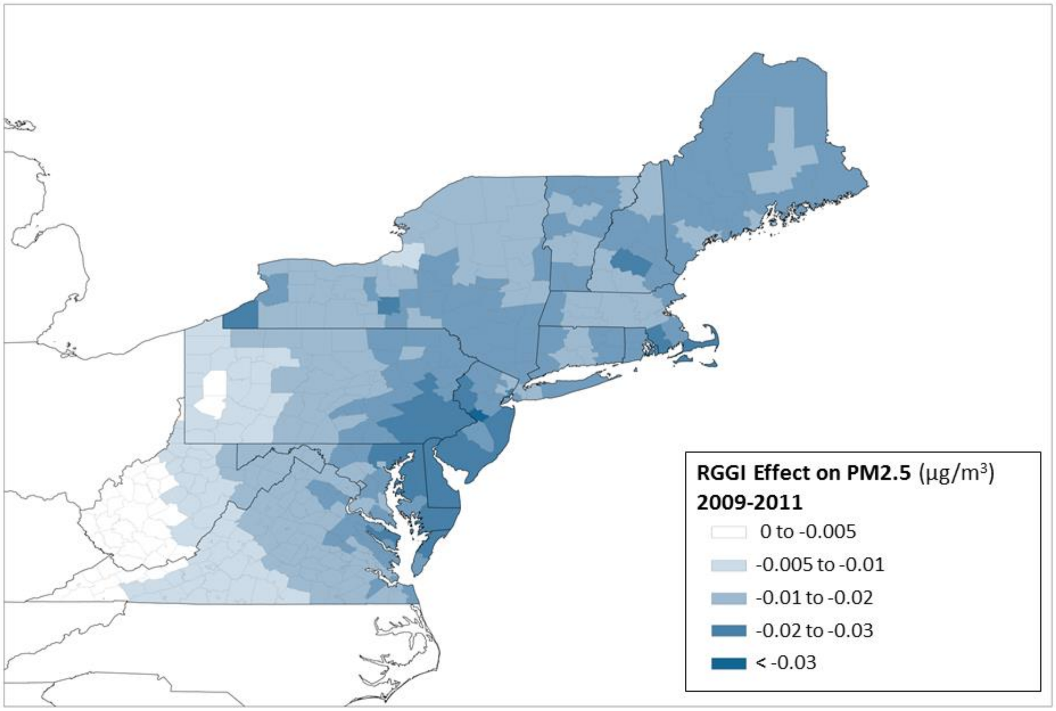
1. Primary fuel type identified from the Emissions and Generation Resource Integrated Database (eGRID) (U.S. EPA 2009).
2. Net generation data from the EIA Form 923 (U.S. EIA, 2009b). Net generation includes generation from all fuel types, not just the primary fuel type. Excludes generation from nuclear units.

## 4.3 Impacts on Air Quality due to RGGI

RGGI resulted in incremental improvements to air quality in every year of the program's first six years. However, because air pollutants can be transported long distances from where they are first emitted, the spatial distribution of air quality improvements resulting from RGGI differs from the locations of plants where emission reductions originated.

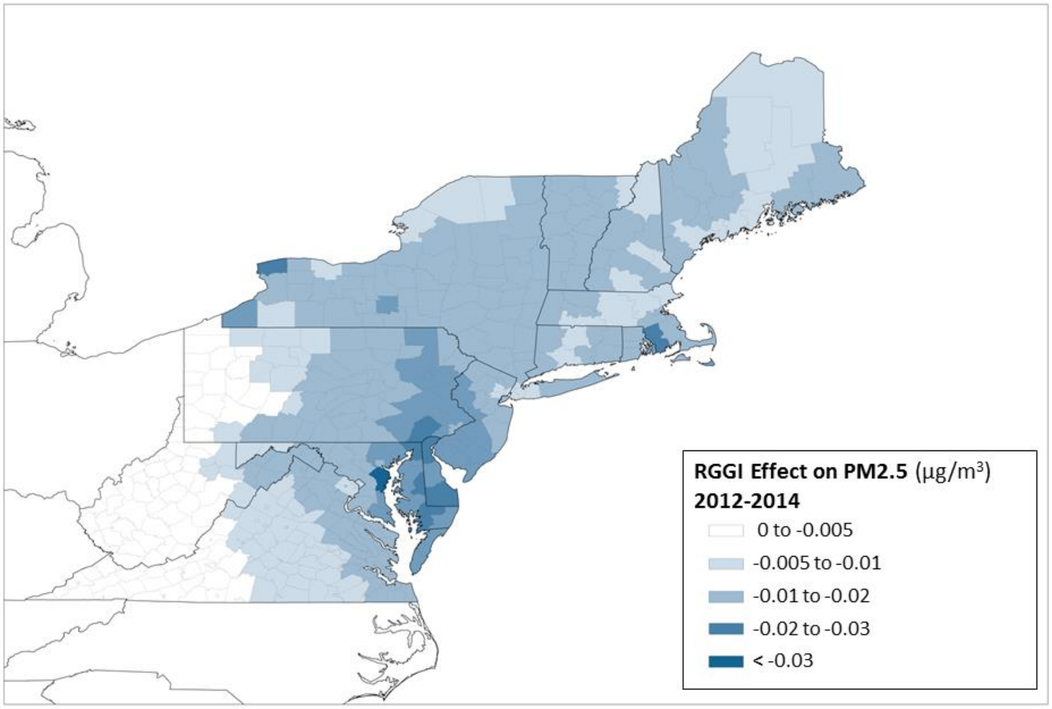
Figure 10 and Figure 11 illustrate the spatial distribution of county-level changes in air quality due to RGGI for the first and second compliance periods, respectively. Generally, the most significant air quality improvements occurred in states and counties adjacent to or downwind of Maryland's power plants regulated under RGGI, although certain counties in New York (i.e., Chautauqua County and Tompkins County), and New England (Merrimack County, NH and Bristol County, MA) with or downwind of large coal plants also experienced notable air quality improvements due to RGGI. Counties in Delaware experienced the largest absolute declines in ambient $PM_{2.5}$ under RGGI because of their location immediately downwind of Maryland's coal plants, which account for the largest absolute reductions in $SO_2$ emissions as a result of RGGI.

**Figure 10. RGGI Effect on Annual Average $PM_{2.5}$, 2009 to 2011**




Source: Abt Associates analysis (2017).

### Figure 11. RGGI Effect on Annual Average $PM_{2.5}$, 2012 to 2014




Source: Abt Associates analysis (2017).

Regional transport of pollution means that changes in emissions from plants located in RGGI states also impact air quality in non-RGGI states. Our modeling results show substantial air quality benefits in the non-RGGI states of Pennsylvania and New Jersey[36] due to emission reductions from plants located in RGGI states. However, as noted earlier, this analysis did not estimate possible shifts in generation and emissions that may have occurred in non-RGGI states in response to RGGI, so these changes cannot be considered net of those changes in emissions and air quality.

All counties in RGGI states met EPA's annual average $PM_{2.5}$ standard during the 2009 to 2014 timeframe and still met this standard when we modeled air quality without RGGI. EPA, however, does not set NAAQS at "zero-risk" levels,[37] which means that incremental benefits to health occur even when air quality improvements exceed EPA standards.

It is important to note that our analysis only addressed changes in annual average $PM_{2.5}$ concentrations, and that $PM_{2.5}$ concentrations are highly variable over the course of a year. A single short-term exposure to high $PM_{2.5}$ concentrations can lead to more severe human health outcomes than multiple exposures to low $PM_{2.5}$ concentrations, which is why EPA sets a 24-hour $PM_{2.5}$ standard as well as an annual average $PM_{2.5}$ standard. To the degree that RGGI states' investments in energy efficiency programs aimed

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36 Note that New Jersey was a participant in the RGGI program in the first compliance program (2009 to 2011) but not in the second (2012 to 2014).

37 The Clean Air Act does not require EPA to establish air quality standards at a zero-risk level or at background concentrations, but rather at a level that reduces risk sufficiently to be protective of public health "…with an adequate margin of safety." (U.S. EPA, 2010).

specifically at reducing peak load, it is possible that RGGI had an amplified impact on low air quality days. However, the scope of this analysis did not include RGGI's effects on daily air quality changes.

Table 5 and Table 6 show RGGI's effect on air quality, as measured by changes in annual average levels of ambient $PM_{2.5}$, in RGGI states and non-RGGI states, respectively. RGGI's effect on air quality over time was largely consistent with its effect on emissions over time. Changes in air quality due to reductions in average $PM_{2.5}$ levels were the most significant in every state in 2009, and by a fairly significant margin over air quality improvements in other years. The next largest impact on average annual $PM_{2.5}$ occurred in 2012 to 2014, and RGGI's effect on average annual $PM_{2.5}$ was lowest in 2010 and 2011. Overall, air quality improvements in RGGI's first compliance period were larger than those in the second compliance period.

