Power Sector Emissions under Tightening Carbon Dioxide Quotas*

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Abstract

The Regional Greenhouse Gas Initiative (RGGI) was passed by a collection of 10 northeastern states and is the first cap-and-trade policy in the United States to specifically target carbon dioxide emissions from the electricity sector. We exploit the introduction of this policy and subsequent tightening of the carbon cap to assess how carbon dioxide emissions have changed within RGGI states while also identifying emissions leakages that occurred. When using aggregated state-level emissions data, we find that RGGI-induced emissions reductions are not meaningfully different from what has occurred outside of the region. Alternatively, when using plant-level data a statistically significant emissions reduction appears from both coal and natural gas-fired plants in RGGI states relative to non-RGGI states. This suggests that aggregated analyses mask a stronger impact of the RGGI at the emissions source. There is also evidence that plant-level emissions have increased in neighboring non-RGGI regions, but only from natural gas plants.

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1 Introduction and Background

The warming effect of greenhouse gas accumulation is widely accepted in the scientific community, however the regulation of greenhouse gas emissions remains a hotly contested and debated topic — especially in the United States. Despite global collaboration efforts and agreements to reduce greenhouse gasses, specific policies intended to reduce these emissions have not been widely applied and are mostly regionally-based. Within the United States, market-based instruments like emissions taxes or carbon permit trading systems have been proposed at both state and Federal levels, but they have been met with limited political support.[1] One market-based system that has been put in place is the Regional Greenhouse Gas Initiative (RGGI) which is a coalition of nine states (originally 10 states) in the northeastern United States that have voluntarily agreed to a gradually more restrictive cap on carbon dioxide emissions from the electric power sector.

The RGGI was the first cap and trade system for carbon dioxide emissions put in place in the United States, and this carbon trading system has been in force since 2009. When the policy began, the RGGI implemented a carbon cap of 188 million allowances for the 10 state region which tightened incrementally on an annual basis. The original coalition of 10 states included Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont. In 2012 New Jersey left the coalition but is on track to to rejoin the RGGI by 2020. Pennsylvania and Virginia have also both passed legislation to join the RGGI.

In the time since the policy's original implementation, the consortium of states within the RGGI voted to lower their emissions cap in 2014. This was done because the emissions cap was effectively non-binding due to an unanticipated abundance of cheap natural gas as prices collapsed from more than \$13 per million BTU in July 2008 to just over \$3 per million BTU

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[1] For example, California has passed an emissions trading scheme, while the state of Washington has proposed a carbon tax that failed to garner enough votes to pass.

one year later in July 2009. Natural gas prices continued to decline, motivating an organic market driven substitution away from coal and hence lower emissions nationwide. However, the newly enacted emission cap reductions from 2014 were far more strict. For example, the original 2020 cap was 78,175,215 allowances which equated to 41% of the emissions allowances in 2009. The new adjusted RGGI cap for 2020 is 56,283,807 allowances or 29.9% of the 2009 level. After more than 46 quarterly auctions in the 11-year existence of the policy, more than $3.3 Trillion has been collected in revenues which have been proportionally dispersed back to individual RGGI states.[2] This results in an average of more than $100 billion per year that has been extracted from the utilities sector alone in these ten states, a sum large enough that should affect production activities of power producing plants.[3]

While it is true that carbon dioxide emissions have been falling across the United States due to coal plant retirements, the cost-competitiveness of natural gas since the price collapse, and increased renewable energy capacity, early analyses of the RGGI indicate that over half of the observed decline in emissions in the RGGI-area are due to the policy (Murray and Maniloff (2015)). However, because the RGGI is a regional initiative that takes place within a larger body of electricity flow between both adopting and non-adopting states, there is great potential for spillover effects from the policy. In fact, early predictions expected carbon-intensive power generation to flow from non-adopting states into RGGI adopting states (Chen 2009). Early empirical research concerning the RGGI has largely borne out this expectation. Kim and Kim (2016) determine that leakage has occurred by using synthetic control methods and yearly state-level data on the share of natural gas used to generate electricity. Lee and Melstrom (2018) also make use of state-level electricity flows, though at a quarterly interval. Fell and Maniloff (2018) and Chan and Morrow (2019) are the

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[2] Auction results and accumulated proceeds can be found here: https://www.rggi.org/auctions/auction-results

[3] Once dispersed to states, these permit revenues have been used to fund activities like energy efficiency audits and improvements, renewable energy development, low-carbon city services and consumer billing credits to offset higher prices. A report on state by state investments is available in RGGI (2016) which can be found here: https://www.rggi.org/investments/proceeds-investments

only others that use plant-level data to show that leakage has occurred. Fell and Maniloff (2018) use the proximity of Ohio and Pennsylvania and designate them 'leaker' states. They find that the capacity factor of natural gas-fired plants have changed in these leaker states following the implementation of the RGGI. Chan and Morrow (2019) show that leakage has occurred for both carbon dioxide emissions and associated emissions, and they are the only other paper to use observed emissions (not simply electricity generation) as we do in this paper. The consensus of this early literature is that carbon leakage is occurring, and that this occurs by increased power production in neighboring (non-adopting) states at natural gas-fired plants. In cases which coal-fired electricity from the RGGI-area is replaced by natural gas-fired electricity outside of the RGGI region, this implies an overall net reduction in emissions due to lower carbon contents of the fuels despite the increase in emissions outside the RGGI.

Another unintended spillover effect that has been studied considers how the passage of the RGGI has affected co-pollutants like Sulphur-dioxide (SO_2) and Nitrogen-oxide (NO_x) which are also emitted on combustion. Numerical studies have found that any co-benefits that may accrue are dependent on the level of regulation on the other pollutants (Fullerton and Karney (2018)).[4] An important leakage effect that has been caused by the RGGI's implementation is that SO_2 has shifted from the RGGI region to areas with higher marginal damages from SO_2 (Chan and Morrow (2019)).

Our paper makes several contributions to the existing literature. First, we are able to identify the differential effect of the RGGI on plant-level emissions for both coal and natural gas-fired units. Given the differing carbon content and production costs of each primary fossil-fuel, and existing evidence from the literature, it is possible that the RGGI has had a differential impact on plant-level emissions for these alternative electricity generating fuels. Second, we assess not only the introduction of the RGGI as prior authors have done, but also

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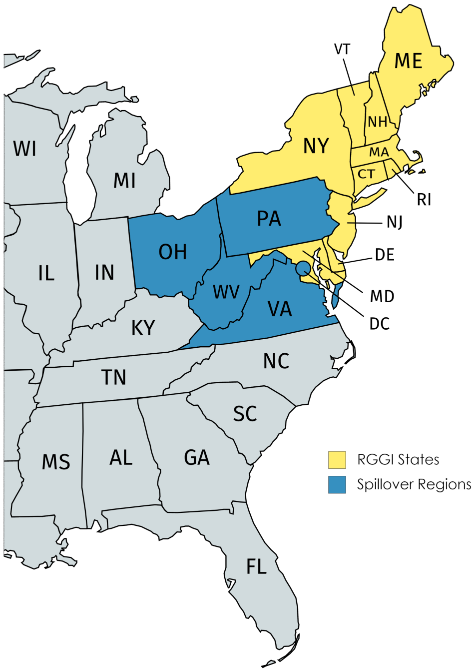
[4] As a practical example, potential interactions with the existing SO_2 permit system.

measure how the tightening of the cap since 2014 has changed emissions. The RGGI is not unique in its need to lower the emissions quota from the original policy design. Haites (2018) notes that all emissions trading systems have accumulated surplus allowances and lowered their carbon caps. By separately estimating reductions during these two treatment periods we are able to determine the cumulative effect of the RGGI on emissions - under binding and non-binding cap scenarios. After modelling and addressing the prior two factors within the RGGI (multiple plant types and multiple policy treatment dates), we use the same protocol to assess leakage that has occurred as a result of the policy. Prior authors have shown that nearby states and states within the same electricity balancing authority jurisdiction have witnessed an increase in electricity generation, especially from natural gas-fired plants. However, our study is able to determine how plant-level emissions have changed in these non-RGGI regions to makeup for reductions in electricity generation within the RGGI region by plant and by treatment period (as well as cumulatively). Additionally, we aggregate all power sector emissions at the state level to determine if the combined effect of the RGGI has resulted in meaningfully reducing emissions state-wide. Lastly, we determine how the RGGI has impacted co-pollutants at both the state-level and plant-level cumulatively and by treatment period.

