2020-05

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Yan, J. (2020). The impact of climate policy on fossil fuel consumption: evidence from the Regional Greenhouse Gas Initiative (RGGI) (Master's thesis, University of Calgary, Calgary, Canada). Retrieved from https://prism.ucalgary.ca.

http://hdl.handle.net/1880/112062

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The Impact of Climate Policy on Fossil Fuel Consumption: Evidence from the Regional Greenhouse Gas Initiative (RGGI)

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF ARTS

GRADUATE PROGRAM IN ECONOMICS

CALGARY, ALBERTA

MAY, 2020

Abstract

Climate policies such as a carbon tax or a cap-and-trade program are increasingly being used to reduce emissions. In the United States, the Regional Greenhouse Gas Initiative (RGGI) is a cap-and-trade program to reduce emissions. In this paper, I use detailed state-level data to estimate the impact of RGGI on coal and natural gas consumption in the electric-power industry. I find that the program directly caused coal and natural gas phase-out within regulated states. Specifically, the program decreases coal and natural gas consumption for electricity generation by 73% and 31%, respectively, within regulated states. However, in nearby, un-regulated states I find an increase in natural-gas consumption of 259% and a decrease in coal consumption of 7%. As a result, annually the program reduced carbon dioxide emissions by 4.3 million tons in regulated states, but the program also increased carbon dioxide emissions by 3.2 million tons in unregulated states. I also find that the program decreased the efficiency of coal-fired and gas-fired plants which reduces the program's effectiveness for lowering emissions. Nonetheless, in aggregate, the program reduced carbon dioxide emissions by 1.1 million tons per year.

Table of Contents

1. Introduction

Climate change is an important issue today. Human activities, including the burning of fossil fuels and deforestation for agriculture or urbanization, have increased the concentration of atmospheric carbon dioxide and other heat-trapping gases (Stocker et al., 2013). Climate change has had several consequences such as rising sea levels, melting glaciers, droughts, changes in precipitation, and extreme weather conditions. In response, many countries have enacted policies to alter the magnitude or timing of climate change. Market-based policies, such as carbon taxes and cap-and-trade programs, are the most efficient at slowing climate change and reducing greenhouse gas emissions while limiting impact on economic growth.

Cap-and-trade programs are tradable permit systems for emissions that are implemented at the state or national level and can include multiple countries. Many cap-and-trade programs exist around the world, such as the United States sulfur-dioxide-allowance-trading program under the Clean Air Act Amendments of 1990, the trading of nitrogen oxides in the eastern United States, the European Union Emissions Trading System, and California's cap-and-trade system under Assembly Bill 32. In a cap-and-trade program, the government sets an overall limit on emissions, and defines permits, or limited authorizations to emit, up to the level of the overall limit. Permits are allocated to individual carbon-emitting sources. They could be allocated to the largest carbon emitters, such as power companies and manufacturing plants, or to suppliers that introduce carbon fuels into the production process such as oil producers and importers, coal mines, and natural gas drillers. Permits are allocated for free based on past emissions history are auctioned to the highest bidders. If auctioned, the revenue collected from the auctions can be used to develop energy efficiency programs and renewable energy. Once firms obtain a permit, they can trade permits among themselves. Firms with emissions exceeding the number of permits they hold must purchase additional permits or face penalties. Firms that can economically reduce their emissions below their allowance may seek to sell their permits for a profit. The permit price is determined through market supply and demand. Environmental groups or other organizations may also purchase and retire permits, driving up the price of the remaining permits to help reduce overall emissions.

In this paper, I will use a climate policy of the Regional Greenhouse Gas Initiative (RGGI), a regional cap-and-trade program for electric-power sector in the U.S., to estimate the impact of the program on the consumption of coal and natural gas by electric power plants in order to measure its effectiveness for reducing carbon dioxide emissions.

RGGI is the first mandatory market-based cap and trade program in the United States to reduce greenhouse gas emissions. It is a cooperative effort between Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont to cap and reduce carbon dioxide emissions from the power sector. The program established a regional cap on the amount of carbon dioxide emissions from power plants by issuing a limited number of tradable carbon dioxide allowances. Each allowance authorizes a regulated power plant to emit one short ton of carbon dioxide emissions. The states involved in RGGI distribute the allowances by holding quarterly auctions. The proceeds generated from the auctions are used to invest in energy efficiency, renewable energy, and other consumer benefit programs. The RGGI program commenced on January 1, 2009, and it is currently in its fourth three-year compliance period.

RGGI has been consequential for the environment and economy. First, the program has reduced carbon dioxide emissions within regulated states. Several literatures show the evidence. Ceres, a non-profit sustainability advocacy organization reports that, between 2005–2013, RGGI states experienced a reduction in power sector carbon dioxide emissions of over 40%. More specifically, between 2009-2014, emissions in RGGI states dropped 35% compared to only 12% in non-RGGI states. Ruth et al. (2008) explore the impacts of the state of Maryland joined RGGI. They find the carbon dioxide emissions are lower after the state joined RGGI and emissions leakage is small. Murray and Maniloff

(2015) use a three-stage econometric model of electricity generation at the state level and simulate baseline emissions. They quantify the impact of several factors on the reduction of greenhouse gas emissions in RGGI states. These factors include an increase in the price of coal, a decrease in the price of natural gas, a change in the price of carbon, a change in renewable portfolio standards, the unemployment rate, and finally the RGGI program effect. They find that RGGI is the dominant factor in the 40% decline of emissions in regulated states, while the reduction of natural gas prices accounts for more than one-third of the region's emissions decline. Zhou (2016) shows RGGI has helped decrease the total carbon dioxide emissions from the power sectors of Delaware and Maryland (RGGI states) by at least 4.73% from 2009 to 2013.

Second, some studies show the program has no negative impact on the region's economic growth. For example, based on a research of Analysis Group which is an economic consulting firm, over the third three-year compliance period (2015–2017), RGGI produced $1.4 billion in net positive economic activity in the nine-state region. Electrical consumers and local economies of each RGGI state also experienced net benefits from the RGGI program. When spread across the region's population, these economic impacts amount to nearly $34 in net positive value-added per capita. Hibbard et al. (2018) find RGGI has yielded $5 billion in economic benefits and resulted in tens of thousands of jobs. However, results discussing RGGI's impact on the price of electricity are controversial. Based on the Ceres report, the price of electricity has decreased across the RGGI region since the program took effect in 2009. Conversely, according to a recent study funded by the Cato Institute, RGGI allowance costs increased already high regional electricity prices. The study's results show that the prices in RGGI states rose 64% more than in comparison states. This increase includes direct RGGI cost pass-through and indirect cost. The direct emissions allowance cost was $436 million in 2015, about half the price differential between RGGI states and non-RGGI states. The indirect costs include the premium charges for transmission distances, transmission congestion, and capacity when some RGGI states import power from non-RGGI states.

Four main factors could have caused the reduction in carbon dioxide emissions within RGGI states. The first one is the direct impact of RGGI on the reduction of coal and natural gas consumption for electricity generation. Since RGGI increases the cost of emissions, the power plants within RGGI states will consume less coal and natural gas for electricity generation. As a result, emissions decline. The second factor is the low price of natural gas resulting from the expansion of hydraulic fracturing technology just happened before the program starting time. The decline of natural gas prices after 2008 caused power plants in the United States to switch from using coal to natural gas. Since coal-fired generators emit more carbon dioxide than gas-fired generators, the switch can reduce carbon dioxide emissions. Several studies show this evidence (Knittel, Metaxoglou, and Trindate 2015; Johnson, LaRiviere, and Wolff 2016; Cullen and Mansur 2017; Linn and Muehlenbachs 2018, Kim and Kim 2016). The third factor is the switch from fossil fuel to non-fossil fuel energy sources such as solar and wind power. For example, Kaffine and Fell (2018) found an impact of increased wind generation on the decline of coal generation. That results in emissions decrease. The last factor is emissions leakage resulting from a production shift to non-RGGI areas. Emissions leakage refers to the shift of electricity generation from capped sources subject to the cap-and-trade program to higher-emitting sources not subject to the program. In this case, fossil fuel consumption for electricity generation in the non-RGGI area may have increased after the implementation of RGGI. As a result, carbon dioxide emissions will go up in the area. Several articles show evidence of emissions leakage of RGGI (Fell and Maniloff 2018; Chan and Morrow 2019; Lee and Melstrom 2018; Chen 2009).