Delaware, Maryland, Pennsylvania, and New Jersey experienced the largest changes in $PM_{2.5}$ in 2009, and Delaware experienced the highest average reduction in annual $PM_{2.5}$ among all RGGI and non-RGGI states over the full time period. Pennsylvania experienced the largest average improvement among non-RGGI states. Improvements in air quality were the lowest in all states in 2011.

### Table 5. RGGI Effect on Annual Average $PM_{2.5}$ in RGGI States

| State | RGGI Effect on Annual Average $PM_{2.5}$ in RGGI States (Counties weighted by population) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | Average |
| DE | -0.12 | -0.02 | -0.01 | -0.03 | -0.05 | -0.03 | -0.04 |
| MD | -0.06 | -0.01 | 0.00 | -0.02 | -0.03 | -0.02 | -0.02 |
| RI | -0.05 | -0.02 | -0.01 | -0.02 | -0.02 | -0.01 | -0.02 |
| MA | -0.04 | -0.02 | -0.01 | -0.02 | -0.02 | -0.01 | -0.02 |
| NH | -0.05 | -0.02 | -0.01 | -0.01 | -0.01 | -0.01 | -0.02 |
| VT | -0.04 | -0.01 | -0.01 | -0.01 | -0.02 | -0.01 | -0.02 |
| ME | -0.04 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.02 |
| CT | -0.04 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.02 |
| NY | -0.04 | -0.01 | 0.00 | -0.01 | -0.01 | -0.01 | -0.01 |
| NJ | -0.08 | -0.01 | 0.00 | | | | |

Source: Abt Associates analysis (2017).

**Table 6. RGGI Effect on Annual Average $PM_{2.5}$ in Non-RGGI States (PA, DC, VA, WV)**

| State | RGGI Effect on Annual Average $PM_{2.5}$ in non-RGGI States (Counties weighted by population) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | Average |
| NJ | | | | -0.01 | -0.02 | -0.01 | |
| PA | -0.06 | -0.01 | 0.00 | -0.01 | -0.02 | -0.01 | -0.02 |
| VA | -0.04 | 0.00 | 0.00 | -0.01 | -0.01 | -0.01 | -0.01 |
| DC | -0.03 | 0.00 | 0.00 | -0.01 | -0.01 | -0.01 | -0.01 |
| WV | -0.02 | 0.00 | 0.00 | 0.00 | -0.01 | 0.00 | -0.01 |

Source: Abt Associates analysis (2017).

## 4.4 Impacts on Public Health due to RGGI

Our estimates show that RGGI's impact on air quality in the region resulted in substantial improvements to public health throughout the Northeast, in both RGGI and non-RGGI states. Results for avoided adverse health effects and their total estimated value across all RGGI states are presented in Table 7. The number of health effects avoided in RGGI states include 240 to 540 adult mortalities, 27 to 260 non-fatal heart attacks, 145 hospitalizations (respiratory or cardiovascular), and cases of asthma ER visits, asthma exacerbations, and minor respiratory illnesses. Overall, the main driver of the value of health benefits is avoided premature mortality among adults, which constitutes over 98 percent of the total health benefits across the 2009 to 2014 study timeframe. Health benefits due to RGGI also include improvements to productivity and quality-of-life, totaling 31,000 avoided lost work days and nearly 200,000 fewer days with lower levels of activity (e.g., walking, exercising).

To express the value of benefits which occur over multiple years in present value terms, we apply 3 and 7 percent rates of discount to the flow of estimated annual benefits from 2009 to 2014.[38] Results presented in this section are based on 3 percent rate of discount; similar results based on a 7 percent rate can be found in the Appendices.

**Table 7. Health Benefits due to RGGI in RGGI States[39]**

| Health Effect | Incidences avoided due to RGGI. 2009-2014 | Monetized health benefit due to RGGI, 2009-2014 (Million 2015 dollars), 3% discount rate |
|---|---|---|
| Acute Bronchitis | 340 | $0.20 |
| Adult Mortality | 240–540 | $2,400–$5,300 |
| Asthma ER Visits | 160 | $0.09 |
| Asthma Exacerbations | 6,500 | $0.45 |

[38] These rates are based on EPA's guidelines on the use of a social rate of discount in economic analyses of public environmental and health policies and programs.

[39] Public health benefits in New Jersey from 2009-2011 are included in the total public health benefits due to RGGI in RGGI States

| | | |
|---|---|---|
| Cardiovascular Disease Hospital Admissions | 80 | $4.1 |
| Infant Mortality | 0.4 | $4.5 |
| Lower Respiratory Symptoms | 4,300 | $0.11 |
| Minor Restricted Activity Days | 190,000 | $15 |
| Non-fatal Heart Attacks | 27–260 | $4.4–$44 |
| Respiratory Hospital Admissions | 65 | $2.3 |
| Upper Respiratory Symptoms | 6,100 | $0.25 |
| Work Loss Days | 31,000 | $7.5 |
| **Total** | | **$2,400–$5,400** |

Source: Abt Associates analysis (2017).

For health impacts outside the RGGI states, our analysis included results for Pennsylvania, the District of Columbia, Virginia, and West Virginia (Table 8). Although these jurisdictions are not part of the RGGI program, they also accrue health benefits as a result of their location downwind of a RGGI state(s) where emissions reductions occurred as a result of the program. Pennsylvania's low-end benefits estimate of $823 million is greater than the total benefits for any single RGGI state, while Virginia's benefits ($244 million) exceed the estimates for several RGGI states. In addition, the District of Columbia's total benefits are over $18 million.

**Table 8. Health Benefits due to RGGI in Non-RGGI States (PA, DC, VA, WV)[40]**

| Health Effect | Incidences avoided due to RGGI, 2009-2014 | Monetized health benefit due to RGGI, 2009-2014 (Million 2015 dollars) 3% discount rate |
|---|---|---|
| Acute Bronchitis | 180 | $0.10 |
| Adult Mortality | 130–290 | $1,300 - $2,900 |
| Asthma ER Visits | 73 | $0.04 |
| Asthma Exacerbations | 3,400 | $0.23 |
| Cardiovascular Disease Hospital Admissions | 44 | $2.2 |
| Infant Mortality | 0.25 | $2.8 |
| Lower Respiratory Symptoms | 2,200 | $0.06 |
| Minor Restricted Activity Days | 95,000 | $7.7 |
| Non-Fatal Heart Attacks | 14–130 | $2.3–$21 |
| Respiratory Hospital Admissions | 32 | $1.1 |
| Upper Respiratory Symptoms | 3,200 | $0.13 |
| Work Loss Days | 16,000 | $3.6 |
| **Total** | | **$1,300–$2,900** |

[40] Public health benefits in New Jersey from 2012 to 2014 are included in the total public health benefits due to RGGI in non-RGGI states.

Source: Abt Associates analysis (2017).

Because of uncertainties regarding RGGI's effect on generation and emissions in non-RGGI states, we discount the low-end range of benefits estimated by BenMAP for non-RGGI states by 50 percent to create a new low-end, before adding these to benefits for RGGI states for a cumulative estimate. The high-end benefits for non-RGGI states are not adjusted, and are equal to 100 percent of BenMAP's high-end estimate. The range of cumulative health benefits due to RGGI are shown in Table 9. The total estimated value of health benefits associated with the RGGI program range from $3.0 to $8.3 billion (2015 dollars) in the region, with a central estimate of $5.7 billion (3 percent discount rate). The benefits estimates represent the value of reductions to affected populations in the health risks associated with $PM_{2.5}$.

**Table 9. Cumulative Health Benefits due to RGGI[41]**

| Health Effect | Avoided Health Effects due to RGGI, 2009-2014 | | Value of Health Benefits due to RGGI, 2009-2014 (Million 2015 dollars) | | |
|---|---|---|---|---|---|
| | Low | High | Low | Central | High |
| Acute Bronchitis | 420 | 510 | $0.25 | $0.27 | $0.3 |
| Adult Mortality | 300 | 830 | $3,000 | $5,600 | $8,200 |
| Asthma ER Visits | 200 | 230 | $0.11 | $0.12 | $0.13 |
| Asthma Exacerbations | 8,200 | 9,900 | $0.57 | $0.63 | $0.69 |
| Cardiovascular Disease Hospital Admissions | 100 | 120 | $5.2 | $5.8 | $6.3 |
| Infant Mortality | <1 | <1 | $5.9 | $6.6 | $7.3 |
| Lower Respiratory Symptoms | 5,400 | 6,500 | $0.14 | $0.15 | $0.17 |
| Minor Restricted Activity Days | 240,000 | 280,000 | $19 | $21 | $23 |
| Non-Fatal Heart Attacks | 35 | 390 | $5.5 | $33.5 | $61.6 |
| Respiratory Hospital Admissions | 82 | 98 | $2.8 | $3.1 | $3.4 |
| Upper Respiratory Symptoms | 7,700 | 9,300 | $0.31 | $0.34 | $0.37 |
| Work Loss Days | 39,000 | 47,000 | $9.2 | $10.1 | $11 |
| **Total** | | | **$3,000** | **$5,700** | **$8,300** |