To preview results, we find that plant-level emissions have declined in the RGGI region for both natural gas and coal-fired plants since the implementation of the policy. Coal plant emissions have fallen by approximately 1.1 million tons per plant per year on average, and that natural gas plant emissions have fallen by approximately 449,000 tons per plant per year on average. The causal effect that the RGGI permit system reduced plant-level CO_2 emissions is robust to numerous modeling specifications including the addition of linear time trends, accounting for early policy adoption, synthetic control design, and collapsing the time dimension entirely as suggested by Bertrand et al. (2002). Moreover, it should be noted that that plants within RGGI states already had lower emissions on average (relative to

Figure 1: RGGI Adopting States (Yellow), Leaker Areas (Blue)



non-RGGI states).[5] It is encouraging from an emissions-reduction standpoint to find in the analysis that the RGGI policy lowered these emissions-levels even further.

Concerning the RGGI's total impact on emissions, our estimates support prior findings that carbon leakage is occurring. We find for both the implementation of the RGGI and the cap-tightening of 2014, each treatment period led to increased emissions from natural gas-fired plants outside of the RGGI territory.[6] Figure 1 highlights these leaker areas next to RGGI states. For these outside groups we estimate a net increase in average emissions at natural gas plants between 420,000 – 480,000 per plant, per year. We do not find any evidence of coal plants replacing emissions in the leaker regions; instead, emissions from coal plants in leaker regions have fallen during this time. Lastly, we find no statistically significant effect of the RGGI on emissions when we repeat our analysis using aggregated state-level emissions

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[5] Figures 3 and 4 show average emissions at the plant-level by RGGI and non-RGGI states.

[6] These models consider two separate "leaker" regions, (i) non-RGGI-adopting states within the 'PJM' balancing authority and (ii) the neighboring states of Pennsylvania and Ohio as has been done in previous research.

data as is done in much of the previous literature. The differential conclusions between our state-level analyses and plant-level analyses is due to a standard problem with aggregating data – in our case, the aggregated data masks strong emissions reductions at individual plants with emissions increases from other plants in the same time period.[7] Analyses using disaggregated microdata are most appropriate when measuring production responses to a policy such as the RGGI.

2 Empirical Strategy

Our analysis begins with a state-level examination of the RGGI effect on emissions relative to non-RGGI states. This analysis does not distinguish the fuel source of electricity generating plants and takes the form of a standard differences-in-differences model. The RGGI is sharply defined along state lines, so electricity generating sources outside of the RGGI are used as a 'treatment-free' comparison group subject to the same global factors that both treated and untreated units face (e.g. commodity price changes). There is a clear start date to the carbon trading policy which began in 2009 which we use as the first 'treatment' period.[8] We are also able to use variation in the intensity of treatment because the cap on emissions was lowered in 2014, and this subsequent policy intervention serves as our second treatment period. While the state-level analysis is meant to be illustrative, the plant-level analysis is more appropriate since it can distinguish the fuel source of each plant. To integrate the differential effect of the RGGI based on the fuel source each plant uses, we measure the impact of the RGGI on plant-level emissions using a triple difference-in-differences framework. This is an important source of variation because plants that use coal or natural gas will likely be impacted by

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[7] As an illustrative example, consider measuring jobs created, jobs destroyed and net employment changes. At individual plants, jobs may be created or destroyed in abundance, but with aggregate data one may measure a net employment change of zero since created jobs will cancel destroyed jobs in aggregation.

[8] The first auction took place on September 25, 2008 but the permits are for future emissions so we begin our treatment policy in 2009.

carbon pricing differently since these fuel sources have different carbon factors.[9]

2.1 Data Description

The data on plant-level emissions are collected from the Energy Information Administration. These data measure the amount of carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrogen oxide (NO_x) emissions produced by each power-plant and are at an annual frequency from 2001-2017. We merge the reported emissions for each plant with data on yearly generation by fuel input to determine the thermal input for each plant (e.g. bituminous or lignite coal versus natural gas, etc.).

Table 1 shows state-level and plant-level summary statistics for each pollutant. It is evident that CO_2 emissions account for by far the largest share of total emissions across all plant types, and coal fired plants emit approximately 5 to 6 times more CO_2 than natural gas plants. Also, there is a tremendous amount of variation in emissions across plants with some plants emitting zero or near zero emissions while other plants have many magnitudes greater emissions than the mean. This highlights the importance of conducting the analysis at the plant-level rather than higher level aggregations since the RGGI policy (and subsequent cap reductions) will not be binding across all plants but will impose constraints on others.

2.2 Econometric Specification

The basis of our analysis uses the method of differences-in-differences. The state-level version of the model is given by equation (1).

$$\begin{aligned} CO2_{st} &= \beta_1 Begin_t + \beta_2 Lower_t + \beta_3 RGGI_s \\ &+\gamma_1 Begin_t * RGGI_s + \gamma_2 Lower_t * RGGI_s + \varepsilon_{st} \end{aligned} \tag{1a}$$

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[9] Carbon factors are the amount of carbon released per unit of heat (BTU).

Table 1: Summary Statistics

State-level Emissions	RGGI Region	Non-RGGI
CO_2	134.501	517.380
	(139.326)	(451.210)
SO_2	0.400	1.477
	(0.673)	(1.966)
NO_x	0.173	0.688
	(0.206)	(0.597)

Plant-level Emissions	RGGI Region	Non-RGGI
Coal-powered		
CO_2	15.778	31.676
	(16.700)	(40.518)
SO_2	0.080	0.108
	(0.114)	(0.187)
NO_x	0.022	0.042
	(0.026)	(0.060)
Natural Gas-powered		
CO_2	3.664	6.090
	(7.446)	(15.628)
SO_2	0.008	0.013
	(0.039)	(0.055)
NO_x	0.004	0.008
	(0.010)	(0.022)

Notes: Emissions are expressed in 100,000 tons. Mean is shown with standard deviations below in parentheses. Unit of observation is a state-year (top) and a plant-year (bottom).

$$\varepsilon_{st} = \mu_s + \lambda_t + t\mu_s + \nu_{st} \tag{1b}$$

The plant-level model is shown in equation (2). Here, instead of aggregating all emissions to the state-level we are able to measure the differential impacts that the RGGI policy has had on plant-level emissions depending on their primary fuel source.

$$\begin{aligned} CO2_{ist} = {} & \beta_1 Begin_t + \beta_2 Lower_t + \beta_3 RGGI_s + \beta_4 C_i + \beta_5 NG_i + \beta_6 Begin_t * RGGI_s \\ & + \beta_7 Begin_t * C_i + \beta_8 Begin_t * NG_i + \beta_9 Lower_t * RGGI_s + \beta_{10} Lower_t * C_i \\ & + \beta_{11} Lower_t * NG_i + \beta_{12} RGGI_s * C_i + \beta_{13} RGGI_s * NG_i \\ & + \gamma_1 Begin_t * RGGI_s * C_i + \gamma_2 Lower_t * RGGI_s * C_i \\ & + \gamma_3 Begin_t * RGGI_s * NG_i + \gamma_4 Lower_t * RGGI_s * NG_i + \varepsilon_{ist} \end{aligned} \tag{2a}$$

$$\varepsilon_{ist} = \mu_i + \lambda_t + t\mu_s + \nu_{ist} \tag{2b}$$

Where $CO2_{ist}$ is the amount of carbon dioxide emissions (in 100,000 tons) from plant i in state s in year t. The variable $RGGI_s$ is a dichotomous indicator for RGGI adopting states, $Begin_t$ is a dichotomous indicator that is set to 1 in the years that the RGGI was in force (2009-present). We also include an additional time indicator ($Lower_t$) to indicate when the cap on emissions was updated and lowered in 2014. Addressing the cap reduction in this manner is new to the empirical literature on the RGGI. The variables, C_i and NG_i indicate whether the generating source uses coal or natural gas as a fuel source. The stochastic component ε_{ist} contains a collection of fixed effects and time trends (and their interactions depending on the specification) to account for unobservables that may be correlated with the policy adoption and emissions. All models are estimated by least squares. Standard errors are clustered by plant for plant-level estimates, and clustered by state for state-level estimates.

The primary coefficients of interest are those attached to the triple interactions (γ_1 through γ_4) in equation (2) as these represent the treatment effect of carbon legislation on plant-level emissions for coal or natural gas generating sources relative to plant-level emissions outside of the RGGI area. This baseline model is later amended to include further treatment and control units to determine if the RGGI caused emissions leakage in nearby regions ($Leaker_s$ for 'leaker' states and PJM_s for plants in the PJM balancing authority but not under RGGI jurisdiction). In the tables presenting results that follow, we only show parameter estimates from the triple interactions for the sake of brevity. For example, the estimate associated with the interaction of $PJM * NG * Begin$ is the treatment effect of RGGI on plant-level emissions at natural gas generating units in the PJM territory, which would measure whether or not carbon-leakage has occurred at natural gas plants in the non-RGGI PJM territory.