Among these articles, Fell and Maniloff (2018) is an important one since it’s one of the few articles that econometrically estimate of leakage from RGGI. They use detailed electricity generation and transmission data to show that emissions leakage does exist with RGGI. They find RGGI causes a reduction in coal-fired generation in RGGI states. However, the program causes the increase of natural gas-sourced electricity generation in RGGI-surrounding regions which results in emissions leakage. They estimate the amount of carbon dioxide emissions reduced based on coal and natural gas-sourced electricity generation changes within RGGI states and nearby emissions leaker states. However, when they calculate the emissions based on generation, they use the average heat rate of coal and natural gas. It’s not an accurate approach if the heat rate changes with time. The heat rate of a power plant is the inverse of its efficiency. If the efficiency of power plants within RGGI states changes with time, the heat rate will change also. A recent study by Bailey (2020) shows RGGI coal plant owners have not made the expected investments in efficiency-improving capital and the efficiency of coal plants within RGGI states have decreased since the program started. The decreased efficiency will reduce the ability of power plants to lower carbon dioxide emissions.

In this paper, I use a consumption approach instead of a generation approach following the analysis of Fell and Maniloff (2018) to provide a more accurate estimation of carbon dioxide emissions reduction. This approach will adjust for the change of power plant efficiency within RGGI states. I find that RGGI has reduced coal consumption for electricity generation significantly since the program starts. It also has reduced natural gas consumption for electricity generation slightly. However, the program has increased natural gas consumption for electricity generation in emissions leaker states (Pennsylvania, Ohio) that caused emissions go up within this area. I test whether the increase of natural gas consumption in the potential emissions leaker states is caused by the drop of natural gas prices. I find the drop of natural gas prices plays a much smaller role than RGGI on the emissions leakage. I also find no strong evidence of fuel switching within RGGI states either from coal to natural gas or fossil fuel (Coal, Natural Gas, Oil) to renewable energy. The RGGI program directly caused the reduction of coal and natural gas consumption for power plants within the regulated states because the cost of emissions increased. I also test whether the efficiency of coal and natural gas power plants within RGGI states has decreased since the program starts. I find a decreased efficiency of both coal and natural gas power plants within RGGI states. In the end, I calculate the amount of carbon dioxide emissions reduced based on the change of coal and natural gas consumption within RGGI states and nearby emissions leaker states.

The rest of the thesis is divided in eight sections: Section 2 describes the data and identification method of this study. Section 3 presents the results and discussing. Section 4 tests whether RGGI increases the renewable electricity generation within regulated states. Section 5 tests whether the efficiency of coal and natural gas power plants has decreased since the program starts. Section 6 provides a calculation of the amount of reduced carbon dioxide emissions based on the estimated fossil fuel consumption changes of electricity generation. Section 7 provides several robustness checks of this study, and section 8 concludes.

2. Data Description and Identification Methods

2.1 Data Description

This study uses detailed monthly state-level electric power data provided by the EIA. The main dataset is fossil fuel consumption for electricity consumption by year, industry type, and state. The dataset provides coal, natural gas, petroleum, and other fossil-fuel-consumption levels for the electric-power industry in every state of the United States from January 2001 to May 2019. I use the data for coal and natural gas consumption in the electric-power industry from January 2001 to December 2018 for my analysis. I also merge the data for fuel cost, coal-, natural gas- and renewable-net electricity generation levels in the same period. The fuel cost includes coal and natural gas prices. Figure 1 plots the average monthly national coal price and natural gas price from January 2001 to December 2018. Natural gas has much a higher price per unit of heat input compared to coal. However, the price of natural gas declined across the study period mostly due to increasing Shale gas development. The decline in the price of natural gas relative to the price of coal may cause power plants to switch from using coal to using natural gas to generate electricity in both RGGI and non-RGGI areas. In addition, I include U.S. electric-power industry estimated emissions annual data by state. Figure 2 shows the reduction of carbon dioxide emissions from the total electric-power industry within RGGI states and non-RGGI states from 2001-2018. The initial emissions level is normalized to 100 and the vertical line represents the start of the RGGI program in 2009. The figure indicates that emissions from both RGGI and non-RGGI states dropped significantly over time. The emissions from RGGI states dropped more dramatically following the implementation of the program. Since the state of New Jersey withdrew from the program on January 1, 2012, I do not include observations from New Jersey in the study based on Huang and Zhou (2019).

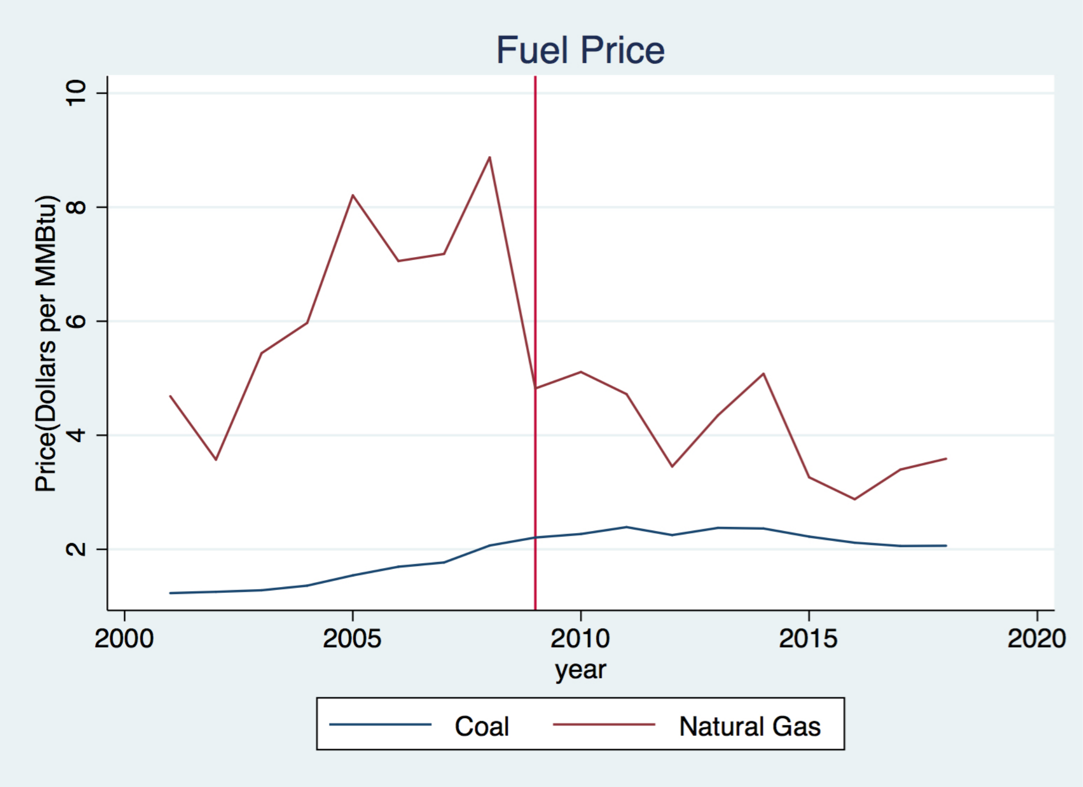


Fig.1. Fuel Price Notes: Plotted using electric power monthly data on the average cost of coal and natural gas delivered for electricity generation. The vertical line indicates the first month of the program (January 2009).