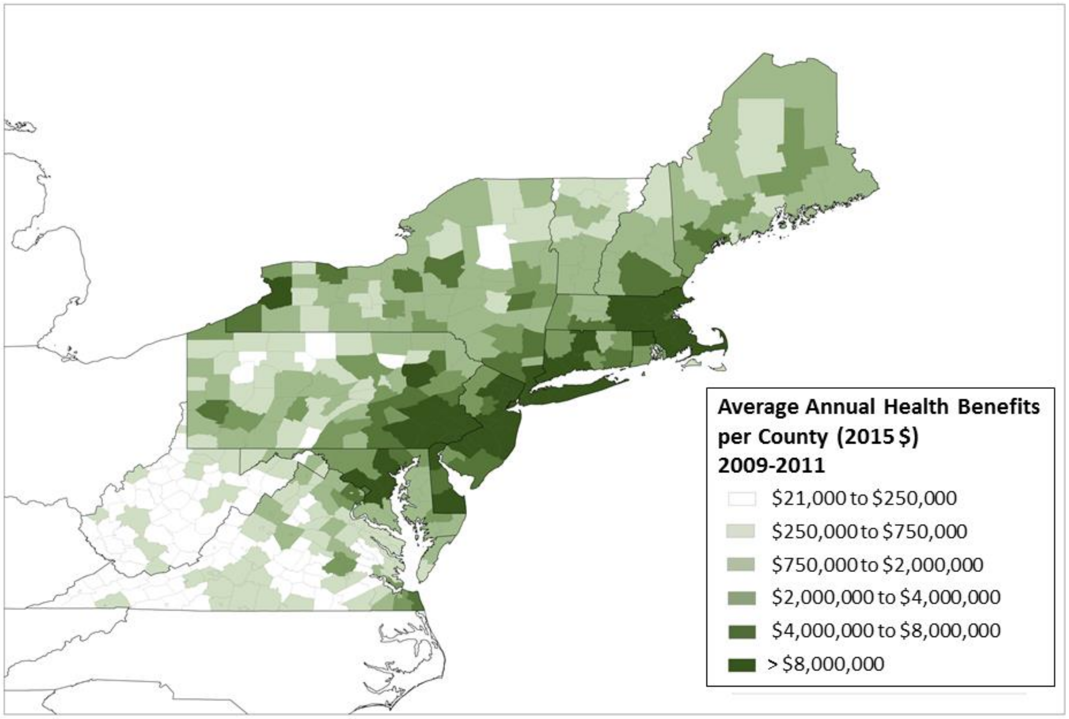
Source: Abt Associates analysis (2017).

Note: Value of avoided health effects is the sum of health benefits to states participating in RGGI and other northeastern states, based on a 3 percent rate of discount.

Figure 12 and Figure 13 show the geographic distribution of health benefits at the county level (central estimates, 3 percent discount rate). In each RGGI state, the most significant benefits were realized in 2009

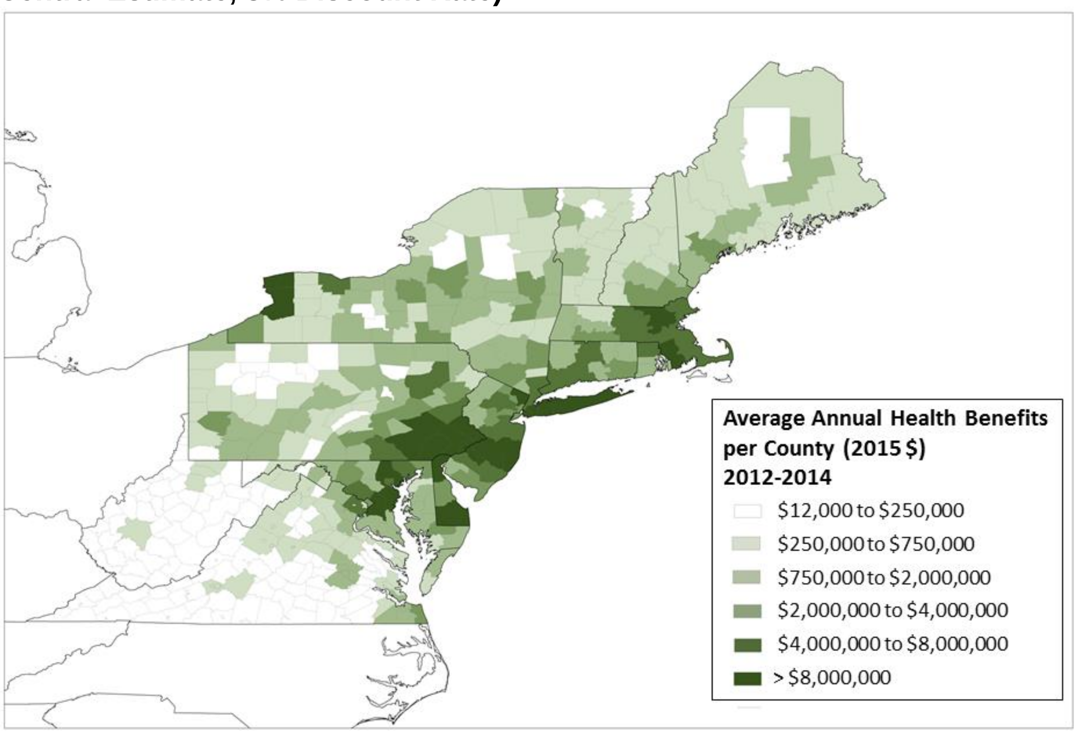
[41] Public health benefits in New Jersey from 2009-2011 are included in the total public health benefits due to RGGI in RGGI States. Public health benefits in New Jersey from 2012-2014 are included in the total public health benefits due to RGGI in non-RGGI States.

**Figure 12. Annual Health Benefits of RGGI, 2009 to 2011 (Central Estimate, 3% Discount Rate)**




Source: Abt Associates analysis (2017).

**Figure 13. Annual Health Benefits of RGGI, 2012 to 2014 (Central Estimate, 3% Discount Rate)**




Source: Abt Associates analysis (2017).

Figure 14 and Figure 15), the year with the largest estimated reductions in $SO_2$ emissions. State-level benefits were lower in 2010 and 2011, increased in 2012 and 2013, and decreased in 2014. Among the RGGI states, the largest health benefits by value are in New York, followed by New Jersey and Massachusetts. This is in contrast to the air quality results, which indicated the largest changes in air quality in Delaware, due to differences in population size across counties in the RGGI states. The same air quality change will result in different numbers of avoided cases (and therefore different monetized benefits) based on the affected population. For example, in 2010, $PM_{2.5}$ emissions in New York County decreased by 0.008 $\mu g/m^3$, resulting in a range of total health benefits of $4.8 to $10.8 million (2015 dollars). In the same year, the air quality change in New Castle County, DE was larger (0.014 $\mu g/m^3$), but resulted in lower benefits of $3.5 to $7.9 million (2015 dollars) (see sidebar for more information of the role of population on health benefits).

## The Role of Population in Public Health Benefits in Two Maryland Counties

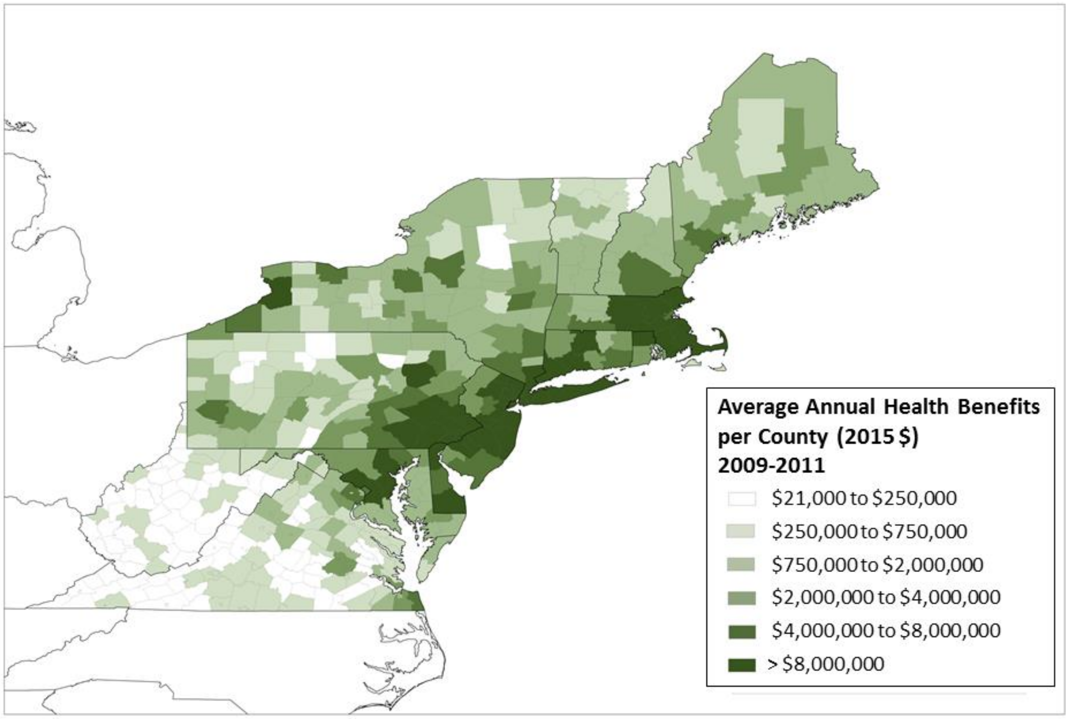
The benefits of RGGI to public health for a given county are a function of the county's population, baseline level of health, and changes to the level of ambient $PM_{2.5}$ attributable to RGGI. Because of differences in population and baseline health, counties with similar RGGI-driven $PM_{2.5}$ reductions can experience very different public health outcomes. The table shows avoided health outcomes for two counties in Maryland with different population sizes. Although RGGI results in a comparable $PM_{2.5}$ reduction in both counties (i.e., 0.022 to 0.023 $\mu g/m^3$), Baltimore County's population is about 810,000, while St. Mary's population is only 110,000. Because of these population differences, health benefits of RGGI are much more significant for Baltimore County than for St. Mary's County.