In addition to estimating incremental changes in emissions from the introduction of the policy or the tightening of the cap, we also compute the cumulative or 'combined' treatment effect of the policy on emissions. This is the sum of the coefficients associated with the triple interactions. For example, summing the parameter estimates of $Begin_t * RGGI_s * NG_i + Lower_t * RGGI_s * NG_i$ (from equation (2), $\gamma_3 + \gamma_4$) yields the cumulative effect of the RGGI on plant-level natural gas emissions. These estimates are near the bottom of each table.[10]

3 State-level Emissions

Figure 2 offers a first look at our eventual state-level findings. The axis on the left pertains to non-RGGI states and the axis on the right pertains to RGGI states. In this figure, we chart average state-level emissions in the RGGI region and average state-level emissions in non-RGGI states. Note the difference between this figure and Figures (3) and (4) that present the emissions data at the plant-level across groups. The state-level emissions data shows a

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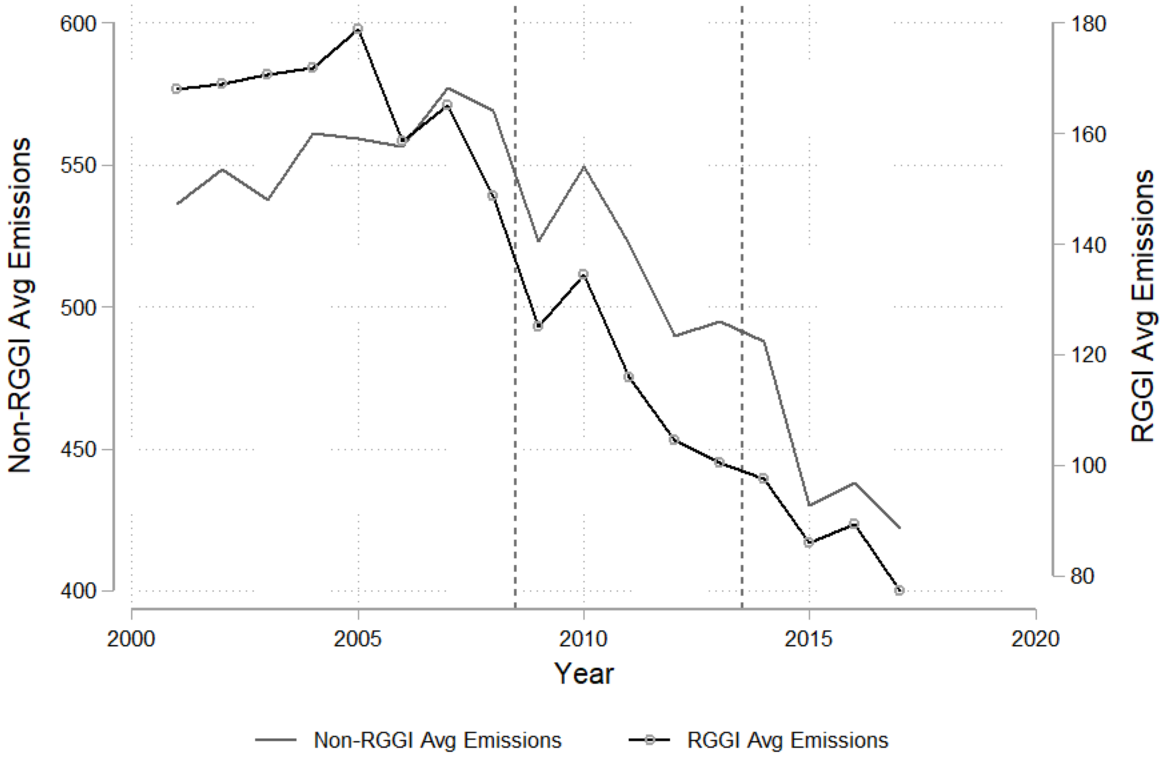
[10] Full model estimates are available using the online data and code appendix.

Figure 2: State-level Emissions by Region



much different trend for non-RGGI states than that found in the plant-level data used in Figures (3) and (4) and suggests that the aggregation may miss important differences across plants.

Nevertheless, in Figure 2 it is more evident that emissions have fallen for both RGGI and non-RGGI states and there does not appear to be much of a difference between the paths of each group. This drop in emissions is is likely driven by many factors, some of which are common to both RGGI and non-RGGI adopting states, including: macroeconomic distress, increases in the amount of installed capacity of renewable energy and its infusion into the generation mix, the 2009 stimulus bill which subsidized wind and solar power, Obama-era coal regulations, and the drop in the price of natural gas which has driven an increase in the quantity demanded of natural gas-powered electricity. We test whether or not the

Table 2: State-Level Estimates

	(1)	(2)	(3)
Dep Var.	CO_2	SO_2	NO_x
RGGI · Begin	6.579	0.290	0.086**
	(15.134)	(0.207)	(0.035)
RGGI · Lower	61.920**	0.462*	0.046
	(24.281)	(0.272)	(0.036)
State FE	Y	Y	Y
State Trends	Y	Y	Y
R^2	0.990	0.971	0.972
Obs	867	867	867

Notes: Clustered robust standard errors shown in parentheses; *,**,*** denote statistical significance at the 10%, 5%, and 1% levels, respectively

RGGI has impacted emissions at the state-level in Table 2 by pollutant. All specifications measure emissions in units of 100,000 tons, include state fixed effects, state-specific linear time trends, and have standard errors that are clustered by state. Here, we see the confusing result that the RGGI policy had no effect upon implementation and may have actually *increased* emissions in the time period that the cap was tightened. We note, though, that the point estimate in this case is actually incredibly small for state-level emissions. Indeed, this point estimate is smaller in size than some plant-level emissions. Appendix table A3 shows all estimates that are calculated at the state-level (including accounting for leakage to surrounding areas) and Table A4 in the appendix recreates table A3 using the natural logarithm of emissions. We note here that when using the log of emissions we find no statistically meaningful changes in carbon dioxide, though the point estimate is negative.

4 Plant-level Changes in CO_2 Emissions

Figures 3 and 4 illustrate aggregate total emissions by coal-fired and natural gas-fired electricity plants, respectively, over time for RGGI and non-RGGI regions and highlight several important facts.[11] First, RGGI states have significantly lower plant emissions than

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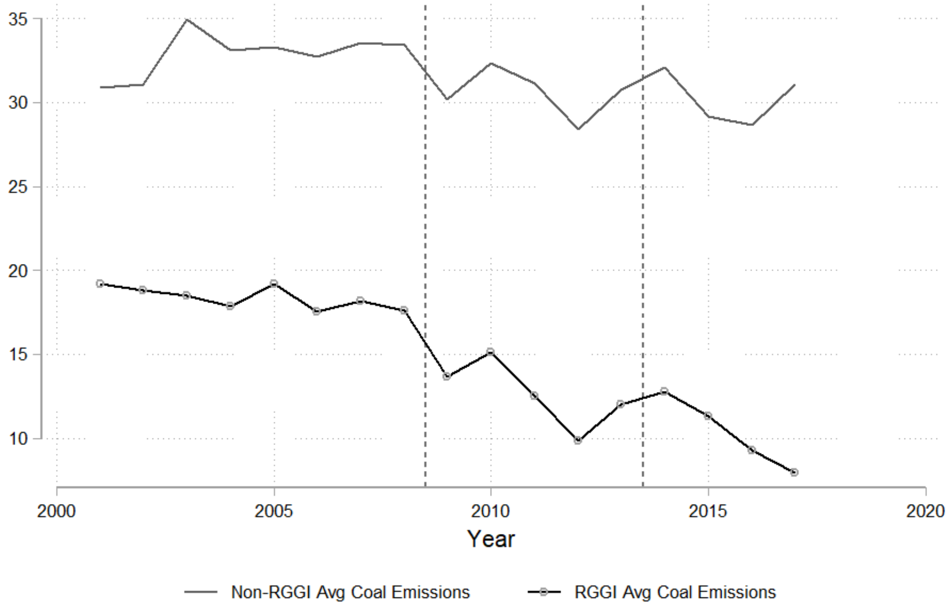
[11] Dotted vertical lines indicate the beginning of the policy in 2009 and the cap reduction in 2014.