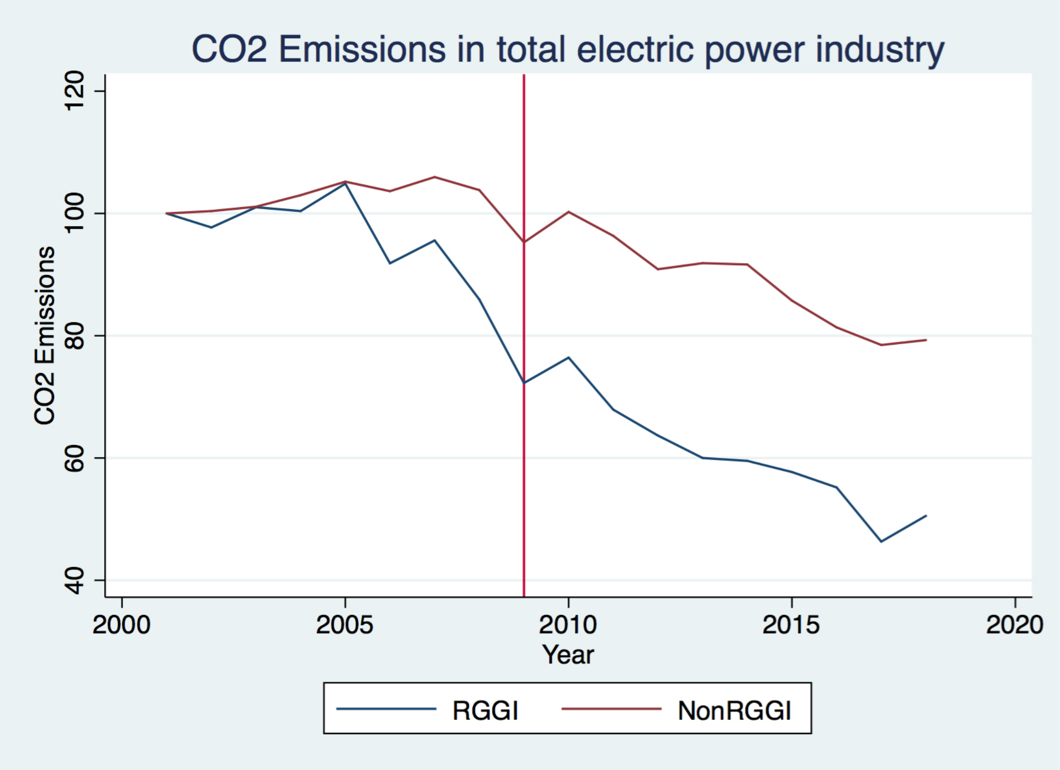


Fig.2. CO_2 emissions in total electric power industry. Notes: Plotted using EIA (US Energy Information administration) detailed state data for electric power industry emissions. The emissions total in 2001 is normalized to 100. The vertical line indicates the first month of the program (January 2009).

2.2 Identification Methods

I adopt a difference-in-differences (DID) approach to estimate the impact of the RGGI program on the reduction of coal and natural gas consumption by the power industry. For considering the potential emissions leakage, I choose the states of Pennsylvania (PA) and Ohio (OH) based on Fell and Maniloff (2018) as the potential emissions leaker states. The power sector in the northeastern United States falls largely within the competitive wholesale market structure. The area of RGGI regulated states is spanned by three electricity grid management regions: New York ISO (NYISO), ISO New England (NEISO), and PJM RTO (formerly Pennsylvania-Jersey-Maryland). These regions can be seen in Figure 3. The NYISO and NEISO regions consist of entirely RGGI-participating states, while the PJM region includes states both in and out of RGGI. This can be seen in Figure 4. The generation from RGGI is likely to be supplanted by generation from Ohio (OH) and Pennsylvania (PA) located within PJM since the two states are very close to the RGGI area. Therefore, it would be suitable to choose the two states as the potential emissions leaker states.

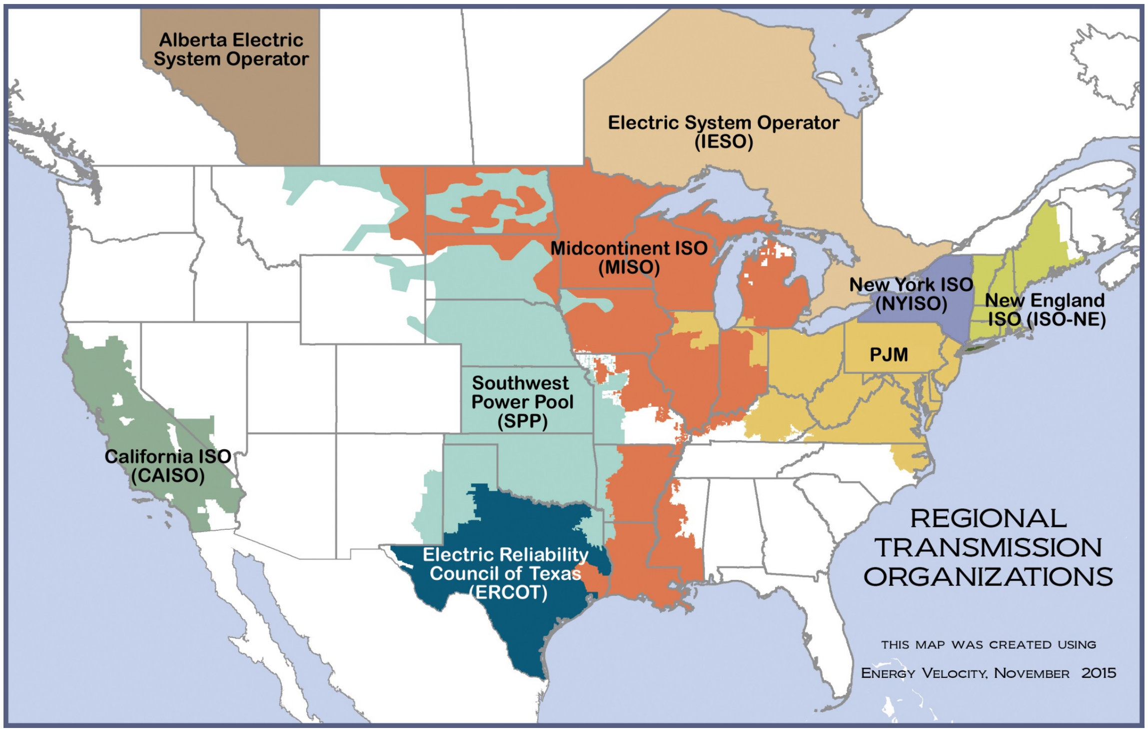


Fig.3. Map of Independent System Operators and Regional Transmission Organization

Source: FERC (Federal Energy Regulatory Commission).

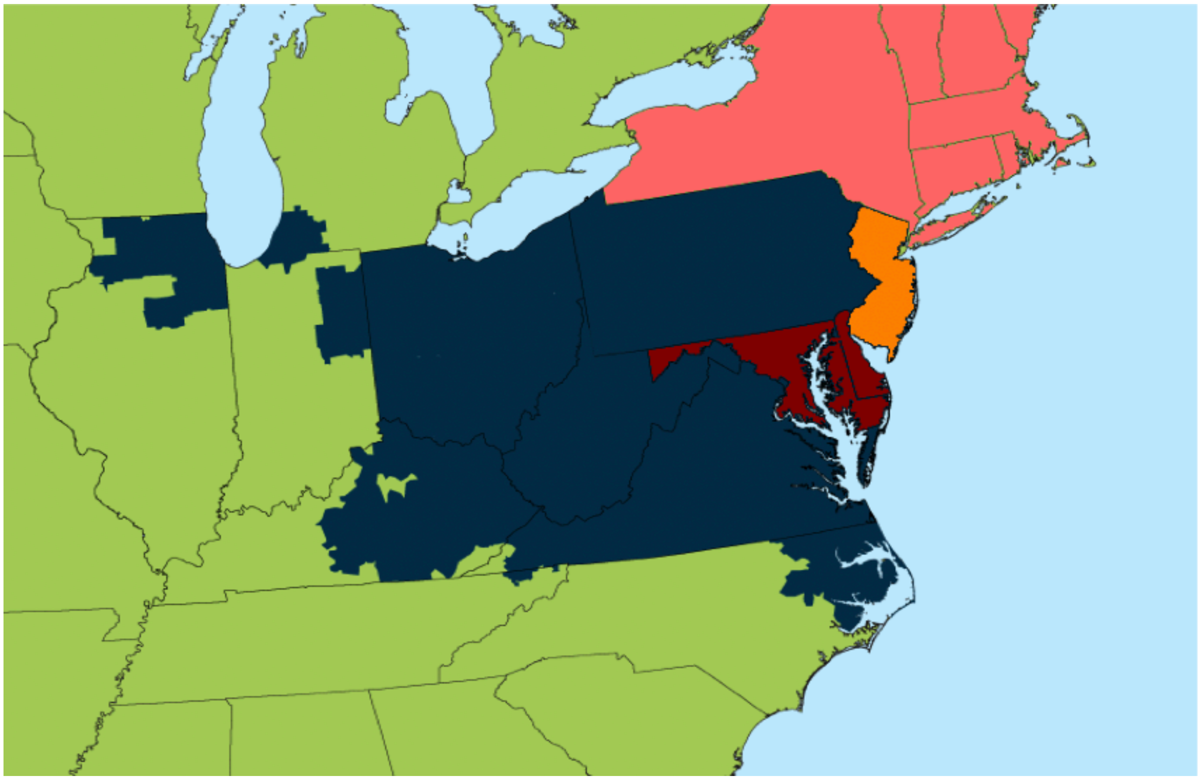


Fig.4. PJM territory and RGGI states Source: Huang and Zhou (2019) Notes: The dark blue and red areas cover the PJM territory. The RGGI states are covered by red and pink areas. The red areas are the two states: Maryland (MD) and Delaware (DE) which are both in PJM territory and RGGI. The orange area is the state of New Jersey which withdrew from RGGI in January 1, 2012.