**Public Health Benefits of RGGI in Baltimore County, MD and St. Mary's County, MD, 2014**

| Health Effect | Incidences Avoided due to RGGI, 2014 | |
|---|---|---|
| | Baltimore County, MD | St. Mary's County, MD |
| Acute Bronchitis | 1.2 | 0.20 |
| Adult Mortality | 1.0–2.3 | 0.10–0.23 |
| Asthma ER Visits | 0.65 | 0.06 |
| Asthma Exacerbations | 23 | 3.7 |
| Cardiovascular Disease Hospital Admissions | 0.37 | 0.04 |
| Infant Mortality | <0.01 | <0.01 |
| Lower Respiratory Symptoms | 15 | 2.5 |
| Minor Restricted Activity Days | 690 | 94 |
| Non-Fatal Heart Attacks | 0.12–1.1 | 0.01–0.08 |
| Respiratory Hospital Admissions | 0.28 | 0.03 |
| Upper Respiratory Symptoms | 22 | 3.6 |
| Work Loss Days | 115 | 16 |

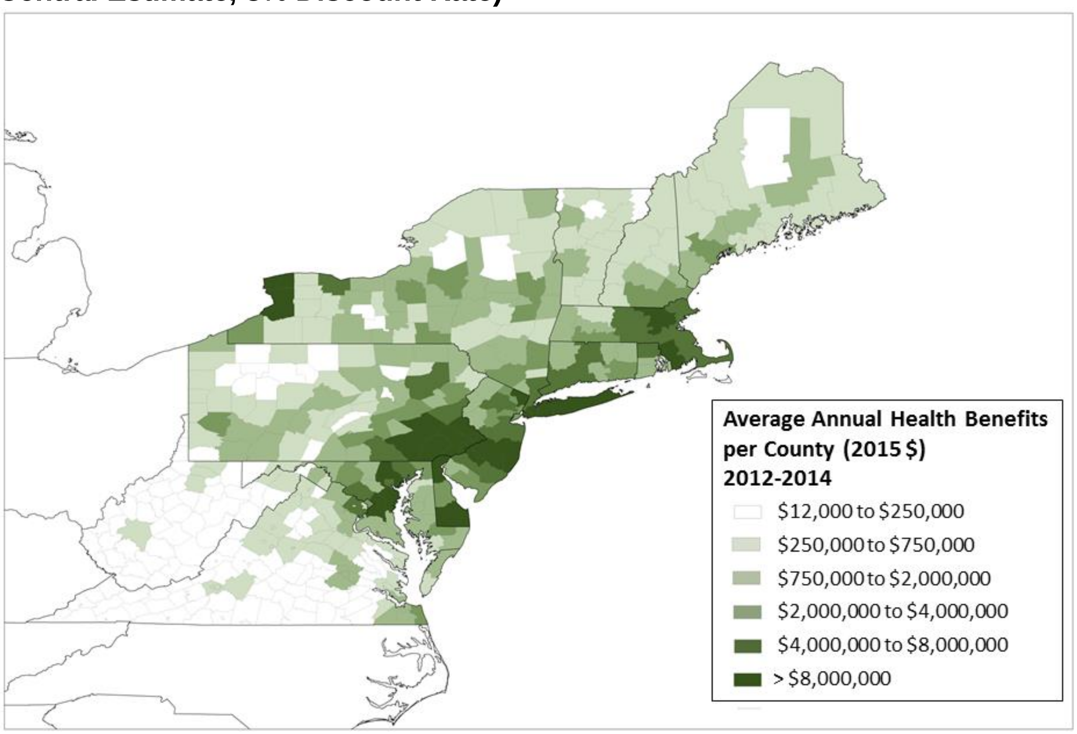
Source: Abt Associates analysis (2017).

**Figure 12. Annual Health Benefits of RGGI, 2009 to 2011 (Central Estimate, 3% Discount Rate)**



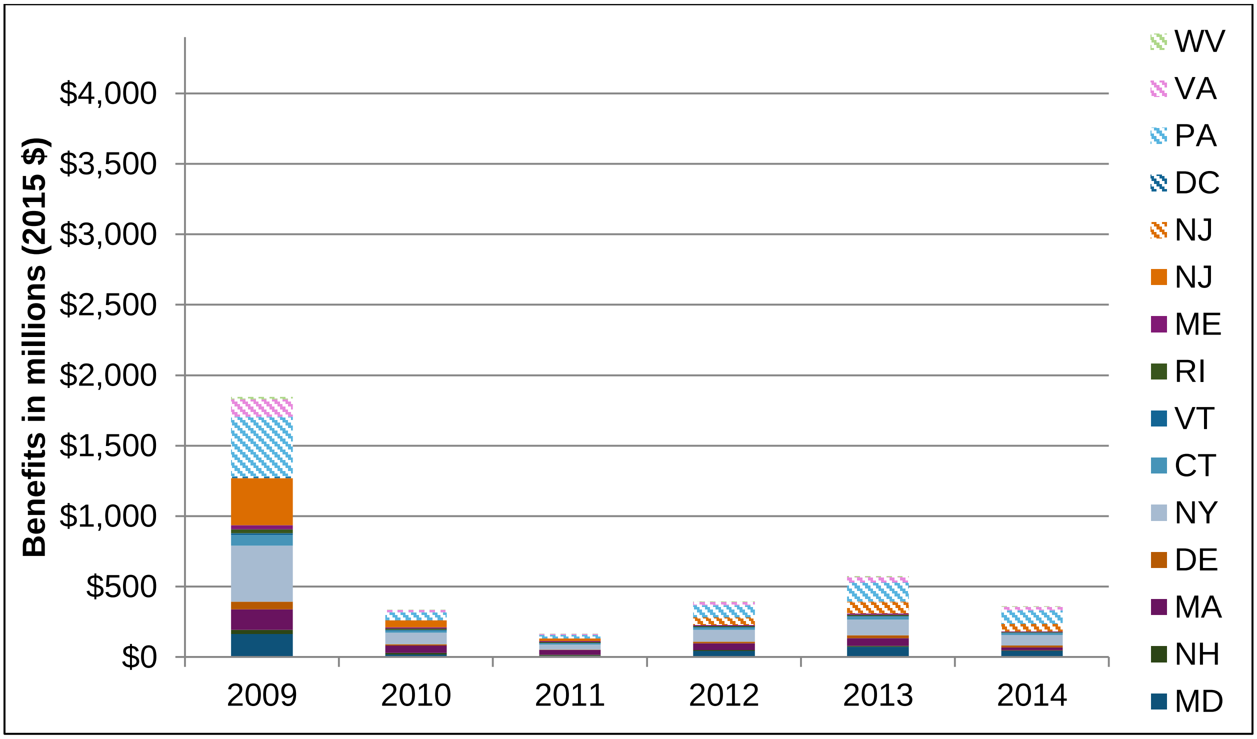

Source: Abt Associates analysis (2017).