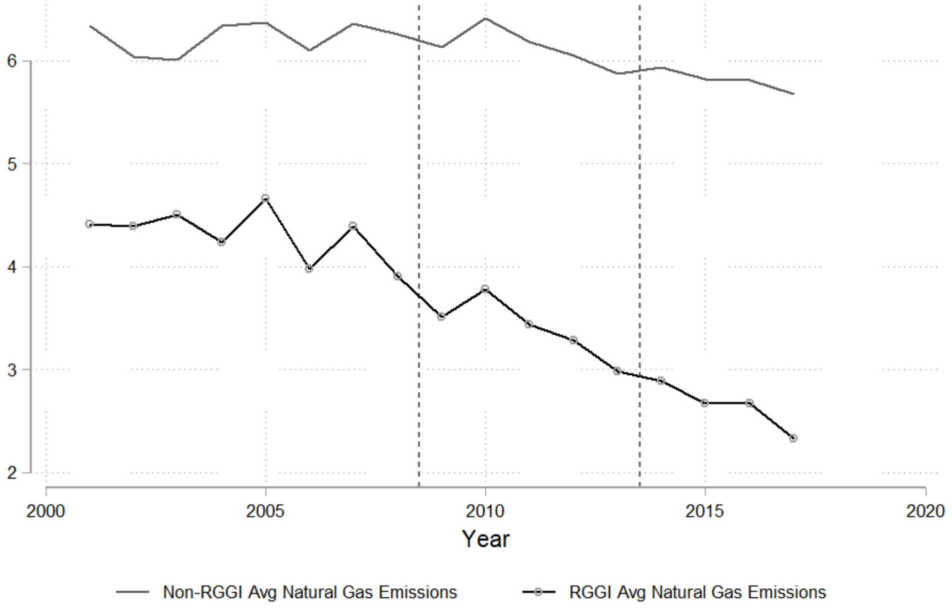
Figure 3: Coal-fired Plant Emissions by Region



non-RGGI states for both types of electricity generation through the entire sample period (around 65% of average emissions in 2001). Second, emissions in RGGI states were on a downward trend well before the RGGI policy took effect. Third, a slight downward trend in emissions also occurred during the sample period for non-RGGI states. This evidence highlights the importance of accounting for differential trends in addition to levels across treated and control groups.

Table 3 displays our initial results from estimating equation (2) and reflect how the RGGI policy has effected plant-level emissions. Columns (1) and (2) estimate the average effect of the policy from 2009 to present. Columns (3) and (4) differentiate the treatment effect for the initial policy implementation and the subsequent cap reduction in 2014. Columns (5) and (6) are a robustness check to determine if the new cap-and-trade policy was preempted by firms in the RGGI region who may have reduced emissions in advance given that the policy was pre-announced. These results are discussed in the next section but are presented here for ease of comparison. Columns (1), (3) and (5) include only plant fixed effects while

Figure 4: Natural Gas-fired Plant Emissions by Region



Columns (2), (4) and (6) include state fixed effects and state-specific linear time trends.[12]

Columns (1) and (2) indicate that emissions have fallen by approximately 4.3 hundred thousand tons each year at coal-fired plants, and by 1.3 – 1.9 hundred thousand tons per year at plants that use natural gas as a result of the overall policy.[13] This finding is robust to the inclusion of state fixed effects and state-specific linear time trends. This model includes only one indicator for the RGGI policy entering into force, as prior authors have done, but this estimated treatment effect may be biased toward zero for two reasons. First, modeling the policy in this way disregards the carbon dioxide emissions cap reduction in the region that occurred in 2014. Furthermore, following the advent of hydraulic fracturing, natural gas prices have broadly declined as the sudden supply increase brought wholesale prices down from their 2008 heights of more than $12 per million BTU to under $2 per million BTU in 2012.

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[12] There are more than 9,000 plants in the data and therefore estimating a model also includes plant-specific linear time trends (an additional 9,000 parameters to estimate) is computationally burdensome.

[13] Recall that the dependent variable in these models is in 100,000 tons

Since lower price signals also caused emissions reductions through substitution from coal to natural gas at the margin, the originally proposed carbon cap was nearly non-binding. Therefore, the remaining nine signatories to the RGGI agreed to lower the cap on emissions beginning in 2014, and lowered future emissions levels to the "adjusted" cap. By implementing a carbon cap that was more reflective of the new fuel-price landscape, this cap reduction stands to have a larger impact than the original intervention. The second reason a single treatment model might yield downward-biased estimates is that it doesn't account for how firms adjust over time to the policy. It is reasonable to expect individual firms to react differently over time as both the original cap and the adjusted cap were designed to incrementally tighten over time. When separating out the treatment period to a pre- and post-cap reduction model (columns (3)-(6)), an estimate of the cumulative (combined) impact of the policy can be calculated.

When both the 2009 and the 2014 policy treatment effects are included in the model we can see that the stricter cap on emissions further reduced coal emissions by more than seven hundred thousand tons at coal-fired plants each year on average. The summation of these two effects shows that, in total, CO_2 emissions fell by approximately 1.1 million tons at each plant on average. This combined effect shows that the prior estimates of the RGGI (columns (1) and (2)) is in fact biased toward zero (4.3 hundred thousand ton reduction compared to 1.1 million ton reduction).

For natural gas plants, we see that both policy interventions decreased average emissions. Summing the pre- and post- cap reduction estimates leads to an estimated total reduction of approximately 4.4 hundred thousand tons per year, per plant. This is, again, a slightly greater reduction than when the cap reduction is ignored (columns (1) and (2)). We note here, though, that this combined effect is larger than the estimate obtained below in the robustness section when synthetic controls are used to match plants based on average (pre-intervention) emissions amounts, but statistically similar to the other robustness estimate

Table 3. Plant-level CO_2 Emissions

	(1)	(2)	(3)	(4)	(5)	(6)
Dep. Var	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
RGGI · Coal · Begin	-4.326***	-4.303***	-3.801***	-3.748***	-3.508***	-3.455***
	(1.632)	(1.630)	(1.207)	(1.214)	(1.153)	(1.120)
RGGI · Coal · Lower	-	-	-7.579***	-7.402***	-7.357***	-7.197***
			(2.753)	(2.799)	(2.596)	(2.586)
RGGI · NatGas · Begin	-1.376***	-1.933***	-0.992**	-1.496***	-0.908*	-1.470***
	(0.489)	(0.503)	(0.409)	(0.424)	(0.473)	(0.486)
RGGI · NatGas · Lower	-	-	-2.162***	-2.996***	-2.091***	-2.954***
			(0.636)	(0.668)	(0.665)	(0.696)
RGGI · Coal · Early					-0.453	-0.406
					(0.905)	(0.878)
RGGI · NatGas · Early					-0.154	-0.408
					(0.324)	(0.322)
Combined Effect, Coal	-	-	-11.380***	-11.150***	-10.864***	-10.652***
			(3.798)	(3.857)	(3.529)	(3.487)
Combined Effect, Natural Gas	-	-	-3.154***	-4.492***	-2.999***	-4.424***
			(1.006)	(1.054)	(1.094)	(1.140)
Plant FE	Y	Y	Y	Y	Y	Y
State Trends	N	Y	N	Y	N	Y
R^2	0.960	0.960	0.961	0.962	0.961	0.962
Obs	52060	52060	52060	52060	52060	52060

Notes: Clustered robust standard errors shown in parentheses; *,**,*** denote statistical significance at the 10%, 5%, and 1% levels, respectively

obtained using the Bertrand et al. (2002) method of collapsing the time dimension.

We present these estimates while noting that plants within RGGI states already had lower emissions on average (relative to non-RGGI states).[14] It is encouraging from an emissions-reduction standpoint to find in the analysis that the RGGI policy lowered these emissions-levels even further. It is reasonable to expect that a carbon dioxide emissions reduction policy in a non-RGGI state would seemingly have larger plant-level reductions since emissions are higher at these plants to begin with.

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[14] Figures 3 and 4 show average emissions at the plant-level by RGGI and non-RGGI states.

5 Policy Spillovers

Prior research has indicated that there may be spillover effects from the RGGI policy both in terms of where new emissions occur (electricity production displaced out of the RGGI region) and how non-regulated co-pollutants change in response to the policy. Here, we use the two treatment model from before to examine how emissions have changed at the plant and state levels outside of the RGGI region, and we also test how emissions from SO_2 and NO_x have changed.