The impact of the policy on coal and natural gas consumption for electricity generation can be estimated by the following regression model:

$$\ln C_{it} = \sum_{j \in J} \alpha_j TREAT_{it}^{j} + \theta_1 \ln(P_{it}) + \eta_i + \delta_t + \varepsilon_{it} \tag{1}$$

C_{it} is the coal or natural gas consumption for the electric-power industry in state i and at time t. $TREAT_{it}^{j}$ is the treatment dummy, with J= [RGGI, Leaker]. $TREAT_{it}^{RGGI}$=1 if state i is a RGGI-participating state and t≥ 2009 (when RGGI is in effect) and $TREAT_{it}^{Leaker}$=1 if state i is OH and PA during the time t when RGGI is in effect. P_{it} is the city gate natural gas price in state i at time t. The reason of including this price is to estimate the impact of the low price of natural gas caused by the Shale gas boom on coal and natural gas consumption for electricity generation. η_i and δ_t are the state and year-month fixed effects, and ε_{it} is the error term. This model estimates both treatment effects for RGGI regulated states and potential emissions leaker states. The control group consists of the coal or natural gas consumption in states that are neither RGGI regulated states nor potential leaker states for electricity generation. It includes the rest of all US states except New Jersey. The coefficient α_j is the coefficient of primary interest because it captures the average treatment effect on the treated. It estimates the impact of RGGI on coal and natural gas consumption for electricity generation within RGGI and potential leaker states after the implementation of the policy.

To further test the evidence of emissions leakage, I use interface-level data from the PJM Regional Transmission Organization (RTO), a monthly transmission data across individual PJM interfaces. Transmission can occur in either direction across an interface. The interfaces are all external which connect PJM to other transmission organizations. The data period is from January 2004 to December 2018. Four interfaces connect the PJM to RGGI states: NYISO, Linden, Neptune, and Hudson. If the electricity transmission from these four interfaces has increased over the RGGI implementation time, the existence of leakage is validated. I only keep the data from these four interfaces and use the following regression model to test this argument:

$$Y_{it} = \beta After + \theta_i + \varepsilon_{it} \tag{2}$$

Y_{it} is the net transmission across interface i at time t, the net transmission is defined as the sum of exports from PJM at interface i less the imports into PJM at that interface. After is a dummy equal to one, if the time is from January 2009 to December 2018, otherwise it is zero. The parameter θ_i is the interface fixed effect. The ε_{it} is an error term. The estimated coefficient β should be considered a conditional difference in means. It cannot be interpreted as a causal treatment effect. The coefficient measures the change in electricity transmission from PJM to the RGGI regulated states after the start of the program.

Before getting the estimation results, table 1 shows summary statistics on the average of monthly coal and natural gas consumption, coal and natural-gas-sourced electricity generation, renewable-sourced electricity generation, and net transmission across interfaces within RGGI and non-RGGI states, except New Jersey, during the pre- and post-program periods. I select observations from January 2004 to December 2018 to match the data period for electricity transmission. Several points can get from this table. First, the coal consumption for electricity generation and coal-sourced electricity generation within RGGI states have dropped a lot since the program starts. Second, the natural gas consumption for electricity generation and natural-gas-sourced electricity generation within RGGI states have increased since the program starts. However, since they have also increased even more within non-RGGI states, the results can’t indicate the program has caused an increase of natural-gas-sourced electricity generation within RGGI states. Third, the renewable generation within RGGI states has increased a little. Fourth, there is a large amount of electricity transmission between PJM and RGGI states which can indicate the emissions leakage exists. The increased amount of net electricity transmission can fully replace the reduced amount of coal-generated electricity within RGGI states.

Table 1

Summary Statistics

VARIABLES	RGGI States	Non-RGGI States
Coal Consumption (Short Tons)		
January 2004-December 2008	377,332.1	2,083,890
January 2009-December 2018	142,776.8	1,659,673
Change	-234,555.3	-424,217
Coal Generation (MWh)		
January 2004-December 2008	889,015.4	3,982,711
January 2009-December 2018	324,621	3,050,936
Change	-564,394.4	-931,775
Natural Gas Consumption (Mcf)		
January 2004-December 2008	6,901,116	11,860,884
January 2009-December 2018	8,528,017	16,418,930
Change	1,626,901	4,558,046
Natural Gas Generation (MWh)		
January 2004-December 2008	861,579.8	1,502,272
January 2009-December 2018	1,078,994	2,171,203
Change	217,414.2	668,931
Renewable Generation (MWh)		
January 2004-December 2008	1,317,155	2,093,126
January 2009-December 2018	1,365,779	2,438,378
Change	48,624	345,252
Net Transmission (MWh)		
January 2004-December 2008	385,910	140,340
January 2009-December 2018	860,760	212,910
Change	474,850	72,570

Notes: Data from EIA detailed state data. Data for electricity net transmission in RGGI states is the amount of electricity transmission across interfaces NYISO, Linden, Neptune and Hudson. Data for electricity net transmission in non-RGGI states is the amount of electricity transmission across the rest of all interfaces.

3 Results and Discussion

3.1 Coal and Natural Gas Consumption Results

Table 2 below reports the result of RGGI impacts on coal consumption within RGGI and Leaker states estimated by equation 1. The table indicates that coal consumption for the total electric power industry within RGGI states has reduced significantly since the beginning of the program, approximately 73% (e^ (-1.305)-1=-73%) up to December 2018. The results also show the coal consumption level in potential Leaker states dropped slightly after the implementation of the program, approximately 7% (e^ (-0.0711)-1=-7%). This evidence indicates that emissions leakage is not from coal as we would expect an increase rather than decrease after the program's initiation. Natural gas prices have a positive relationship with coal consumption. This indicates the low price of natural gas may cause power plants to switch fuel use from coal to natural gas, which further reduces the coal consumption for electricity generation.

Table 2

The impact of RGGI on Coal Consumption in RGGI States and Potential Leaker States

VARIABLES	ln(Coal Consumption)
RGGI	-1.305***
	(0.0319)
Leaker	-0.0711
	(0.0554)
ln(Natural Gas Price)	0.169***
	(0.0287)
Observations	10,046
R-squared	0.923

Notes: The dependent variable is ln(monthly coal consumption). The sample includes both RGGI and non-RGGI states. The treatment group consists of RGGI states and emissions leaker states (OH, PA), respectively. The control group consists of all other states. The post-policy period is defined as January 2009-December 2018. Statistically significant at the ***1% level; **5% level; *10% level.

Table 3 below reports the result of RGGI impacts on natural gas consumption within RGGI and Leaker states estimated by equation 1. The results indicate that natural gas consumption within the RGGI states has decreased by approximately 31%(e^(-0.372)-1=31%) since the start of the program. This suggests that there was no significant within-RGGI fuel switching from coal to natural gas plants. The RGGI program directly caused the reduction of coal and natural gas consumption for electricity generation within the regulated states since the cost of emissions increased. However, the program has caused natural gas consumption to increase by about 259%(e^(1.279)-1=259%) within potential leaker states PA and OH in the same period. Natural gas prices play a smaller rule in the effect on the change of natural gas consumption. This demonstrates the low price of natural gas has an effect on the natural gas consumption for electricity generation within RGGI states and emissions leaker states. Both RGGI and the price of natural gas can cause an increase in the consumption of natural gas for electricity generation in leaker states, and in turn, this will cause emissions to increase outside the RGGI area. Collinearity may exist between the treatment group and the natural gas price. Therefore, I test the VIF (Variance Inflation Factor) ratio of multicollinearity, which is reported in Table 4 and 5. The value of the ratio is all under 10, which indicates the multicollinearity issue is not worrisome.

Table 3

The impact of RGGI on Natural Gas Consumption in RGGI States and Potential Leaker States

VARIABLES	ln(Natural Gas Consumption)
RGGI	-0.372***
	(0.0379)
Leaker	1.279***
	(0.0742)
ln(Natural Gas Price)	-0.147***
	(0.0377)
Observations	10,462
R-squared	0.894

Notes: The dependent variable is ln (monthly natural gas consumption). The sample includes both RGGI and non-RGGI states. The treatment groups consist of RGGI states and emissions leaker states, respectively. The control group consists of all other states. The post-policy period is defined as January 2009–December 2018. Statistically significant at the ***1% level; **5% level; *10% level.