**Figure 13. Annual Health Benefits of RGGI, 2012 to 2014 (Central Estimate, 3% Discount Rate)**



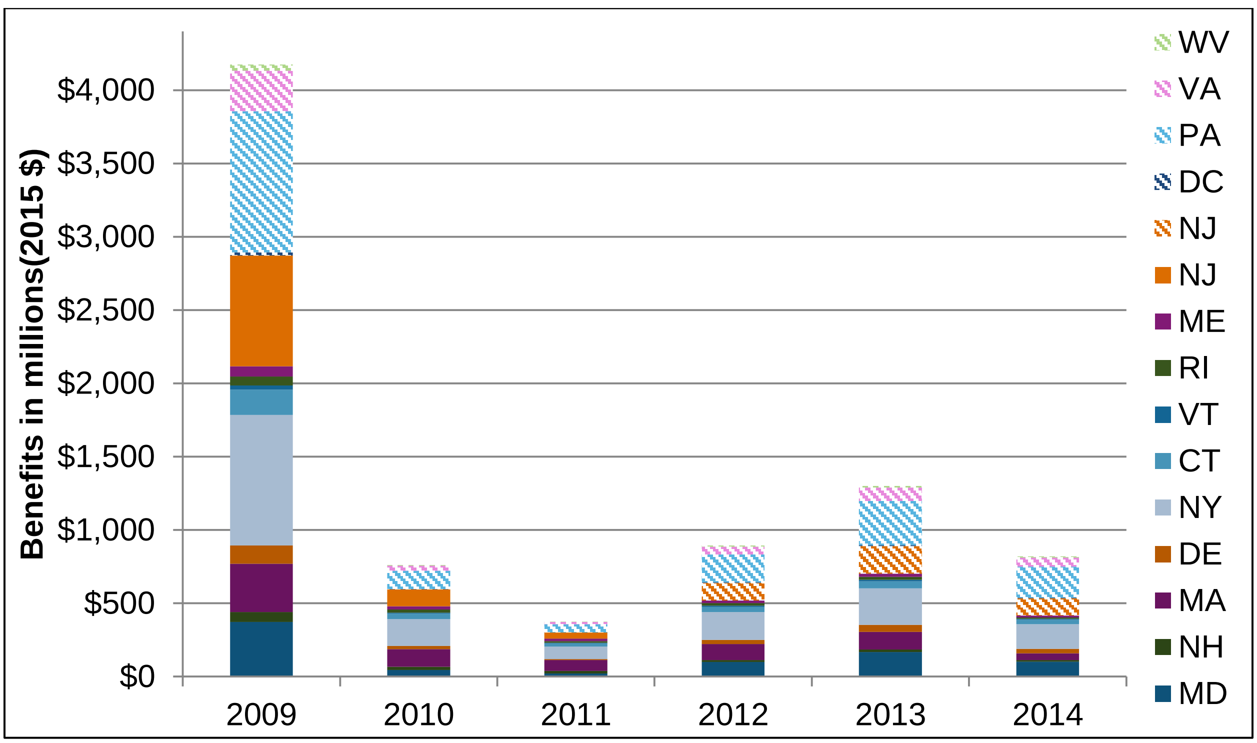

Source: Abt Associates analysis (2017).

**Figure 14. RGGI Public Health Benefits by State (Low Estimate, 3% Discount Rate)**




Source: Abt Associates analysis (2017).

**Figure 15. RGGI Public Health Benefits by State (High Estimate, 3% Discount Rate)**




Source: Abt Associates analysis (2017).

## 4.5 Key Findings and Implications

During the first six years of RGGI implementation, the program resulted in sizable reductions in key criteria air pollutants, especially $SO_2$ emissions, which contribute to the formation of $PM_{2.5}$. RGGI-induced reductions in ambient $PM_{2.5}$ occurred throughout densely populated areas of the northeastern corridor all the way to western New York and into New England, and resulted in significant benefits to human health. These benefits include hundreds of avoided cases of premature deaths, heart attacks, asthma attacks, and hospital admissions, and tens of thousands of avoided cases of other health symptoms, lost work days, and restricted activities. The estimated value of the health, productivity, and quality-of- life benefits associated with RGGI ranges from $3.0 billion to $8.3 billion, with a central estimate of $5.7 billion (2015 dollars, 3 percent discount rate).

RGGI's effect on annual air quality and public health are most significant in 2009 and 2013. This pattern is consistent with RGGI's two effects on wholesale power markets: 1) changes in power prices to absorb $CO_2$ allowance costs, which results in a shift of dispatch to lower-carbon sources, and 2) investments in energy efficiency, which reduce electricity demand and emissions. In addition, there is evidence that plant owners took early action to reduce $CO_2$ emissions in anticipation of RGGI.

As noted above, RGGI-induced changes at a relatively small number of legacy coal plants drive a high proportion of RGGI's total reductions in key air pollutants and health benefits. The fleet of power plants in RGGI states will be, on average, cleaner in the near future than the current fleet,[42] so future RGGI-induced reductions in generation are likely to result in lower total health benefits going forward.

However, the cleaner electricity grid does create opportunities for additional health benefits if energy demand from other sectors—transportation and buildings—shifts onto to a cleaner grid in RGGI (and neighboring) states, a process known as "electrification." Reductions of air pollutants and health benefits from decarbonizing other energy demand could be significant. For example, a 2016 study assessed future health and climate benefits that would occur if the eight northeastern states participating in the Zero Emission Vehicle (ZEV) program[43] transitioned to a vehicle fleet of about 65 percent ZEVs by 2050 (American Lung Association in California, 2016). According to the study, this would result in about $12 billion in annual health benefits.[44] Many RGGI states (e.g., Massachusetts, Rhode Island) are currently implementing or developing GHG mitigation plans to achieve 80 percent reductions in GHG emissions

42 A number of states in the region are implementing GHG mitigation plans that require 80 percent reductions in GHG emissions by 2050, relative to 1990 levels.

43 The ZEV program requires that automakers meet a threshold of electric vehicle sales in participating states. The exact number of electric vehicles required is linked to each automaker's total sales within the state. The eight northeastern states participating in the ZEV program, along with California and Oregon, include: Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Rhode Island, and Vermont.

44 The study reports state-level combined health and climate benefits, and we assume that health benefits constitute 62 percent of combined benefits. This assumption is based on the fact that health benefits across all states constitute 62 percent of combined health and climate benefits across all states.

by 2050,[45] and these plans include strategies for electrification of energy used in light-duty vehicles and building heating and cooling.

As in any analysis, there were certain uncertainties in data, assumptions, and models used in this study which influenced estimates. Table 10 below describes these sources of uncertainty and their potential impact on estimated changes in emissions, air quality, and health benefits due to RGGI, as well as our approach to addressing individual uncertainties within models or through quantified sensitivity cases. The fact that quantitative estimates of energy savings from RGGI investments in efficiency which persist after 2014 and reductions in ozone due to RGGI are excluded from this analysis implies a likely underestimation of benefits. We also applied a sensitivity factor of 50 percent to health benefits estimated for non-RGGI states to account for the lack of conclusive information describing RGGI's incremental effect on generation and emissions in these states. As such, our estimates of total health benefits due to RGGI are probably conservative.

**Table 10. Key Uncertainties in the Analysis**

| Source of Uncertainty in the Analysis | Impact on Estimates | Likely Significance on Estimates of Health Benefits |
|---|---|---|
| Analysis excludes avoided emissions, air quality, and health benefits that occur after 2014 resulting from states' investments in energy efficiency from 2009 to 2014. | **Underestimation.** The magnitude of these excluded benefits is not known, but could be significant given the magnitude of EE investments particularly in 2013 and 2014. | Possibly significant. |
| Analysis excludes health benefits associated with reductions in ozone. | **Underestimation.** The effect of ozone reductions on health benefits is known to be smaller in magnitude than that of reductions in ambient $PM_{2.5}$. | Probably minor. |
| Analysis excludes changes in emissions in non-RGGI states as a result of RGGI. | **Overestimation**. Unable to determine magnitude based on current information, but the potential for lower benefits is addressed through a sensitivity factor that discounts benefits in non-RGGI states by 50 percent. | Possibly significant. |
| Gaps in baseline emissions datasets. | **Indeterminate.** Gaps for missing years in EPA emissions databases were addressed by adjustments to data describing adjacent years. | Probably minor. |

[45] The base year against which each of these states calculates their 2050 emissions reduction goal in their GHG mitigation plans varies—some states use a base year of 1990, while others use 2001.

| Source of Uncertainty in the Analysis | Impact on Estimates | Likely Significance on Estimates of Health Benefits |
|---|---|---|
| Uncertainties in assumptions and inputs used in dispatch, air quality, and health benefits modeling. | **Indeterminate.** Low- and high-end estimates from the BenMAP model account for uncertainties in the relationship between population exposures and health effects. Historical actual data were used in dispatch and air quality models, thereby reducing some sources of error. | Possibly significant. |

Source: Abt Associates analysis (2017).