5.1 Emissions Leakage

It is evident that carbon emissions have fallen for both coal and natural gas fired power generation plants within the RGGI region. However, it remains unclear whether or not emissions from the RGGI region have simply been replaced by emissions outside the region as prior work implies might have happened, or whether these emissions reductions exist across a broader region. To identify whether or not leakage has occurred we rely on the fact that electricity supply and demand is subject to the physical limitations of transmission. Moreover, we exploit variation in the overlapping network of 'balancing authorities' whose job it is to dispatch (or curtail) electricity transmission depending on the load demand profile of an area which does not necessarily fall evenly across RGGI-adopting state lines. This section explores the accumulated impact of carbon legislation by determining how plant-level emissions have changed immediately outside the RGGI area.

While the RGGI coalition is defined sharply along state lines, electricity generation and balancing is dependent on supply and demand conditions across geopolitical barriers like state lines or balancing authority regions which vary in their state-to-state makeup. For instance, the New York ISO balances supply and demand within New York only, but the PJM balancing authority balances generation and demand across West Virginia, Pennsylvania, Ohio (and parts of other states) *in addition to* many of the RGGI states. Moreover, these balancing authorities coordinate with one another to help electricity flow unimpeded within the entire Eastern Interconnection that covers states east of Colorado and north of Texas.[15,16] To the extent that carbon-intensive generation is removed from RGGI states but is still supplied by carbon-intensive sources within the same balancing authority, the actual change in emissions due to carbon pricing may be either overestimated or non-existent.

To account for the change in plant-level emissions in nearby or overlapping states we include an additional set of difference-in-differences parameters that measure the change in emissions from coal and natural gas-fired plants in non-RGGI states that are part of the PJM balancing region as in Chan and Morrow (2019), as well as in the 'leaker' states of Ohio and Pennsylvania as in Fell and Maniloff (2018). These estimates are shown in Table 4 with columns (1) and (2) measuring leakage into 'leaker' states not in the PJM, and columns (3) and (4) measuring leakage into plants that reside in states that are in the PJM region but are not signatories to the RGGI agreement.

Beginning with the estimated effect within the RGGI region, we find the change in plant-level emissions is quantitatively similar to the estimates found before. We see that each phase of the RGGI policy has decreased coal plant emissions by approximately 4.3 and 7.8 hundred thousand tons, respectively, with a combined effect of reducing coal plant CO_2 emissions by more than 1.1 million tons. Again, we also see that natural gas plant emissions fell in each phase of the RGGI by approximately 1.3 and 2.6 hundred thousand tons. The combined effect is again approximately 3.8 hundred thousand tons per plant, per year on average. These estimates are inline with the prior estimates of Table 2 and robustness estimates in appendix table A1-A2.

Looking now to carbon emissions leakage, we find evidence that some carbon emissions were pushed out to the surrounding 'leaker' and non-RGGI non-PJM region. Columns (1)

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[15] Including parts of northern Texas.

[16] There is also the Western Interconnection and the Texas 'ERCOT' interconnection. Electricity within each interconnection flows at a different phase, so electricity physically cannot (and generally is not) transported across interconnections without the phase of the current being transformed.

and (2) both consider how emissions have changed at plants in Ohio or Pennsylvania ('leaker' states), but differ in their inclusion of state fixed effects and state trends. Columns (3) and (4) use plants that are part of the PJM balancing authority, but that are outside of the RGGI region. In both cases, the point estimates are slightly attenuated when including state trends and fixed effects. We find evidence across all specifications that some emissions have been pushed outside of the RGGI region.

Depending on whether the plant is in a 'leaker' state or is in a PJM (non-RGGI) state, plant-level carbon emissions at natural gas plants increased by 4.3-4.8 hundred thousand tons on average across both policy treatment periods. The introduction of the policy is associated with a 1.3-1.5 hundred thousand ton increase, and the cap tightening is associated with a 2.8-3.2 hundred thousand ton increase. The net increase in average emissions at natural gas plants outside of the RGGI-area is roughly equal to the decrease in average emissions at natural gas emissions within the RGGI region. The tightening of the carbon cap ($Lower_t$) did not have a statistically significant effect for coal in the PJM-area, but the policy introduction is associated with lower emissions. In 'leaker' states Pennsylvania and Ohio, the point estimate on coal emissions is negative for both policy interventions ($Begin_t$ and $Lower_t$), but is not statistically significant. Summing across policy periods we find a net decrease in coal plant emissions outside of the RGGI area, but this is only statistically significant at the 5% level in the PJM territory.

Columns (2) and (3) of appendix table A3 calculate emissions spillover at the state-level for carbon dioxide. There is some evidence that emissions have fallen in the 'Leaker' region due to the RGGI policy, but again we find that when the natural log of emissions is used as the dependent variable this effect dissipates.

Table 4: Plant-level Carbon Leakage

	(1)	(2)	(3)	(4)
Dep. Var.	CO_2	CO_2	CO_2	CO_2
RGGI · Coal · Begin	-3.950***	-3.922***	-4.329***	-4.276***
	(1.223)	(1.229)	(1.232)	(1.237)
RGGI · Coal · Lower	-7.851***	-7.712***	-7.954***	-7.775***
	(2.767)	(2.813)	(2.783)	(2.826)
RGGI · NatGas · Begin	-0.842**	-1.348***	-0.743*	-1.255***
	(0.416)	(0.434)	(0.421)	(0.440)
RGGI · NatGas · Lower	-1.808***	-2.656***	-1.707***	-2.574***
	(0.639)	(0.679)	(0.645)	(0.687)
Leaker · Coal · Begin	-1.656	-1.667		
	(1.039)	(1.030)		
Leaker · Coal · Lower	-2.658	-2.684		
	(2.093)	(2.076)		
Leaker · NatGas · Begin	2.061***	1.561**		
	(0.696)	(0.709)		
Leaker · NatGas · Lower	4.229***	3.271***		
	(1.210)	(1.220)		
PJM · Coal · Begin			-3.196***	-3.135***
			(0.926)	(0.929)
PJM · Coal · Lower			-2.226	-2.106
			(1.578)	(1.609)
PJM · NatGas · Begin			1.983***	1.504**
			(0.629)	(0.656)
PJM · NatGas · Lower			3.688***	2.761***
			(0.941)	(0.985)
RGGI Combined Effect, Coal	-11.801***	-11.634***	-12.283***	-12.051***
	(3.824)	(3.881)	(3.847)	(3.901)
RGGI Combined Effect, Natural Gas	-2.650***	-4.004***	-2.450**	-3.829***
	(1.016)	(1.075)	(1.025)	(1.088)
Non-RGGI Combined Effect, Coal	-4.314	-4.351	-5.422**	-5.241**
	(2.983)	(2.955)	(2.370)	(2.406)
Non-RGGI Combined Effect, Natural Gas	6.290***	4.832***	5.671***	4.265**
	(1.816)	(1.839)	(1.486)	(1.559)
Plant FE	Y	Y	Y	Y
State Trends	N	Y	N	Y
R^2	0.961	0.962	0.961	0.962
Obs.	52060	52060	52060	52060

Notes: Clustered robust standard errors shown in parentheses; *,**,*** denote statistical significance at the 10%, 5%, and 1% levels, respectively

5.2 RGGI Impact on Non-regulated Emissions

Finally, to measure the full impact of the RGGI on electric power sector emissions we also investigate whether or not associated emissions have been changed (those that are not regulated under the RGGI carbon permit market). Perhaps generation has shifted not only from coal to natural gas, as we have seen above both inside and outside the RGGI region, but also to sources that have a relatively higher sulphur content. In this section we re-estimate both the plant-level and state-level models with Sulphur Dioxide and Nitrous Oxide emissions as the dependent variable to see if plant-level (Table 5) or state-level (Table A3) emissions have changed for these pollutants.

Beginning at the plant-level, we do find evidence that the RGGI has led to decreases in in SO_2 for both coal and natural gas plants. For natural gas plants, both policy interventions are negative and statistically significant with a combined effect of removing upwards of 2 thousand tons per plant per year on average. For coal-fired plants, we find that both treatment effect estimates are negative, though only the second policy intervention can be differentiated from zero. The cumulative effect of these policies at natural gas plants is a decrease of approximately 4.1-5.1 thousand tons per plant per year on average (all of which are statistically significant at the 1% level), and 5.2-7.4 thousand tons at coal plants with is only marginally significant in one specification . For NO_x emissions, we find that only natural gas plants have seen a cumulative decrease in emissions. There is no cumulative effect on these emissions from coal plants.