Table 4

Test for Multicollinearity (Coal Consumption)

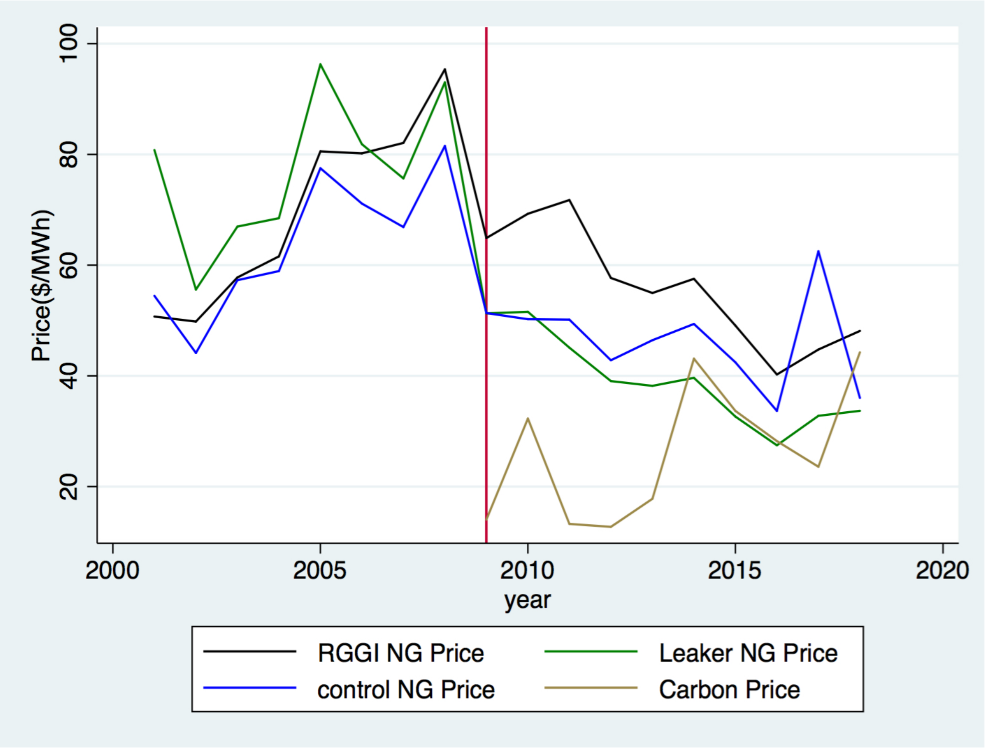
Variable	VIF	1/VIF
RGGI	2.36	0.423129
Leaker	2.34	0.428106
ln(Natural Gas Price)	4.49	0.222899

Table 5

Test for Multicollinearity (Natural Gas Consumption)

Variable	VIF	1/VIF
RGGI	2.52	0.396901
Leaker	2.34	0.428151
ln(Natural Gas Price)	3.70	0.270496

To further investigate which factor, the low price of natural gas or RGGI's carbon price plays a bigger role in the leakage, I plot the natural gas price for RGGI states, leaker states, control states and the carbon price within RGGI states. The unit of measure for both prices is $/MWh, which is the cost of the natural gas consumed and the cost of the carbon emissions produced to generate 1 MWh of electricity. I use natural-gas-sourced electricity generation and emissions data for the calculation, so the price level is the upper bound cost of the natural gas consumed, and the carbon emissions produced for electricity generation.[1] Figure 5 shows a similar declining price trend in the three regions from 2001 to 2018, thus, I cannot conclude that the leakage merely reflects low gas prices within leaker states. Additionally, the RGGI program plays an important role in the leakage. The program increases the cost of carbon emissions for electricity generation within RGGI states and the generation activities must rely on leaker states out of the regulated area. I assume this type of leakage occurs mainly with natural-gas-sourced electricity generation due to the significant increase in consumption of natural gas for electricity generation that has occurred in leaker states since the start of the program.



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[1] For the calculation of natural gas prices, I first calculate the heat rate using natural gas consumption divided by natural-gas-sourced electricity generation level. Then I multiply the heat rate by city gate natural gas prices to get the cost of natural gas consumed. I average the cost across RGGI states, leaker states and control states. For the calculation of carbon price, I first divide natural-gas-sourced carbon dioxide emissions for electricity generation by generation level within RGGI states. Then I multiply the calculated value by the auction carbon price of RGGI.

Fig.5. The carbon price versus the natural gas prices Notes: Plotted by calculating the natural gas price and the carbon price paid by generating 1 MWh of electricity. The black line is the average natural gas price paid within RGGI states. The green line is the average natural gas price paid within emissions leaker states PA and OH. The blue line is the average natural gas price paid within all other states. The brown line is the average carbon price paid within RGGI states. The vertical line indicates the first month of the program, January 2009.

3.2 Transmission Results

Table 6 below reports the results estimated by equation 2. The results show the net export of electricity within the four interfaces increased following the start of the program, which indicates that RGGI-induced emissions leakage exists. For a given interface, the net electricity exports have increased by about 97,257MWh per month since the program starts. In total, the net electricity exports have increased by about 389,028 MWh per month within the four interfaces which is similar to the difference reported in Table 1.

Table 6

Electricity Transmission Result

VARIABLES	Net Transmission
After	97,257*** (29,208)
Observations	516
R-squared	0.270

Notes: The dependent variable is the net transmission across a specific interface. The sample includes PJM interfaces NYISO, Linden, Neptune, and Hudson. The post-policy period is defined as January 2009–December 2018. Statistically significant at the ***1% level; **5% level; *10% level.

3.3 Dynamic Effects of the RGGI Program

Several assumptions need to be satisfied to validate the estimation above. First is the common trend assumption, which is the trend of coal and natural gas consumption within RGGI states—control states and Leaker states-control states are parallel in the pre-policy period. The second assumption is that the policy should not influence coal and natural gas consumption of the control group; thus, coal and natural gas consumption within the control states should not increase significantly after the introduction of the policy. The third assumption is that there is no anticipatory effect. If the electric power industry reduces coal and natural gas consumption before the implementation of the policy, it will underestimate the effect of the policy on coal and natural gas consumption for power generation.

I use a dynamic model to assess how the policy affects coal and natural gas consumption over time. It can test the validity of the common trend assumptions. The regression model is as follows:

$$\ln C_{it} = \sum_{j \in J} \alpha_{jt} D_t TREAT_i^j + \theta_1 \ln(P_{it}) + \eta_i + \delta_t + \varepsilon_{it} \tag{3}$$

where D_t equals one between January and December for all years between 2001 and 2018, except 2008, and otherwise it equals zero. The year 2008 is excluded and serves as a reference year. The coefficient α_{jt} is the coefficient of primary interest because it measures the difference in coal consumption between RGGI states and control states or between leaker states and control states in each year from 2001 to 2018 relative to the reference year.

Figure 6-9 displays the DID estimate coefficients by evolution over time. Several points are obtained from these figures. First, the coefficients are all close to zero before the reference period. This indicates both RGGI and leaker treatment groups have similar pre-treatment trends as the control group. It provides solid evidence for the common trend assumption. Second, both coal and natural gas consumption in RGGI states have dropped with coal consumption dropped significantly. Third, in the leaker states, coal consumption has dropped slightly since the program starts, but natural gas consumption has increased dramatically. This can indicate the emissions leakage is mainly from natural gas not from coal.

Fig.6. The Dynamic Effects on Coal Consumption for Electricity Generation Within RGGI States Notes: The dependent variable is ln (monthly coal consumption level). Data are state-level monthly coal consumption for electricity generation January 2001–December 2018 from EIA. The reference period is January 2008–December 2008. Each dot captures the average differences in coal consumption between RGGI states and the control states relative to the differences in the reference year. The vertical line indicates the first month of the program, January 2009. RGGI states make up the treatment group. The dashed line indicates the 95% confidence interval.