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# Appendix A – Emissions Data Sources and Analysis

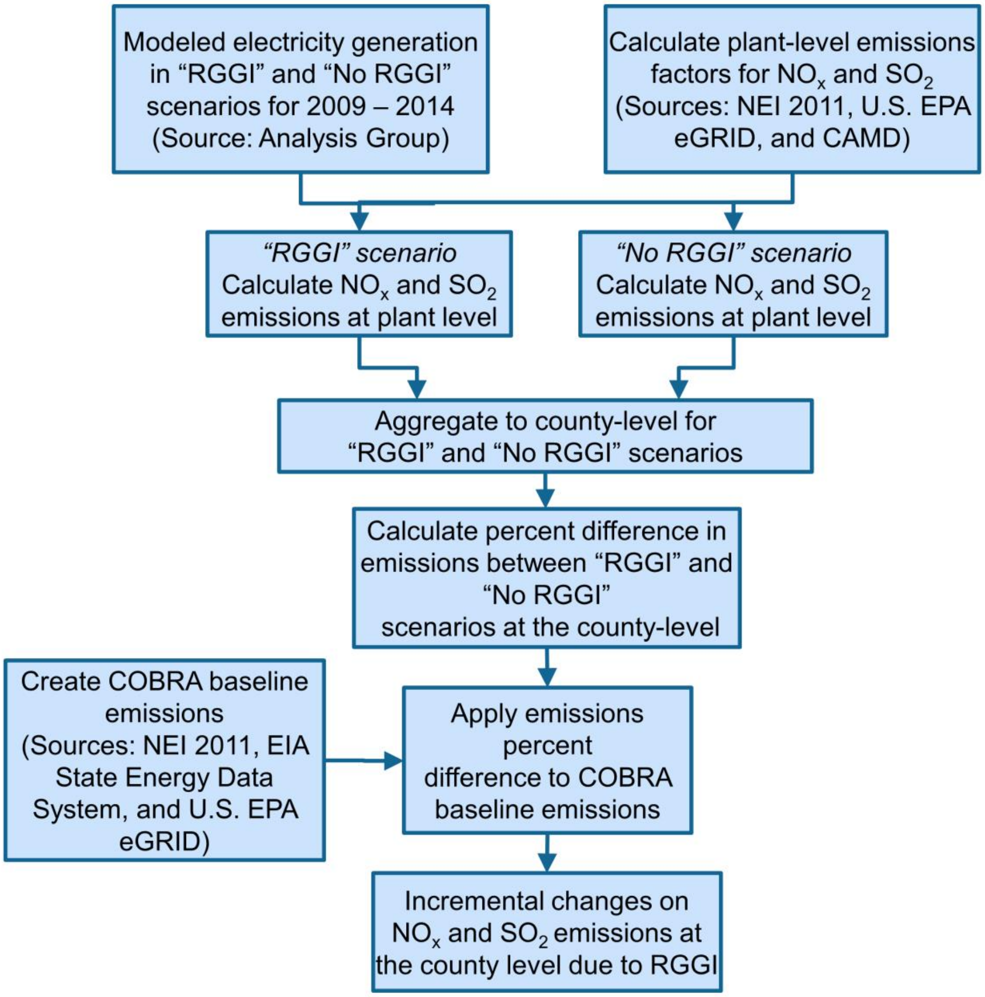
## Detailed Analytic Approach

We developed a baseline of emissions for the RGGI scenario from actual emissions in the EPA's 2011 National Emissions Inventory (NEI) data. We chose the NEI dataset because it enabled us to represent emissions inventories from all sectors in the economy. This is necessary for Step 2 of our analysis because COBRA models changes in air quality based on a complete inventory of criteria pollutant emissions from all sectors (e.g., power plants, transportation, industrial processes.

We calculated emissions for the modeled electricity generation levels under the RGGI and No RGGI scenarios by (1) calculating plant-level emission factors and (2) applying plant-level emissions factors to modeled generation levels. We calculated plant-level $SO_2$ and $NO_x$ emissions factors (tons pollutant/MWh generated) by dividing NEI-derived baseline emissions by actual generation. We created unique emissions factors for each year, which enabled us to reflect the effects of pollution control installations, operational characteristics, and changes in fuel mix for each plant. We applied these emissions factors to the modeled generation levels under RGGI and No RGGI to determine emissions under RGGI and No RGGI, respectively. Our workflow to calculate incremental changes in $NO_x$ and $SO_2$ emissions at the county level is illustrated in Figure 16.

We then aggregated the modeled RGGI and No RGGI emissions to the county level and calculated the ratio of emissions between the RGGI and No RGGI scenarios. We applied this ratio to the actual RGGI emissions baseline to construct the counterfactual emissions inventory for No RGGI. The difference between the RGGI emissions inventory and the RGGI emissions baseline is the incremental change in emissions due to RGGI, which we input into COBRA under Step 2.

**Figure 16. Approach to Estimating County-Level Changes in Emissions due to RGGI**




Source: Abt Associates analysis (2017).

## Description of Datasets Used

### Analysis Group Datasets

We used results of modeling runs conducted by Analysis Group as part of their 2011 and 2015 retrospective studies of RGGI’s economic impacts. These datasets provided estimates of annual plant-level electricity generation for all power plants located in RGGI states, for the RGGI and No RGGI scenarios (Analysis Group, 2011, 2015).

Analysis Group modeled electricity generation per unit with power system dispatch models, which simulate the optimal distribution of the electric power system load among generation facilities. Analysis Group used GE Energy’s Multi-Area Production Simulation (MAPS) model for the first compliance period (see Analysis Group, 2011) and the PROMOD model for the second compliance period (see Analysis Group, 2015).

These dispatch models are useful for this retrospective analysis of RGGI because they compute optimal dispatch based on observed fuel prices, transmission system constraints, and operational constraints at a high geographic and temporal resolution. However, dispatch models cannot perfectly simulate power producers' actual, real-world decisions. For example, dispatch models tend to show that very small changes in marginal costs lead to significant changes in dispatch patterns, which is not always the case.

The modeled "RGGI" scenario reflects actual "RGGI" data accurately when aggregated to the regional scale. However, differences between the modeled "RGGI" scenario and actual "RGGI" data emerge at the county or plant level. Accuracy at the plant level is necessary to model public health benefits, because the estimated effect of changes in generation on emissions is highly dependent on the age, fuel use, and emissions controls of a given plant, and the effect of changes in emissions on public health are highly dependent on the emissions' location. We adopt a percent difference approach to deal with differences between the modeled RGGI scenario and actual RGGI data, as described in the main text.

### National Emissions Inventory

The NEI is a comprehensive estimate of air emissions that EPA develops from data reported primarily from state, local, and tribal air agencies. The NEI includes emissions from multiple sources, including point sources (e.g., power plants), non-point sources (e.g., residential heating), on-road sources (e.g., light-duty vehicles), and non-road sources (e.g., boats, lawn and garden equipment). NEI datasets are available from 2008, 2011, and 2014. For our analysis, we used the 2011 NEI dataset. We estimated annual power plant emissions for each year in the 2009 to 2014 period by modifying the NEI 2011 baseline. We estimated plant-level emissions changes relative to 2011 based on fuel use ratios from the State Energy Data System and annual emissions factor ratios from the EPA Emissions and Generation Resources Integrated Database (eGRID). We also cross-checked our annual plant-level emissions estimates with other data sources, such as EPA's Clean Air Markets Division (CAMD), and spot-corrected our baseline as necessary.

### EPA Emissions and Generation Resource Integrated Database

EPA's eGRID contains environmental data from all U.S. plants that supply power to the electric grid and provide data to the federal government. The database was developed by Abt Associates and CAMD. We use eGRID's plant-level $SO_2$ and $NO_x$ emissions rates to adjust our annual emissions inventories to account for installation of emissions controls. Plant-level $SO_2$ and $NO_x$ emissions rates are available for 2009, 2010, 2012, and 2014. For years of interest without a corresponding eGRID dataset, we calculate average emissions rates from adjacent years for which data are available.

### U.S. Energy Information Administration (EIA) Annual Electric Generator Capacity Data (Form EIA-860)

The Annual Electric Generator Data is compiled from submissions of survey Form EIA-860. Form EIA-860 gathers generator-level data from all U.S. power plants with total nameplate capacity of one megawatt or greater. We used plant-level data for generators surveyed in 2009-2014. We used Form EIA-860 to identify the county in which plants are located.

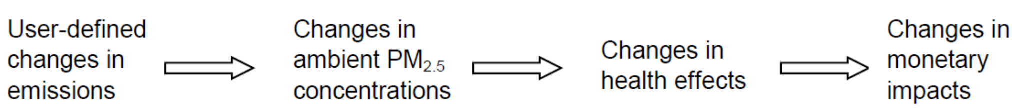
# Appendix B – Estimating Air Quality Changes: Co-Benefits Risk Assessment (COBRA) Model

To estimate the air quality impacts of RGGI in 2009-2014, we used EPA's COBRA model. COBRA is a free screening tool that helps state and local governments evaluate the costs and benefits of clean energy and climate mitigation policies. COBRA provides preliminary estimates of the effects of air pollutant emission changes (e.g., $NO_x$, $SO_2$, and $PM_{2.5}$) on ambient air concentrations of $PM_{2.5}$, translates the estimated changes in ambient $PM_{2.5}$ concentrations into the number of avoided adverse health effects, and then provides a monetary value of the avoided health effects. COBRA enables policymakers and planners to identify and highlight air quality and public health co-benefits achieved through energy efficiency or renewable energy policies.

## COBRA Model Components

Abt Associates originally developed COBRA in 2002 for EPA and continues to support updates of the screening tool. The model consists of four components, shown in Figure 17.

### Figure 17. Components of the COBRA Model




Source: *COBRA User Manual* (U.S. EPA, 2015c).

A brief explanation of the two of the four components of the model that were used in this analysis is included below.[46] In lieu of COBRA's health valuation functions, we used the BenMAP model described in the next section.

### User Inputs of Emissions Changes

COBRA contains baseline emissions estimates based on the National Emissions Inventory. Note that we prepared customized versions of the COBRA model that contain baseline emissions estimates for each modeling year 2009-2014 (see Section 3.2). We then created COBRA scenarios by entering increases or decreases to the baseline emissions estimates.