As we saw with carbon-leakage, here we again find some evidence of emissions leakage of SO_2 in Pennsylvania and Ohio and the non-RGGI PJM territory. This finding is particularly true for natural gas plants which have seen an increase of about 7-8 thousand tons per plant per year on average which is statistically significant at the 5% level. We do see that SO_2 emissions from coal plants have decreased following the first policy intervention leading to a cumulative decrease of 13-18 thousand tons per plant per year. For NO_x emissions leakage,

Table 5: Plant-level SO_2 and NO_x Emissions

	(1)	(2)	(3)	(4)	(5)	(6)
Dep. Var.	SO_2	SO_2	SO_2	NO_x	NO_x	NO_x
RGGI · Coal · Begin	-0.010	-0.019	-0.021	0.006	0.006	0.005
	(0.017)	(0.016)	(0.017)	(0.004)	(0.004)	(0.004)
RGGI · Coal · Lower	-0.041	-0.054*	-0.053*	0.003	0.003	0.004
	(0.030)	(0.030)	(0.030)	(0.005)	(0.005)	(0.006)
RGGI · NatGas · Begin	-0.021***	-0.016***	-0.016***	-0.007***	-0.007***	-0.006***
	(0.006)	(0.005)	(0.005)	(0.001)	(0.001)	(0.001)
RGGI · NatGas · Lower	-0.031***	-0.026***	-0.025***	-0.009***	-0.009***	-0.008***
	(0.007)	(0.007)	(0.007)	(0.002)	(0.002)	(0.002)
Leaker · Coal · Begin		-0.072**			-0.003	
		(0.032)			(0.006)	
Leaker · Coal · Lower		-0.114**			-0.002	
		(0.045)			(0.008)	
Leaker · NatGas · Begin		0.039**			0.007*	
		(0.017)			(0.004)	
Leaker · NatGas · Lower		0.044**			0.006	
		(0.019)			(0.004)	
PJM · Coal · Begin			-0.061**			-0.004
			(0.024)			(0.005)
PJM · Coal · Lower			-0.073**			0.004
			(0.033)			(0.006)
PJM · NatGas · Begin			0.033**			0.007**
			(0.014)			(0.003)
PJM · NatGas · Lower			0.038**			0.008**
			(0.016)			(0.004)
RGGI Combined Effect, Coal	-0.052	-0.073	-0.074*	0.009	0.008	0.009
	(0.045)	(0.045)	(0.045)	(0.009)	(0.009)	(0.009)
RGGI Combined Effect, Natural Gas	-0.051***	-0.042***	-0.041***	-0.016***	-0.015***	-0.014***
	(0.012)	(0.012)	(0.012)	(0.003)	(0.003)	(0.003)
Non-RGGI Combined Effect, Coal		-0.186**	-0.134**		-0.005	0.000
		(0.076)	(0.056)		(0.014)	(0.011)
Non-RGGI Combined Effect, Natural Gas		0.083**	0.071**		0.012	0.014*
		(0.035)	(0.029)		(0.008)	(0.007)
Plant FE	Y	Y	Y	Y	Y	Y
State Trends	Y	Y	Y	Y	Y	Y
R^2	0.750	0.754	0.753	0.828	0.829	0.829
Obs.	55260	55260	55260	55248	55248	55248

Notes: Clustered robust standard errors shown in parentheses; *,**,*** denote statistical significance at the 10%, 5%, and 1% levels, respectively

we only find evidence of an increase in emissions at natural gas plants in the non-RGGI plants in the PJM region, an increase of about 1,400 tons per plant, per year.

Regarding state-level impacts (columns (4) to (9) of Table A3), there is limited evidence that the RGGI has impacted non-regulated emissions emissions. We find an increase in the amount of NO_x emissions after the introduction of the RGGI in 2009, but again find that this effect is gone when the natural logarithm of emissions is used instead. There is some evidence of a decrease in SO_2 emissions due the introduction of the cap-and-trade system when the natural logarithm of emissions is used (Table A4).

6 Alternative Specifications

The prior analysis included several variations in control and treatment design by plant type, incorporating the enhanced emissions cap, and adjusting how unobservables are modeled. In this section, we explore four separate robustness checks that account for common concerns with the use of difference-in-differences modeling as a method to determine treatment effects — parallel trends assumption between treated and control groups and identifying an appropriate control group. We first determine whether or not electricity generating plants within the RGGI region pre-empted the policy by making production changes in advance of RGGI states signing on to the agreement. Next, we remove trends in the data entirely and estimate the model in a manner suggested by Bertrand et al. (2002).[17] Lastly, we provide an event study analysis for both coal and natural gas plant emissions. This model is fully saturated with indicators for each year interacted with the RGGI indicator. This model is shown below in equation (3). Lastly, we incorporate a synthetic controls technique of matching treated and control units based on propensity scores.

The RGGI was operational at the beginning of 2009, but the policy was discussed among eventual member states as early as 2003. In late December 2005, seven of the RGGI states

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[17] This is similar to the classic issue exhibited by Moulton (1990).

announced an agreement to implement the RGGI, as outlined in a Memorandum of Understanding (MOU) signed by the Governors of Connecticut, Delaware, Maine, New Hampshire, New Jersey, New York, and Vermont. This MOU, as amended, still provides the major policy design elements and governance rules of the RGGI to this day. Two years later, Massachussets and Rhode Island both signed the MOU, and Maryland soon followed. Given the foreknowledge of joining the RGGI and the delay before the policy officially began in 2009, it is possible that plants within RGGI adopting states began to implement or change their generation *prior* to the first compliance period. If this occurred, then the estimated effect above would be biased toward zero.

To address this issue, we augment the model in equation (2) with an additional pre-2009 indicator ($Early_t$) to determine whether or not plants within the RGGI began to change behavior prior to the actual implementation of the carbon permit trading system.[18] These estimates are found in columns (5) and (6) of Table 2. We find no evidence that coal or natural gas plants pre-empted the policy. The 'pre-treatment' effects (parameter estimates for $RGGI * Coal * Early$ and $RGGI * NatGas * Early$) are not statistically distinguishable from zero for either plant type, and the estimated treatment effect for both the 2009 cap and the 2014 are statistically similar to the estimated effect in specifications that do not include the pre-treatment parameters.

We next address the general concern with difference-in-differences models that is explored by Bertrand et al. (2002). Bertrand et al. (2002) show in Monte Carlo simulations that OLS implementation of difference-in-differences can result in standard errors that are too low which would lead to over-rejection of the null hypothesis. This is potentially worse when the time dimension is long and the number of clusters is low. Because our data is at a yearly level and the time dimension is relatively short (and the number of clusters is large), excessive serial correlation bias is not likely to be a problem. Bertrand et al. (2002) find that much of

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[18] $Early_t = 1$ when a state signs the MOU.

the potential bias can be resolved by clustering standard errors. In our paper, all reported results are clustered at the plant-level already.[19]

To address any remaining tendencies to over-reject, Bertrand et al. (2002) find a method that works well is to remove the time dimension by collapsing the data into simple pre-periods and post-periods (in our case, one pre-period, one period for the RGGI passage, and one period for the cap tightening). Results form this model are presented in appendix table A1 where we still find evidence of reduced plant-level emissions. The point estimates indicate a decrease of approximately 3.2 and 6.2 hundred thousand tons at coal plants for each policy period, and a combined decrease of approximately 9.4 hundred thousand tons. For natural gas plants we see a decrease of about 1.2 and 1.7 hundred thousand tons per policy period, and a combined decrease of approximately 2.8 hundred thousand tons. These estimates are statistically similar to our prior treatment effect estimates for natural gas plants, and indicate a a slightly lower effect at both coal and natural gas plants than previously estimated (9.4 hundred thousand ton decline compared to a 1.1 million ton decline for coal, and 2.8 hundred thousand ton decline compared to 4.5 hundred thousand ton decline at natural gas plants).

Another method of gauging model validity is through the use of an event-study model. Here, the model is saturated with indicators interacted with each year of the data except the year prior to the policy implementation. In other words, estimated coefficients in this model show the average effect in the RGGI in each year both before and after the policy implementation, with reference to emissions just prior to the implementation. This model is shown below in equation (3).

$$CO2_{ist} = \beta_0 + \beta_1 RGGI + \sum_{\substack{t=t_0 \\ t\neq 2008}}^{t} \Big[\beta_2^t RGGI * I(Year = t)\Big] + \lambda_t + \varepsilon_{ist} \tag{3}$$

Figure 5 displays coefficients of the event-study model for coal plants (top) and natural

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[19] There are no meaningful changes to standard errors or estimated significance levels when the standard errors are clustered by state or by plant-type.

gas plants (bottom). Here we see that within the RGGI, emissions do begin to fall following the policy implementation for both type of plants.