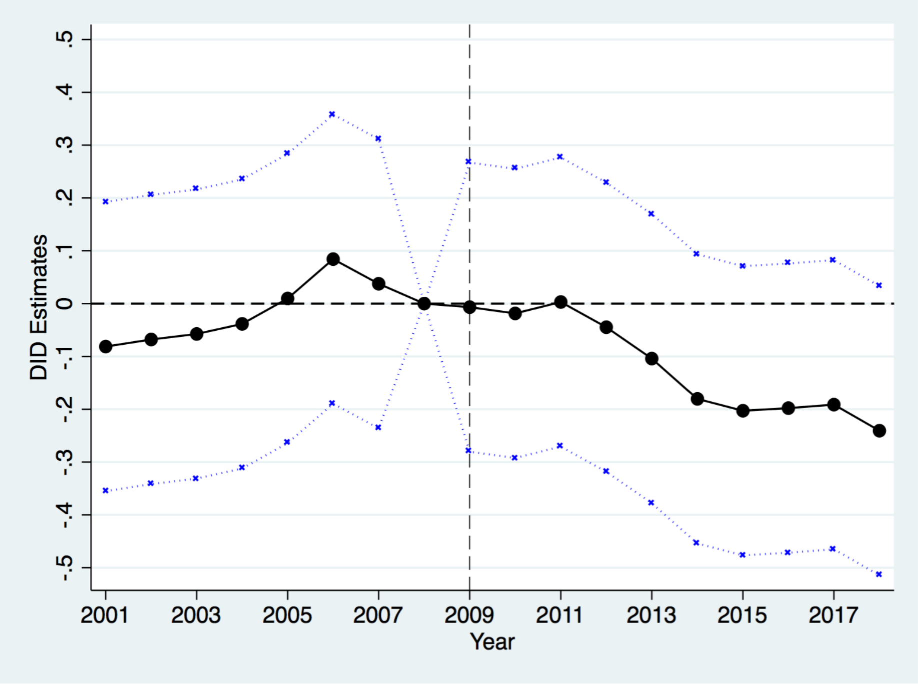

Fig.7. The Dynamic Effects on Coal Consumption for Electricity Generation Within Emissions Leaker States (PA and OH) Notes*:* The dependent variable is ln (monthly coal consumption level). Data are state-level monthly coal consumption for electricity generation January 2001–December 2018 from EIA. The reference period is January 2008–December 2008. Each dot captures the average differences in coal consumption between leaker states and the control states relative to the differences in the reference year. The vertical line indicates the first month of the program (January 2009). Leaker states, PA and OH, are the treatment group. The dashed line indicates the 95% confidence interval.

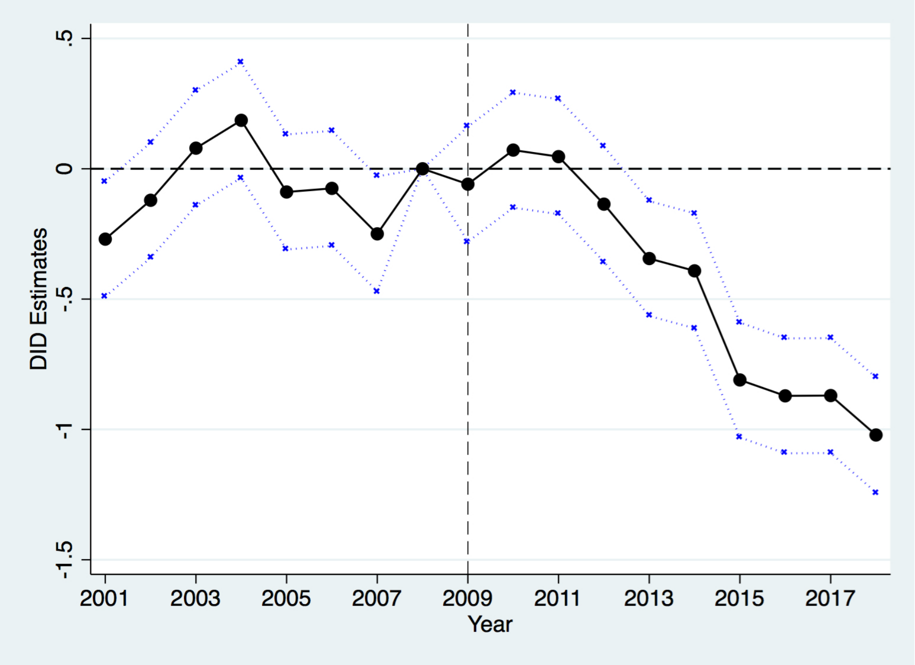

Fig.8. The dynamic effects on natural gas consumption for electricity generation within RGGI states Notes*:* The dependent variable is ln (monthly natural gas consumption level). Data are state-level monthly natural gas consumption for electricity generation January 2001–December 2018 from EIA. The reference period is January 2008–December 2008. Each dot captures the average differences in natural gas consumption between RGGI states and the control states relative to the differences in the reference year. The vertical line indicates the first month of the program, January 2009. RGGI states make up the treatment group. The dashed line indicates the 95% confidence interval.

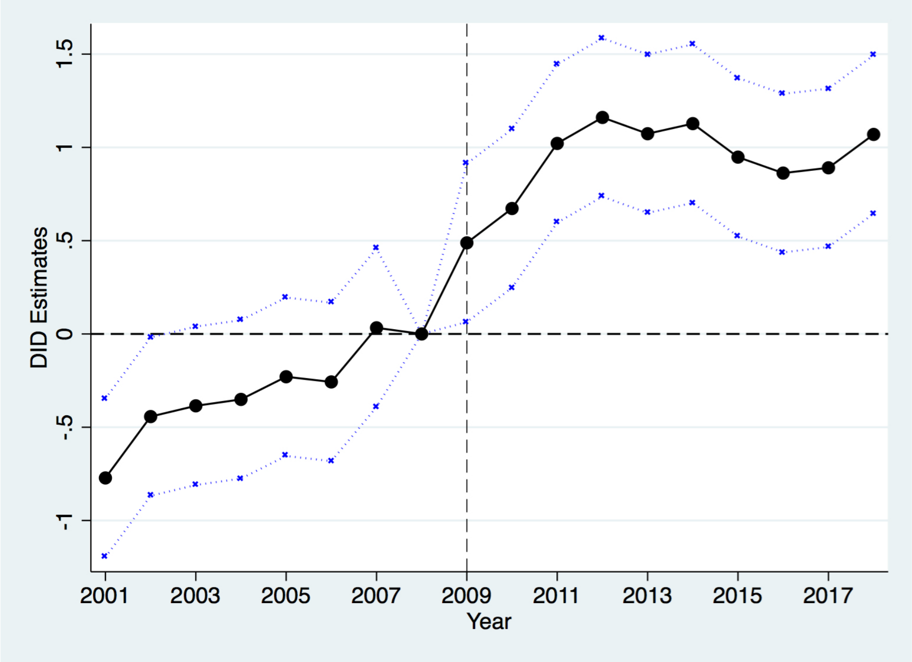

Fig.9. The Dynamic Effects on Natural Gas Consumption for Electricity Generation Within Emissions Leaker States (PA and OH) Notes: The dependent variable is ln (monthly natural gas consumption level). Data are state-level monthly natural gas consumption for electricity generation January 2001–December 2018 from EIA. The reference period is January 2008–December 2008. Each dot captures the average differences in natural gas consumption between leaker states and the control states relative to the differences in the reference year. The vertical line indicates the first month of the program, January 2009. Leaker states PA and OH represent the treatment group. The dashed line indicates the 95% confidence interval.

The assumption that this program should not influence coal and natural gas consumption in the control group seems plausible as states farther away from leaker region has less direct access to RGGI and are therefore unlikely places for leakage. Additionally, given that the formation of RGGI was largely a political process among geographically close states, it seems reasonable to assume that the decision to initiate RGGI was largely related to generator behavior. I assume there is no anticipatory effect and the treatment is exogenous (Fell & Maniloff, 2018).

4 Renewable electricity generation within RGGI states and leaker states

In this section, I test whether renewable electricity generation has increased since the program starts. From the analysis above, I find RGGI has caused reduced coal and natural gas consumption within RGGI states. It might be possible that the energy source for electricity generation has switched from fossil fuel to renewable within RGGI states or RGGI states import renewable-sourced electricity from leaker states.

In order to test this, I use the state-level monthly net generation data by different energy sources. I only keep renewable-sourced electricity net generation data (solar, wind, hydro, biomass, and so on). I select the study time period from January 2001 to December 2018 also. The estimation regression model is equation 1, but now the dependent variable is replaced by the renewable-sourced net generation level in state i and year t. The regression doesn't include natural gas prices. The control group is the same. Table 7 reports the result of this estimation. The results indicate that the renewable generation has decreased for both RGGI states and leaker states since the program starts. It can provide evidence that no fuel switching from fossil fuel to non-fossil fuel for electricity generation exist within RGGI states. The reduction of renewable generation in leaker states can also show us RGGI hasn't caused RGGI states to import renewable-sourced electricity from nearby states. [2]

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[2] I also run the dynamic effect of this estimation. The common trend is satisfied between the both treatment groups and the control group before the starting of the program.