### Changes in Air Quality (i.e., ambient $PM_{2.5}$ concentrations)

Based on changes in emissions levels, the COBRA model then calculates changes in particulate matter, which reflect changes in air quality. Specifically, COBRA estimates $PM_{2.5}$ concentrations using a simple air quality model known as the Phase II Source-Receptor (S-R) Matrix. The S-R Matrix consists of fixed transfer coefficients that reflect the relationship between annual average $PM_{2.5}$ concentration values at a single receptor in each county (a hypothetical monitor located at the county centroid) and the contribution by $PM_{2.5}$ species to this concentration from each emission source (E.H. Pechan & Associates Inc., 1994). COBRA models the formation of secondary $PM_{2.5}$ from $NO_x$ and $SO_2$ by (1) assuming up to 25 percent of $NO_x$ and 100 percent of $SO_2$ transform into ammonium nitrate and ammonium sulfate, respectively,

[46] For more detailed information, see the *COBRA User Manual* (U.S. EPA, 2015c).

depending on the limiting concentration of ammonia, (2) modeling secondary reactions among gaseous and particulate species, and (3) calibrating COBRA modeling results to measured $PM_{2.5}$ values.

## Benefits of COBRA

The COBRA model allows us to quickly estimate air quality impacts based on a simplified air quality model. COBRA displays county-level results in both tabular and geographic formats. The mapping feature allows users to see changes in ambient $PM_{2.5}$ levels at the county level.

## Limitations of COBRA

More sophisticated (and resource-intensive) air quality modeling approaches are available and would provide more refined estimates of the benefits of emissions reductions. Importantly, COBRA does not account for all air pollutants, such as ozone, carbon dioxide, and mercury. Therefore, the health benefits based on COBRA air quality results are likely a conservative estimate because many health impacts are exacerbated by other harmful air pollutants but are not included in the scope of the COBRA model.

Another key limitation of COBRA is that the health effects inputs cannot be easily customized. COBRA relies on population, incidence (i.e., the baseline probability of a health effect), and income data for a specific modeling year. Therefore, we did not use the health impact and valuation components of COBRA in our analysis of RGGI, and instead relied upon the BenMAP model.

# Appendix C – Estimating Changes in Public Health: Benefits Mapping and Analysis (BenMAP) Model

Abt Associates designed and implemented the original BenMAP model for EPA, which was the first publicly available model for estimating the number and economic value of health impacts resulting from changes in air quality. EPA's current version of BenMAP (known as BenMAP-Community Edition) is being deployed around the world by governments, researchers, and policy analysts for generating monetized estimates of public health improvements resulting from reductions in air pollutants. For example, BenMAP has been used for local- and regional-scale analyses (e.g., Cohan et al., 2007; Nowak et al., 2013) and climate assessments (e.g., Hill et al., 2009; Tagaris et al., 2009).

We estimated the public health impacts of RGGI in 2009-2014 using the BenMAP model, Version 4.0.67. This is a legacy version of BenMAP that allows us to use configuration files EPA used for the 2012 PM National Ambient Air Quality Standards (NAAQS) Regulatory Impact Analysis (referred to below as the "2012 PM RIA configuration").[47]

We input COBRA-generated county ambient $PM_{2.5}$ estimates into BenMAP, which BenMAP used to calculate RGGI's effect on $PM_{2.5}$ relative to observed ambient $PM_{2.5}$ for 2009-2014. We selected BenMAP over COBRA for this step of the analysis because BenMAP allows us to capture changes in baseline population, incidence, and valuation over the study period. While COBRA is an appropriate tool for estimating ambient air quality, the fact that its datasets are tied to a specific calendar year limits its representation of how air quality affects public health over time.

BenMAP linked air quality changes to public health metrics by applying empirical relationships between $PM_{2.5}$ and multiple health effects.[48] BenMAP applied these statistical relationships to population datasets for 2009-2014. BenMAP uses county-level population projections based on the 2010 U.S. Census of Population and Housing and forecasting models developed by Woods and Poole (2011).

Based on the 2012 PM RIA configuration, BenMAP monetized the health impacts using "unit values" for each health endpoint (presented in Table 11). The unit values are based on published estimates of the costs of treating the illness (which can include both direct medical costs and costs of lost productivity), or the willingness to pay (WTP) to avoid the illness or to reduce the risk of premature death (i.e., value per statistical life, VSL). The unit values based on WTP estimates reflect expected growth in real income over time. This is consistent with economic theory, which argues that WTP for most goods (such as health risk reductions) will increase if real incomes increase.

In BenMAP, we estimated economic values in 2015 dollars and using income levels for each year of the analysis (e.g., 2009 income levels for valuing health impacts for 2009). In Table 11, we present the unit values at 2014 income level. Because some of the health benefits from emissions reductions in a particular year are expected to occur over several years, BenMAP discounts the estimated stream of

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47 In BenMAP, configuration files specify the health impact and valuation functions, as well as settings for aggregation and pooling across the incidence and valuation results.

48 The health impact functions are described in detail in Appendix E of the *BenMAP User's Manual* (U.S. EPA, 2012).

economic benefits to the analysis year using either a 3 percent or a 7 percent discount rate. We further adjusted all results to 2015 present values.

### Table 11. Health Effects and Their Economic Values (2015 dollars/case)

| Avoided Health Effect | Economic Value (2015 dollars, 2014 Income Level)[1] |
|---|---|
| **Time-varying costs[2]** | |
| Adult Mortality[1] (3% discount rate) | $8,937,339 |
| Adult Mortality[1] (7% discount rate) | $7,960,346 |
| Non-Fatal Heart Attacks (3% discount rate) | $38,253–$298,337 |
| Non-Fatal Heart Attacks (7% discount rate) | $36,167–$286,735 |
| **Costs incurred in the year of exposure** | |
| Infant Mortality[3] | $9,961,679 |
| Hospital Admissions (Respiratory, Cardiovascular-related)[4] | $17,135–$46,318 |
| Asthma Emergency Room Visits | $447–$534 |
| Acute Bronchitis | $513 |
| Respiratory Symptoms (Upper, Lower) | $22–$36 |
| Asthma Exacerbations (attacks, shortness of breath, and wheezing) | $62 |
| Minor Restricted Activity Days | $73 |
| Work Loss Days[4] | $160 |

Source: U.S. EPA (2012d and 2012e).

1. The unit values based on WTP estimates reflect expected growth in real income over time. When estimating health benefits, we used the income level specific to each analysis year. In this table, we present the values at 2014 income level.

2. Most health effects and their economic values are expected to occur in the year of analysis. However, not all avoided cases of adult mortality are expected to occur in the year of analysis. In addition, while avoided cases of non-fatal heart attacks are expected to occur in the same year as the emissions change, the costs associated with this health effect would occur over multiple years. Thus, BenMAP uses discount rates of 3 percent and 7 percent to calculate the value of these health effects in present terms.

3. Following U.S. EPA (2012a), we assume that some of the incidences of premature adult mortality related to $PM_{2.5}$ exposures occur in a distributed fashion over the 20 years following exposure. This lag adjustment does not apply to infant mortality because Woodruff et al. (1997) estimated the number of infant deaths occurring in the same year as the emissions change. We applied the lag adjustments to the BenMAP output.

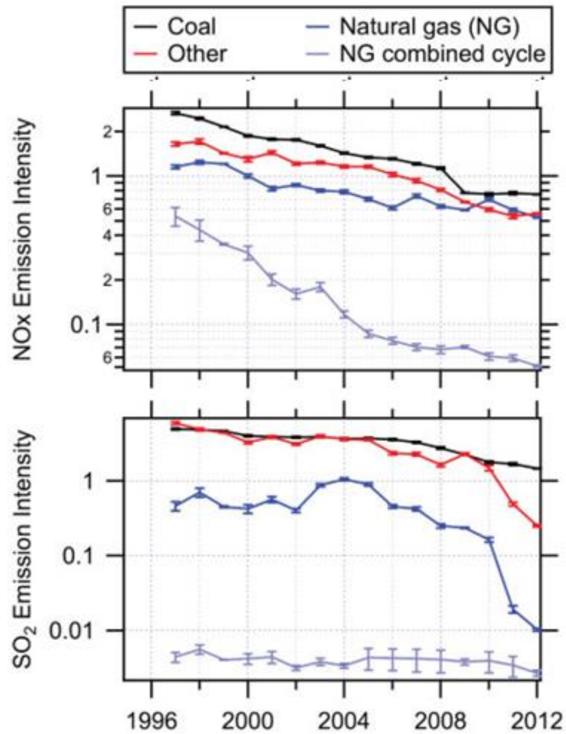
4. BenMAP uses county-specific median daily wages to value work loss days and opportunity costs for hospital admissions. In this table, we report unit values based on the national median daily wage.

The resulting health impact results do not capture all uncertainty surrounding BenMAP's inputs. This analytic step introduces several uncertainties, including population forecasts and the VSL. Another source of uncertainty introduced in this analytic step relates to whether there is regional variability in some inputs. Because BenMAP's health impact and valuation functions represent national-level relationships, the accuracy of regional-level analyses may be improved by identifying region-specific relationships from the literature.[49]

[49] Further details on uncertainty in BenMAP inputs are provided in the appendices of the *BenMAP User's Manual* (U.S. EPA, 2015a).

