COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

DIVISION OF ECONOMICS AND BUSINESS
WORKING PAPER SERIES

Beneficial Leakage: The Effect of the Regional Greenhouse Gas Initiative on Aggregate Emissions

Harrison Fell
Peter Maniloff

Working Paper 2015-06
`http://econbus.mines.edu/working-papers/wp201506.pdf`

Colorado School of Mines
Division of Economics and Business
1500 Illinois Street
Golden, CO 80401

June 2015

Colorado School of Mines
Division of Economics and Business
Working Paper No. **2015-06**
June 2015

Title:

Beneficial Leakage: The Effect of the Regional Greenhouse Gas Initiative on Aggregate Emissions*

Author(s):

Harrison Fell
Division of Economics and Business
Colorado School of Mines
Golden, CO 80401-1887
`hfell@mines.edu`

Peter Maniloff
Division of Economics and Business
Colorado School of Mines
Golden, CO 80401-1887
`maniloff@mines.edu`

ABSTRACT

Subglobal and subnational policies aimed at reducing greenhouse gases are often thought to be less effective than more geographically comprehensive policies as production, and thus emissions, of trade exposed industries may move from the regulated to the unregulated regions. This so-called leakage may negate all emission reductions from the regulated regions and, even worse, may lead to an overall increase in emissions if the unregulated regions have equally or more emissions intensive production. However, if the unregulated regions have less emissions intensive production, the regional regulation may prompt more switching to the relatively cleaner producers than would otherwise occur, creating a type of beneficial leakage. We use detailed electricity generation and transmission data to show that this might be the case for the Regional Greenhouse Gas Initiative (RGGI), a CO_2 cap-and-trade program for the electricity sector in select Northeastern U.S. states. We find evidence that electricity generation did leak out of the RGGI region to surrounding state, but electricity generation in the non-capped jurisdictions is less emissions intensive than in the RGGI region, resulting in a net decrease in aggregate emissions. Back-of-the-envelope calculations suggest that one-quarter of apparent emissions reductions actually leaked but that this served to reduce total combined emissions by an additional one percent.

---

*We thank Ventyx for providing access to their Velocity Suite database tool.

1 Introduction

As a truly global climate policy appears unattainable, many nations have moved forward unilaterally or in coalition with other countries to establish their own emission reduction policies. This sub-global policy development is also now being mimiced at the national level as several sub-national regions are taking the initiative to develop climate policies despite the inability of their respective federal governments to take meaningful action to reduce greenhouse gas emissions.[1] These sub-global and sub-national policies raise concerns about policy-effectiveness. More specifically, the economics literature has well documented how sub-global and sub-national policies may lead to emissions leakages, whereby emission reductions in regulated regions are at least partially offset by policy-induced emission increases in unregulated regions. While this leakage issue has garnered much attention, econometric studies on the topic are rare.

In this paper, we use the sub-national policy of the Regional Greenhouse Gas Initiative (RGGI), a regional cap-and-trade system for CO_2 emissions from electricity generation in the U.S. among select Northeastern states, to econometrically investigate instances of leakage. As it turns out, this is a particularly interesting program to examine given the coinciding expansion of natural gas-fired generation in the RGGI-surrounding areas. This change in generation profiles opens the possibility of "beneficial leakage"; production in the regulated region is decreased and supplanted with less emission intensive production from areas outside of the regulation's jurisdiction.

---

[1] Example of sub-national policies can be found in the U.S. where California and, separately, a collection of Northeastern states under the Regional Greenhouse Gas Initiative have forged their own carbon emissions trading programs. Likewise, in Canada, the province of British Columbia has imposed a carbon tax and Quebec has a carbon trading program.

As noted above, there is already an extensive economic literature on the issue of carbon leakage. This literature is largely focused on the impacts of sub-global policies and uses computable general equilibrium (CGE) modeling frameworks or other numerical simulation models. Carbone and Rivers (2014) provides a thorough review of these types of studies, as well as some basic meta analysis. Their review suggests that "competitiveness" impacts of climate policy in emission-intensive, trade-exposed industries is relatively small.[2] This result is not that surprising given imposed international trade frictions.