Table 7

The impact of RGGI on renewable electricity generation in RGGI States and Potential Leaker States

VARIABLES	ln(Net Renewable Generation)
RGGI	-0.373***
	(0.0208)
Leaker	-0.272***
	(0.0407)
Observations	10,614
R-squared	0.932

Notes: The dependent variable is ln(Net Renewable Generation). The sample includes both RGGI and non-RGGI states. The treatment group consists of RGGI states or emissions leaker states (OH, PA). The control group consists of all other states. The post-policy period is defined as January 2009-December 2018. Statistically significant at the ***1% level; **5% level; *10% level.

5 The Impact of RGGI on the Efficiency of Electricity Generation

In this section, I perform a rough test to see whether the efficiency of coal and natural gas power plants has increased or decreased since the beginning of the program. Moreover, I will investigate the change in electricity generation to find the reason behind the change in efficiency. Since the efficiency and heat rate of power plants are inversely related to each other, I can test whether the heat rate of power plants changes in order to see the efficiency changes. This estimation of heat rate and efficiency changes is important. If heat rate increases and the efficiency of power plants decreases, it will lower the ability of RGGI on the effect of carbon dioxide emissions reduction based on Bailey (2020).

Using state-level fuel consumption and generation data, first I divide the coal consumption level by the coal-generated electricity level for each state at a specific time. The results of this division can represent the average heat rate of coal plants within each state, which is how much coal must be consumed to generate 1 MWh of electricity. I then divide the natural gas consumption level by the natural-gas-generated electricity level for each state at a specific time. The results can represent the average heat rate of natural gas plants within each state, or how much natural gas must be consumed to generate 1 MWh of electricity. The results of these two divisions provide me with two-panel data of the state-level coal plant efficiency and the natural gas plant efficiency.

To estimate the change in efficiency within the RGGI states, I use the difference-in-difference method again. The regression model I use is equation 1, however, the dependent variable is replaced by the state-level average coal and natural gas heat rate of power plants, respectively. The sample is only restricted to RGGI states here. It also doesn’t include natural gas prices and the control group doesn’t change.

Table 8 reports the results of these estimations. The results show both treatment effect parameters are positive, which means the efficiency of both coal plants and natural gas plants have decreased since the beginning of the program. The coal plants are less efficient than natural gas plants. The decreased efficiency causes power plants to use more fuel to generate electricity. That will increase the total carbon dioxide emissions. In general, the average coal heat rate of power plants within RGGI states has increased by about 7.5% (e^ (0.0723)-1=7.5%). The average natural gas heat rate of power plants within RGGI states has increased by about 4% (e^(0.0406)-1=4%).[3]

The reason behind the loss of efficiency could be the reduced generation of both coal and natural-gas-sourced electricity. The expected reduced generation may cause less investment in innovation and result in loss of efficiency for electricity generation. To examine the change in coal and natural-gas-sourced electricity generation, I replace the dependent variable with coal and natural-gas-sourced electricity net generation level in the regression specification mentioned above.

Table 9 reports the results of this estimation. The results show that coal and natural-gas-sourced electricity generation have both declined since the start of the program. Specifically, coal-generated electricity has decreased about 74% (e^(-1.349)-1=74%) and natural-gas-generated electricity has decreased about 37% (e^(-0.460)-1=37%).[4] The results are consistent with the argument in Bailey (2020) that a tradeoff occurs between production and efficiency choices in the face of a carbon price. When the carbon price rises and all other terms are held constant, the plants either become more efficient or decrease production. When the generation level decreases, the efficiency must also decrease. The reduced efficiency of power plants will cause carbon emissions to increase within RGGI states. As a result, RGGI will have a lower effect on the carbon dioxide emissions reduction. The

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[3] I also run the dynamic effect of this estimation. Since the common trend assumption is not satisfied for natural gas heat rate between 2001 to 2005. I drop these years for the estimation.

[4] I also run the dynamic effect of this estimation. The common trend is satisfied for both coal and natural gas sourced electricity generation before the starting of the program.

relatively lower efficiency of coal plants also supports the "market share" effect during which producers directly innovate activity toward abundant factors (Acemoglu, 2003). Since electricity producers may think RGGI will result in a higher cost for coal-sourced electricity generation than natural-gas-sourced electricity generation, they are less likely to invest capital into improving the efficiency of coal plants; therefore, coal plant efficiency declines. The RGGI program also reduces natural-gas-generated electricity by a smaller magnitude. Therefore, a relatively smaller decline in efficiency for natural gas plants still exist. Overall, RGGI causes a decline in efficiency for both coal and natural gas power plants within the regulated states. The main reason behind the loss of efficiency is the expected reduced generation caused by a higher carbon price, which results in less capital investment into improving plant efficiency.

Table 8

The Impact of RGGI on Fossil Fuel Plant Efficiency

VARIABLES	ln(Coal Heat Rate)	ln(Natural Gas Heat Rate)
RGGI	0.0723***	0.0406***
	(0.00752)	(0.0104)
Observations	9,609	7,247
R-squared	0.781	0.597

Notes: The dependent variables are ln (average monthly coal heat rate) and ln (average monthly natural gas heat rate). The sample includes both RGGI and non-RGGI states. The treatment group consists of RGGI states. The control group consists of all other states except emissions leaker states. The post-policy period is defined as January 2009–December 2018. Statistically significant at the ***1% level; **5% level; *10% level.

Table 9

The Impact of RGGI on Fossil Fuel Electricity Generation

VARIABLES	ln(Coal Generation)	ln(Natural Gas Generation)
RGGI	-1.349***	-0.460***
	(0.0313)	(0.0382)
Observations	9,609	10,006
R-squared	0.918	0.900

Notes: The dependent variables are ln (monthly coal-generated electricity level) and ln (monthly natural-gas-generated electricity level). The sample includes both RGGI and non-RGGI states. The treatment group consists of RGGI states. The control group consists of all other states except emissions leaker states. The post-policy period is defined as January 2009–December 2018. Statistically significant at the ***1% level; **5% level; *10% level.

6 Emissions Reduction Estimation

Based on the estimated reduction level of coal and natural gas consumption within RGGI states and the increased natural gas consumption level within the leakage states, I can roughly calculate the amount of carbon dioxide emissions reduced by the program. The reduced amount of carbon dioxide emissions for the reduced coal consumption within RGGI states is about 30.27 million tons, which is approximately 3 million tons per year.[5] The reduced amount of carbon dioxide emissions for the reduced natural gas consumption within RGGI states is about 12.98 million Mcf, which is approximately 1.3 million tons per year.[6] The amount of carbon dioxide emissions leaked is about 32.34 million tons, which is approximately 3.2 million tons per year. Therefore, in terms of emissions, RGGI has resulted in an aggregate decrease of 1.1 million tons of carbon dioxide emissions per year from 2009 to 2018. In total, the program has caused carbon dioxide emissions reduction of 11 million tons from 2009 to 2018. The carbon dioxide emissions from the electric-power sector within RGGI states are about 129.7 million tons in 2008. In terms of percentage, the program has reduced carbon dioxide emissions from the electric power sector by 8.5% within regulated states from 2009 to 2018.

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[5] Based on the average heat content of coal in the electric power sector from 2009 to 2018 and coal CO_2 content of 205 lbs/MMBtu.

[6] Based on the average heat content of natural gas in the electric power sector from 2009 to 2018 and gas CO_2 content of 117 lbs/MMBtu.

7 Robustness Checks

I perform several robustness checks to assess the sensitivity of the estimated treatment effects. First, since states in the western United States may be poor controls for unobserved common time effects in the northeastern U.S., I limit the control group to states in the Eastern Interconnection. Table 10 reports the estimation results when using this new control group. The results are similar to the base result described above. Second, I conduct a temporal placebo using the period 2001–2008 and the treatment time from January 2007 to December 2008. The estimation results are displayed in Table 11. The coefficients are small and statistically insignificant for coal consumption and relatively smaller and less significant for natural gas consumption across specifications. Furthermore, natural gas prices play an insignificant rule in natural gas and coal consumption for electricity generation since the price is high at that time period. These results suggest the policy does not have an obvious impact on coal and natural gas consumption in either RGGI or leaker states before the implementation time.