As a final measure, we use a synthetic controls method to measure the effect of the RGGI on plant-level emissions. In this model we match plants on an estimated propensity score. Plants are matched based on pre-intervention emissions amounts as well as information on the primary fuel type the plant uses. For each treated plant, emissions outcomes are averaged across untreated plant(s) that are most similar, which is used to predict the unobserved potential outcome. The estimated average treatment effect (ATE) is then the difference in the actual emissions outcome from the averaged outcome of plants that are similar.

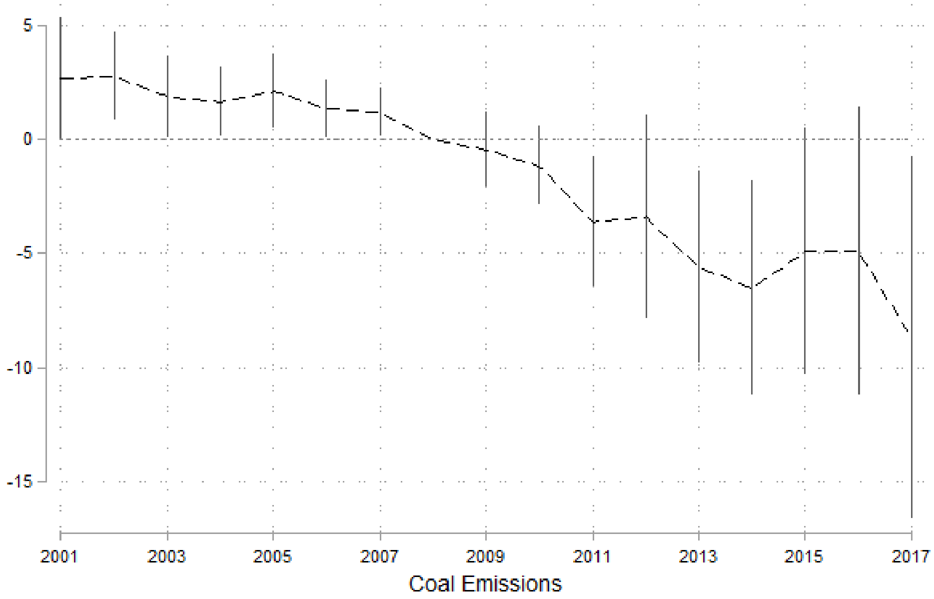
These results are presented in appendix table A1 where we also find that the RGGI has reduced plant-level emissions. In this model, the average treatment effect is a reduction of 6.7 hundred thousand tons of carbon dioxide per plant for coal-fired plants, and an average treatment effect of 0.47 hundred thousand tons for natural gas plants.

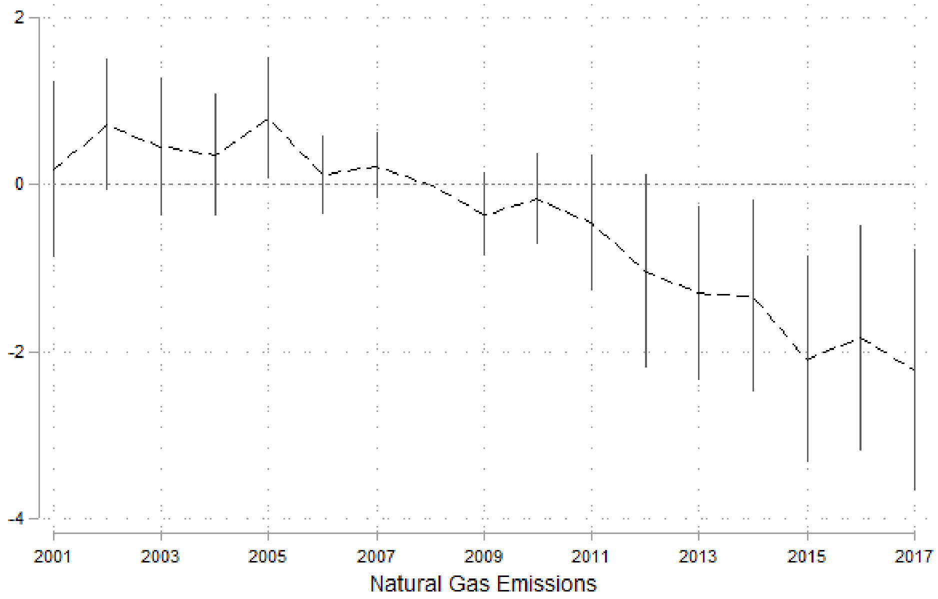
Note that the propensity score method and the Betrand Time Collapse method both yield results that are inline with that from the triple differences-in-differences model. However, the estimated effect for natural gas plants is smaller in magnitude for the propensity score method but is statistically significant from zero. Also, the Bertrand Time Collapse method to a single treatment leads to smaller point estimates and statistical insignificance for coal plants. This is expected since, as discussed in more detail above, the single treatment models ignore the enhanced emissions cap and are likely biased toward zero.

7 Conclusions and Policy Discussion

Despite global collaboration efforts and agreements to reduce greenhouse gasses, specific policies intended to reduce greenhouse gas emissions have not been widely applied and are mostly regionally-based. In this paper, we analyze the efficacy of the first cap-and-trade program that was passed in the United States, the Regional Greenhouse Gas Initiative

Figure 5: Event Study Estimates





(RGGI), and also discuss broader impacts of the policy such as leakage into neighboring areas and effects on unregulated co-pollutants.

Our paper makes several contributions to the existing literature that has investigated the RGGI and its effects. First, we are able to identify the differential effect of the RGGI on plant-level emissions for both coal and natural gas-fired units. Second, we assess not only the introduction of the RGGI as prior authors have done, but also measure how the tightening of the cap since 2014 has changed emissions. Combining these two effects yields an estimate for the cumulative effect of the RGGI on emissions over time. We also assess leakage that has occurred as a result of the policy, and our study is able to determine how plant-level emissions have changed in non-RGGI regions to makeup for reductions in some types of electricity generation within the RGGI region. Additionally, we aggregate all power sector emissions at the state level to determine if the combined effects of the RGGI have resulted in meaningfully reducing emissions state-wide. Lastly, we determine how the RGGI has impacted co-pollutants (such as SO_2 and NO_x) at both the state-level and plant-level cumulatively and by treatment period.

We find that plant-level emissions have declined in the RGGI region for both natural gas and coal-fired plants since the implementation of the policy. Coal plant emissions have fallen by approximately 1.1 million tons per plant per year on average, and that natural gas plant emissions have fallen by approximately 449,200 tons per plant per year on average. Concerning the RGGI's total impact on emissions, our estimates support prior findings that carbon leakage is occurring. We find for both the implementation of the RGGI and the cap-tightening of 2014, emissions has increased from natural gas-fired plants outside of the RGGI territory. For these outside groups we estimate a net increase in average emissions at natural gas plants between 430,000 – 480,000 per plant, per year. We do not find any evidence of coal plants replacing emissions in the leaker regions; instead, emissions from coal plants in leaker regions have fallen during this time as well. Lastly, we cannot say with confidence that the RGGI has led to meaningful statewide emissions reductions relative to treatment-free control states. That is, despite the fact that RGGI plant-level emissions have fallen for both coal and natural gas electricity generation, we cannot reject the notion that the state-level decline in emissions are statistically similar for states within the RGGI compared to those outside of the RGGI. However, this conclusion may be influenced by aggregation over many plants, some of which are greatly affected by the RGGI while others are not. Concerning co-pollutants, however, we do find evidence that the RGGI passage has resulted in fewer SO_2 emissions at both the plant-level and the state-level relative to non-RGGI states.

Our results offer insight into how future policies may better address carbon emissions and climate change as well as highlight some of the pitfalls and roadblocks associated with formulating an effective policy. For example, a market based policy intervention such as the cap and trade RGGI policy (or a carbon tax) appears to be successful at reducing emissions with two caveats: (1) External factors such as the recent decline in natural gas and subsequent substitution away from coal or technological innovation can quickly make existing caps ineffective or inappropriate. The RGGI cap was clearly more binding after the 2014 cap reduction as electricity generation was already moving away from coal. However, in the case that natural gas prices would have increased rather than decreased, the caps could have been too restrictive too quickly. It is important for future policies to be both flexible to change and responsive to external factors in the marketplace. Similar evidence is uncovered in the transportation sector in Andersson (2019) who shows that drivers respond more strongly to changes in carbon tax rates than equivalent (market determined) gasoline price changes. In our setting, it is possible that price movements due to changes in market forces are perceived differently by electricity generating firms than equivalent carbon price changes. (2) Addressing climate change with policies that are restrictive to geopolitical boundaries will be less effective due to spillovers and the exportation of emissions. Domestically proposed climate change policies receive significant political push-back in part for this reason as well as the differential effect on competitiveness for domestic firms. A broad reaching policy crossing political boundaries is clearly the more ideal approach, particularly if it should have meaningful and identifiable enforcement mechanisms.