Several recent papers have also explored sub-national policies using simulation-based modeling. For example, Bushnell and Chen (2012), Bushnell et al. (2014), and Caron et al. (2015) explore leakage possibilities across states due to California's (CA's) recently enacted carbon cap-and-trade system. These papers find the possibility for a large amount of leakage in the electricity sector due to "reshuffling", where states in the regions around CA reshuffle their power exports to CA such that they, at least on paper, export less emissions intensive power (e.g., natural gas-fired power) to CA and use more emissions intensive generation sources (e.g. coal-fired plants) to satisfy their local demand resulting in dramatically increased emissions in the regions surrounding CA. Likewise, the simulation-based analysis of Wing and Kilodziej (2008) on RGGI predicted considerable increases in power exports from states surrounding those covered by RGGI, leading to leakage rates exceeding 50%. Beyond the leakage impacts of sub-national cap-and-trade systems, Jacobsen et al. (2012) create a numeric simulation model to analyze the leakage affects brought about by some states' efforts to limit the GHG per mile of automobiles. They find that these state-level regulations

---

[2] For instance, their meta analysis suggests that a policies aimed at reducing GHG emissions by 20% in developed countries results in a 5% output loss among energy-intensive, trade-exposed industries.

are effective at reducing the emissions rates of new cars within the adopting states, but that there would also be significant leakages in non-adopting states in both used and new car markets.

Econometric estimates of leakage from imposed climate policies are far less common. A rare example can be found in Aichele and Felbermayr (2015) where they econometrically analyze leakage impacts of the Kyoto Protocol. They find that those countries with binding commitments under the Protocol have increased the embodied carbon of imports from non-committed countries by approximately 8%, which they point to as evidence of leakage under the Protocol. Kindle and Shawhan (2012) do not find evidence of RGGI leakage using transmission data, but only use data from the initial years of the program. If the full effects of RGGI were delayed due to, for example, preexisting contracts for electricity procurement, then leakage could have occurred after their period of study. Other related econometric literature can be found in those works exploring "pollution haven" effects and those looking at how regional energy prices affect trade flows and physical location of energy-intensive manufacturing facilities (e.g. Levinson and Taylor (2008), Aldy and Pizer (2011), and Kahn and Mansur (2013)). Similar to the idea of carbon leakage, these studies generally find that that increases in a region's relative energy price or relative stringency of environmental regulation increase the emissions-intensity of imports into these regions and reduces the prevelance of energy-intense manufacturing.

This study adds to the econometric investigations of carbon-policy driven leakage from a sub-national policy by examining the RGGI program. As noted above, this application is particularly interesting for several reasons. First, as a sub-national policy aimed at the electricity industry, the leakage impacts of RGGI are likely quite different from those considered in the simulation-based or econometric models focused on leakage impacts in international trade contexts. More specifically, many of the trade frictions one may consider in an international trade context are much higher than those likely experienced in a domestic electricity trading scenario. Second, while some simulation-based studies of the potential impacts of RGGI exist, these electricity models often have some limiting assumptions made to allow for computationally tractable simulations. By econometrically estimating responses in a reduced form framework we can circumvent these assumptions. Finally, these simulation models were also ex-ante examinations of the program and thus conducted in a time before hydraulic fracturing greatly expanded the natural gas supply in the U.S. By examining actual data, we include this increase gas supply and subsequent drop in gas prices. This turns out to be a key factor as it greatly changed the emission intensity of the unregulated areas surrounding the region regulated under RGGI.

As to our methods, we conduct two distinct, complementary analyses. The first uses detailed electricity generator-unit level data to estimate operational impacts associated with RGGI. For this analysis, we use operational data for coal-fired and natural gas combined cycle (NGCC) generators. We merge this with a rich set of controls including the plants own fuel costs, prices for substitute fuels, regional demand, and controls for regulations a given plant faces. Results indicate that, after controlling for these factors, coal plant capacity factors have decreased substantially in the RGGI region when the policy was in place. Additionally and importantly, we also find that NGCC plants in Pennsylvania and Ohio, two states that are not part of RGGI, saw capacity factors increases by approximately 10 percentage points, after controlling for input prices, demand, and other environmental rules. This suggests that non-RGGI gas generation displaced RGGI region coal generation.

We additionally use the unit-level data to examine changes in operational efficiency of plants in RGGI. This analysis finds little evidence of increased operational efficiency among RGGI plants. This is perhaps unsurprising given the relatively low emissions allowance price in RGGI.