# Appendix D – Supplementary Figures

### Figure 18. $NO_x$ and $SO_2$ Emission Rates across Generation Technologies and Fuel Types




Source: Adapted from de Gouw et al. (2014).

### Table 12. Health Benefits due to RGGI in RGGI States, 7% Discount Rate

| Health Effect | Incidences avoided due to RGGI from 2009-2014 | Monetized health benefit due to RGGI from 2009-2014 (Million 2015 dollars), 7% discount rate |
|---|---|---|
| Acute Bronchitis | 340 | $0.23 |
| Adult Mortality | 240–540 | $2,500–$5,700 |
| Asthma ER Visits | 160 | $0.11 |
| Asthma Exacerbations | 6,500 | $0.54 |
| Cardiovascular Disease Hospital Admissions | 80 | $4.9 |
| Infant Mortality | 0.4 | $5.4 |
| Lower Respiratory Symptoms | 4,300 | $0.13 |
| Minor Restricted Activity Days | 190,000 | $18 |
| Non-fatal Heart Attacks | 27–260 | $5.1–$47 |
| Respiratory Hospital Admissions | 65 | $2.7 |
| Upper Respiratory Symptoms | 6,100 | $0.3 |
| Work Loss Days | 31,000 | $8.9 |
| **Total** | | **$2,500–$5,700** |

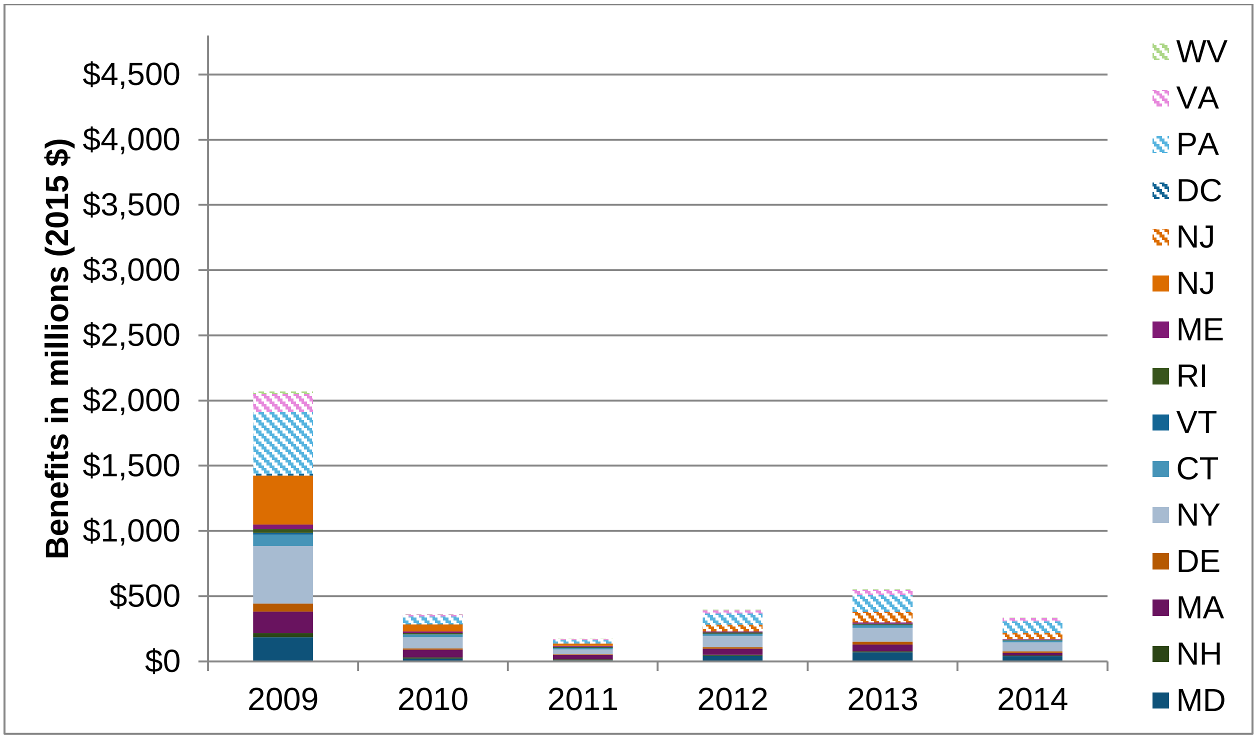
Source: Abt Associates analysis (2017).

**Table 13. Health Benefits due to RGGI in Non-RGGI States, 7% Discount Rate**

| Health Effect | Incidences avoided due to RGGI from 2009-2014 | Monetized health benefit due to RGGI from 2009-2014 (Million 2015 dollars) 7% discount rate |
|---|---|---|
| Acute Bronchitis | 180 | $0.12 |
| Adult Mortality | 130–290 | $1,300–$3,000 |
| Asthma ER Visits | 73 | $0.05 |
| Asthma Exacerbations | 3,400 | $0.27 |
| Cardiovascular Disease Hospital Admissions | 44 | $2.6 |
| Infant Mortality | 0.25 | $3.3 |
| Lower Respiratory Symptoms | 2,200 | $0.07 |
| Minor Restricted Activity Days | 95,000 | $9 |
| Non-Fatal Heart Attacks | 14–130 | $2.6–$24 |
| Respiratory Hospital Admissions | 32 | $1.3 |
| Upper Respiratory Symptoms | 3,200 | $0.15 |
| Work Loss Days | 16,000 | $4.2 |
| **Total** | | **$1,300–$3,000** |

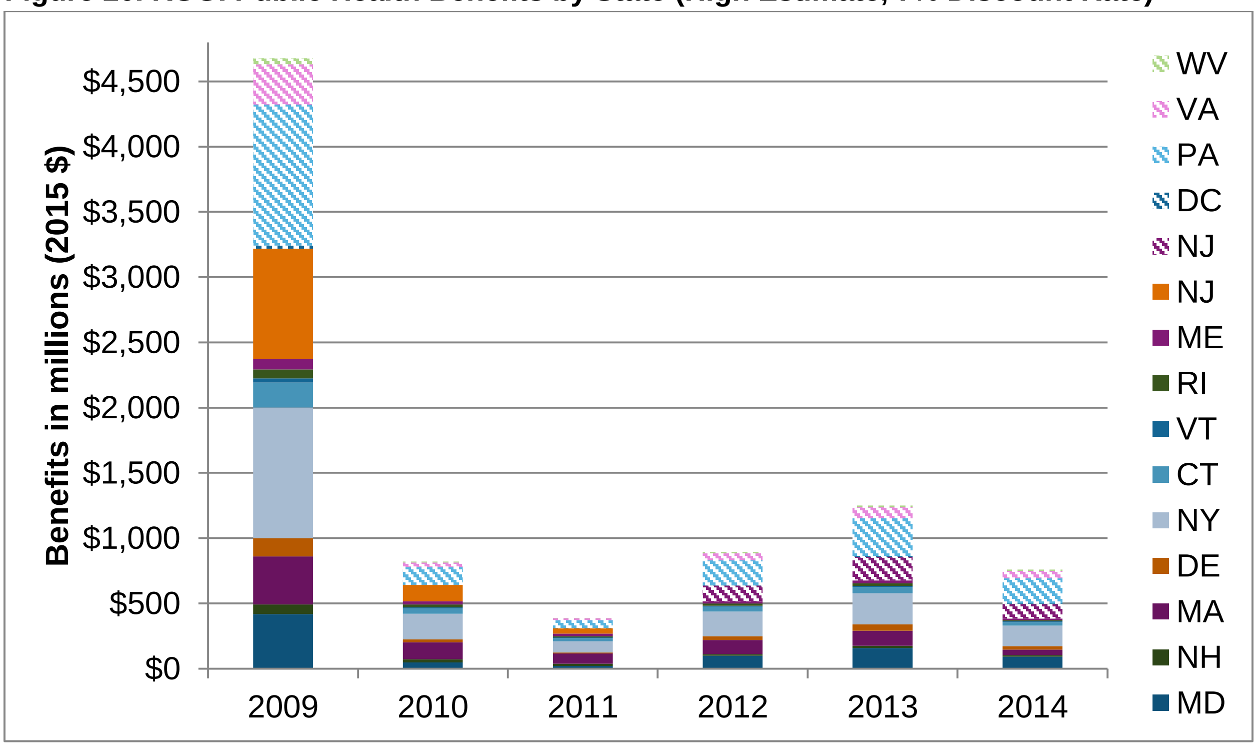
Source: Abt Associates analysis (2017).

**Figure 19. RGGI Public Health Benefits by State (Low Estimate, 7% Discount Rate)**




Source: Abt Associates analysis (2017).

**Figure 20. RGGI Public Health Benefits by State (High Estimate, 7% Discount Rate)**




Source: Abt Associates analysis (2017).