Following Fell and Maniloff, I also perform a sensitivity analysis to look at how treatment effects respond to changes in the merit order. When the natural gas price is high, the carbon price of RGGI should have little effect on the merit order and leakage. To test this, I include two dummy variables, one that equals one for a month in which the monthly natural gas price is in the top 10% of the sample (a "high gas" dummy) from January 2009 to December 2018 and the other that equals one for a month in which the monthly natural gas price is in the bottom 10% of the same sample (a "low gas" dummy). Next, I interact with these two dummies with RGGI and leaker states treatment dummies and estimate the model again. The results of these specifications are reported in Table 12. The table shows when the natural gas price is high, statistically significant RGGI-induced leakage does not occur. When the gas price is low, the leakage increases significantly for natural gas since the carbon price changes the merit order more dramatically. Within RGGI states, when the natural gas price is high, the carbon price is not enough to change the merit order. Although coal plants face higher emissions costs than natural gas plants, they are still a relatively cheaper means of generating electricity. Therefore, coal consumption within RGGI states has not reduced significantly from the result. However, when the natural gas price is low, the carbon price can be enough to switch the merit order. In this case, the total cost of coal plants face will be higher than the total cost for natural gas plants. As a result, the coal consumption for coal plants will be greatly reduced as shown in the results. As shown in Figure 5, the natural gas plants within RGGI also face a relatively high cost when the natural gas price is low, because the carbon price for RGGI increases dramatically when the natural gas price is low for RGGI states. Therefore, natural gas consumption within RGGI states is also reduced. This induces RGGI states to import a large amount of natural-gas-sourced electricity from the leakage states because of the relatively cheaper natural gas price within the leakage states. As a result, the natural gas consumption level in the leakage states has increased greatly since the start of the program.

Table 10

Robustness Check Using a Different Control Group

VARIABLES	ln(Coal Consumption)	ln(Natural Gas Consumption)
RGGI	-1.350***	-0.494***
	(0.0262)	(0.0404)
Leaker	-0.127***	1.158***
	(0.0446)	(0.0766)
ln(Natural Gas Price)	0.123***	-0.141***
	(0.0258)	(0.0434)
Observations	7,703	8,086
R-squared	0.940	0.892

Notes: The dependent variables are ln (monthly coal consumption level) and ln (monthly natural gas consumption level). The sample includes RGGI and non-RGGI states within the Eastern Interconnection. The treatment groups consist of RGGI states and emissions leaker states, respectively. The control group consists of all other states. The post-policy period is defined as January 2009–December 2018. Statistically significant at the ***1% level; **5% level; *10% level.

Table 11

Time Placebo Test

VARIABLES	ln(Coal Consumption)	ln(Natural Gas Consumption)
RGGI	-0.0369	-0.0873
	(0.0292)	(0.0546)
Leaker	0.0456	0.462***
	(0.0516)	(0.107)
ln(Natural Gas Price)	0.0183	0.0758
	(0.0259)	(0.0542)
Observations	4,505	4,607
R-squared	0.969	0.928

Notes: The dependent variables are ln (monthly coal consumption level) and ln (monthly natural gas consumption level). The sample includes RGGI and non-RGGI states. The treatment groups are RGGI states and emissions leaker states, respectively. The control group consists of all other states. The post-policy period is defined as January 2007–December 2008. Statistically significant at the ***1% level; **5% level; *10% level.

Table 12

The Impact of RGGI on Fossil Fuel Consumption Under High and Low Gas Prices

VARIABLES	ln(Coal Consumption)	ln(Natural Gas Consumption)
RGGI X High Gas	-0.486***	0.0930*
	(0.0456)	(0.0507)
RGGI X Low Gas	-1.485***	-0.598***
	(0.135)	(0.101)
Leaker X High Gas	0.00737	0.161
	(0.170)	(0.209)
Leaker X Low Gas	-0.00542	0.852***
	(0.131)	(0.174)
Observations	10,046	10,462
R-squared	0.911	0.890

Notes: The dependent variables are ln (monthly coal consumption level) and ln (monthly natural gas consumption level). The sample includes RGGI and non-RGGI states. The treatment groups consist of RGGI states and leaker states, respectively. The control group consists of all other states. High and Low Gas are dummy variables for the highest and lowest 10% of gas prices from January 2009 to December 2018, respectively. The post-policy period is defined as January 2009–December 2018. Statistically significant at the ***1% level; **5% level; *10% level.

8 Conclusions

An extensive literature describes the impacts of climate policies such as carbon taxes and cap-and-trade programs. This paper uses fossil fuel consumption to examine the impacts of the RGGI cap-and-trade program and finds that the program has reduced the consumption of coal and natural gas for electricity generation within regulated states. However, emissions leakage caused by the program results in a significant increase of natural gas consumption for electricity generation within the leaker states of Pennsylvania and Ohio. The program directly caused the reduction of fossil fuel energy sources for electricity generation. I find no strong evidence of fuel switching from coal to natural gas or from fossil fuel to renewable for electricity generation within regulated states. The paper also finds the program reduced coal- and natural-gas-sourced electricity generation even more significantly within the regulated states. This reduction causes a decline in the efficiency of coal and natural gas plants and may cause carbon dioxide emissions go up, which reduces the program’s effectiveness for lowering emissions.

The RGGI program is a sub-national climate policy that often leads to emissions leakage due to the fact that the regulated regions' abatement can be offset by an increase in emissions in the unregulated regions. Through an analysis of the program’s impact on changes in fossil fuel consumption levels in the electricity generation industry, it is clear this kind of leakage does exist. To avoid emissions leakage, a national cap-and-trade program may be a more effective way to reduce overall carbon emissions. However, given the political system of the U.S. and the relatively independent policy-making power of each state, it is difficult to persuade each state to join a national cap-and-trade program. Consequently, a sub-national cap-and-trade program for carbon emissions reduction remains the primary mechanism for regulating emissions. Thus, it is very useful to evaluate the effectiveness of this kind of regional climate policy. If it effectively reduces emissions, more regions will join the program, ultimately resulting in a national climate policy. In fact, the states of Pennsylvania and Virginia are set to join the RGGI program in the near future, while New Jersey has already rejoined the program. Based on the results of this paper, it may be more effective to include all potential leaker states and even all other PJM states in the program to reduce emissions leakage due to the connections and transmission of electricity between these states. More research is needed to decide which states joining the program would be more effective in reducing emissions leakage.

This paper also has some limitations. First, this paper provides a general estimation of the program’s impact on fossil fuel consumption at the state level. It does not investigate the impacts at the plant level. If the analysis was at the plant level, we could look at the extensive and intensive margin of plants impacted by the program. However, the estimation results in this paper will not change if I had instead used plant-level data. Second, other factors may reduce the consumption of coal and natural gas for electricity generation within RGGI states. Such factors include clean energy policies such as renewable portfolio standards and the investment of auction proceeds into energy efficiency improvement of RGGI. Each of these factors plays a role in the reduction of emissions and the phase-out of fossil fuels within RGGI states. Finally, the U.S. Shale gas boom, which occurred around the start of RGGI and caused electricity generators to switch from coal plants to natural gas plants, also plays an important role in the reduction of emissions within RGGI states and emissions leakage in the nearby states. A more detailed analysis to separate the impacts of other policies and events from the impacts of RGGI is necessary to fully evaluate the performance of this program.

Appendix Different potential leaker states

In this section, I choose all non-RGGI PJM states except New Jersey (NJ) as the potential emissions leaker states and estimate the results again. Table 13 shows the regression results. The results indicate a smaller amount of emissions leakage for natural gas. It means non-RGGI PJM states except PA and OH were less likely to take on leakage. However, emissions leakage still exists that RGGI states may have imported a lot of natural gas sourced electricity from these PJM states and caused emissions to go up in this area.

Table 13

The Impact of RGGI on Coal and Natural Gas Consumption in RGGI States and Potential Leaker States

VARIABLES	ln(Coal Consumption)	ln(Natural Gas Consumption)
RGGI	-1.302***	-0.249***
	(0.0325)	(0.0387)
Leaker	-0.00179	0.748***
	(0.0281)	(0.0374)
ln(Natural Gas Price)	0.172***	-0.108***
	(0.0289)	(0.0377)
Observations	10,046	10,462
R-squared	0.923	0.895

Notes: The dependent variables are ln (monthly coal consumption level) and ln (monthly natural gas consumption level). The sample includes RGGI and non-RGGI states. The treatment groups are RGGI states and potential emissions leaker states: Illinois, Indiana, Kentucky, Michigan, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia. The control group consists of all other states. The post-policy period is defined as January 2009–December 2018. Statistically significant at the ***1% level; **5% level; *10% level.

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