8 Appendix

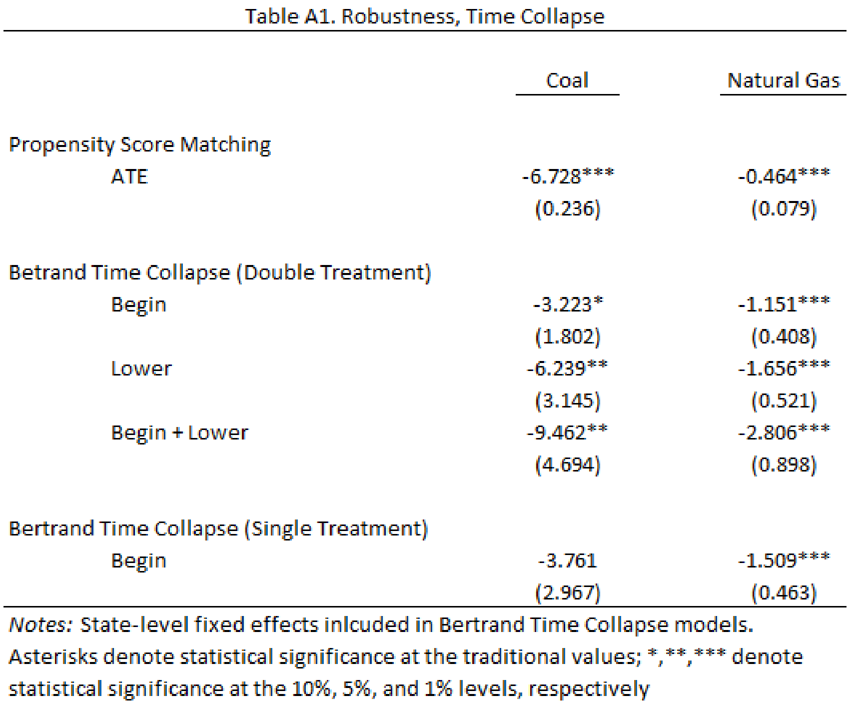


Table A1. Robustness, Time Collapse

	Coal	Natural Gas
Propensity Score Matching		
ATE	-6.728***	-0.464***
	(0.236)	(0.079)
Betrand Time Collapse (Double Treatment)		
Begin	-3.223*	-1.151***
	(1.802)	(0.408)
Lower	-6.239**	-1.656***
	(3.145)	(0.521)
Begin + Lower	-9.462**	-2.806***
	(4.694)	(0.898)
Bertrand Time Collapse (Single Treatment)		
Begin	-3.761	-1.509***
	(2.967)	(0.463)

Notes: State-level fixed effects inlcuded in Bertrand Time Collapse models. Asterisks denote statistical significance at the traditional values; *,**,*** denote statistical significance at the 10%, 5%, and 1% levels, respectively

Table A2. Robustness

	(1)	(2)	(3)	(4)
Dep Var.	CO_2	CO_2	CO_2	CO_2
RGGI · Coal · Begin	-3.748***	-3.553***	-3.702***	-3.570***
	(1.214)	(1.223)	(1.216)	(1.223)
RGGI · Coal · Lower	-7.402***	-6.909**	-7.341***	-7.421***
	(2.799)	(2.841)	(2.799)	(2.801)
RGGI · NatGas · Begin	-1.496***	-1.210***	-1.664***	-1.775***
	(0.424)	(0.408)	(0.437)	(0.445)
RGGI · NatGas · Lower	-2.996***	-2.559***	-3.296***	-3.375***
	(0.668)	(0.647)	(0.688)	(0.691)
Combined Effect, Coal	-11.150***	-10.462***	-11.043***	-10.991***
	(3.857)	(3.914)	(3.858)	(3.866)
Combined Effect, Natural Gas	-4.492***	-3.769***	-4.961***	-5.150***
	(1.054)	(1.016)	(1.085)	(1.094)
Plant FE	Y	Y	Y	Y
State Trends	Y	Y	Y	Y
Fuel-type Trends	N	Y	N	N
Includes CA	Y	Y	N	N
Eastern Interconnection Only	N	N	N	Y
R^2	0.962	0.962	0.962	0.961
Obs	52060	52060	46423	38823

Notes: Clustered robust standard errors shown in parentheses; *,**,*** denote statistical significance at the 10%, 5%, and 1% levels, respectively

Table A3: State-Level Estimates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dep Var.	CO_2	CO_2	CO_2	SO_2	SO_2	SO_2	NO_x	NO_x	NO_x
RGGI · Begin	6.579	5.587	0.527	0.290	0.205	0.203	0.086**	0.076**	0.077**
	(15.134)	(15.395)	(15.630)	(0.207)	(0.198)	(0.205)	(0.035)	(0.034)	(0.035)
RGGI · Lower	61.920**	52.644**	51.823**	0.462*	0.355	0.391	0.046	0.037	0.052
	(24.281)	(23.864)	(25.093)	(0.272)	(0.262)	(0.275)	(0.036)	(0.037)	(0.039)
Leaker · Begin		-28.727**			-1.766**			-0.220	
		(11.574)			(0.845)			(0.145)	
Leaker · Lower		-204.566***			-2.225**			-0.170**	
		(31.775)			(0.901)			(0.083)	
PJM · Begin			-40.500			-0.752			-0.108
			(32.029)			(0.557)			(0.107)
PJM · Lower			-67.102			-0.643			-0.007
			(59.194)			(0.688)			(0.079)
RGGI Combined Effect	68.499*	58.230	52.350	0.752	0.560	0.594	0.132*	0.113	0.130*
	(38.254)	(38.307)	(39.774)	(0.471)	(0.451)	(0.473)	(0.063)	(0.063)	(0.067)
Non-RGGI Combined Effect		-233.293***	-107.603		-3.991**	-1.395		-0.390***	-0.115
		(37.051)	(81.675)		(1.745)	(1.233)		(0.079)	(0.155)
RGGI & Non-RGGI Combined Effect		-175.063**	-55.253		-3.431*	-0.800		-0.277**	0.014
		(68.245)	(99.820)		(1.853)	(1.413)		(0.121)	(0.178)
State FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
State Trends	Y	Y	Y	Y	Y	Y	Y	Y	Y
R^2	0.990	0.991	0.990	0.971	0.973	0.972	0.972	0.972	0.972
Obs	867	867	867	867	867	867	867	867	867

Notes: Clustered robust standard errors shown in parentheses; *,**,*** denote statistical significance at the 10%, 5%, and 1% levels, respectively

Table A4: State-Level Estimates, Natural Log of Emissions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dep Var.	lnCO_2	lnCO_2	lnCO_2	lnSO_2	lnSO_2	lnSO_2	lnNO_x	lnNO_x	lnNO_x
RGGI · Begin	-0.077	-0.076	-0.077	-0.458**	-0.465**	-0.451**	0.020	0.018	0.016
	(0.097)	(0.098)	(0.097)	(0.216)	(0.217)	(0.215)	(0.117)	(0.118)	(0.118)
RGGI · Lower	-0.080	-0.085	-0.084	-0.635	-0.651	-0.653	-0.073	-0.079	-0.049
	(0.185)	(0.185)	(0.186)	(0.391)	(0.393)	(0.391)	(0.197)	(0.198)	(0.199)
Leaker · Begin		0.002			-0.154			-0.059	
		(0.022)			(0.149)			(0.147)	
Leaker · Lower		-0.120***			-0.348**			-0.136*	
		(0.036)			(0.151)			(0.077)	
PJM · Begin			0.006			0.121			-0.093
			(0.104)			(0.326)			(0.137)
PJM · Lower			-0.020			-0.066			0.088
			(0.109)			(0.254)			(0.124)
State FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
State Trends	Y	Y	Y	Y	Y	Y	Y	Y	Y
R^2	0.993	0.993	0.993	0.970	0.970	0.970	0.982	0.982	0.983
Obs	867	867	867	867	867	867	867	867	867

Notes: Clustered robust standard errors shown in parentheses; *,**,*** denote statistical significance at the 10%, 5%, and 1% levels, respectively

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