In our second analysis, we examine RGGI-induced impacts on electricity transmission flows. The dataset is monthly electricity transmission at PJM interfaces. Interfaces are where two sub-units of the electricity grid connect. The primary interfaces to transmit electricity into the RGGI region are into New York from Pennsylvania, Ohio, and Ontario. Our analysis shows a statistically significant result that electricity imports to NYISO from PJM increase substantially during RGGI. Thus it appears electricity transmission into the RGGI region increased during the RGGI period. Furthermore, net exports from PJM to other nearby neighbors did not increase substantially or significantly during the RGGI period.

Taken together, this shows that natural gas generation in Pennsylvania and Ohio increased dramatically during the RGGI period, and this electricity was preferentially sent to RGGI states instead of other states. This provides evidence of generation leakage effect, whereby generation in RGGI regions decreased and was supplemented by increased generation from RGGI-surrounding regions. Interestingly, however, this leakage seems to have reduced aggregate emissions because electricity generation was less emissions intensive in the uncapped region than in the capped region. Back-of-the-envelope calculations suggest that one-quarter of apparent emissions reductions actually leaked but that this served to reduce total combined emissions by an additional one percent. This makes the leakage issue for RGGI quite different from the "reshuffling" issues feared for the recently introduced California carbon cap-and-trade system described in several of the studies cited above.

The remainder of the paper is organized as follows. In the next section, we give a brief description of the RGGI program and of the power system in the Northeast U.S. The estimation strategy is reviewed in Section 3. Section 4 describes the data used. Section 5 discusses the results. Concluding remarks are made in Section 6.

2 Policy and Industry Background

RGGI is a cap-and-trade system for CO_2 emissions from the electricity generation sector, currently covering generators in the states of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, and Vermont.[3] The program began in 2009, with permits being allocated through quarterly auctions. Permit prices from these auctions have been quite low, which is not surprising given that the program began during an economic downturn. However, the program does have a price floor in the auctions which has effectively prevented a complete price collapse. Going forward, the RGGI member states have agreed to continue to increase the stringency of the program, with the cap declining by 2.5% per year for 2015-2020.[4]

From the standpoint of leakage possibilities, another key aspect of the RGGI design is that power imported into RGGI-regulated regions is not subject to the emissions cap or any other border adjustment mechanism. Given this feature, it is obvious that the primary leakage mechanism possible is to reduce generation in RGGI-regulated regions and to cover the load in these regions by importing more power from generation sources outside the RGGI

---

[3] Generators in New Jersery were also covered under RGGI, but New Jersey opted out of the program in 2011

[4] More programmatic details on RGGI can be found on the RGGI Incorporated website: www.rggi.org.

region. To more fully understand this particulars of this mechanism, some discussion of the U.S. power system in the Northeast U.S., and the U.S. more generally, is warranted.

Power generation and transmission in the U.S. is conducted through a somewhat unique mix of traditionally regulated integrated utilities that own both the generation capacity and have a retail arm that sells power to end users and competitive wholesale structures. The power sector in the Northeast U.S. falls largely in the competitive wholesale market structure. In these wholesale markets, generating units sell power on to a wholesale market and retail entities buy power on these markets to eventually sell to end-user consumers.[5] An Independent System Operator (ISO) organizes these wholesale markets such that power supplied and demanded across a particular region is constantly balanced. The RGGI states span three ISO regions - New York ISO (NYISO), New England ISO (NEISO), and PJM. These regions can be seen in Figure 1. As one can see, while NYISO and NEISO regions are made up entirely of RGGI-participating states, PJM covers states both in and out of RGGI. It is also worth noting that power within these regions can be transmitted relatively easily, though some intra-ISO capacity constraints exist. Transmission across adjacent ISO's is possible through more limited "interconnection".

Given this set up, it seems likely that generation from RGGI would most likely be supplanted by generation from Ohio (OH) and non-RGGI regions of PJM, in particular generation from Pennsylvania (PA).[6] We therefore identify our possible "leaker" states as OH and

---

[5] Beyond sales through the wholesale markets, bilateral trading between generating and retail units also exist in these markets.

[6] Leakage could also occur through IESO, the ISO representing parts of eastern Canada, but the trade flows between NYISO and IESO have historically already been in the direction of IESO to NYISO, so there would seem less of a possibility of a RGGI-induced change on that front. To the extent RGGI did incentivize leakage from RGGI to IESO, that would largely be met with increased hydro production from IESO given its generation mix. This type of leakage pattern would thus only reinforce our beneficial leakage concept.

PA and use this designation in our analysis of generating units and transmission flows.

3 Empirical Methodology

The general goal of our empirical investigation is two-fold. First we test if RGGI had differential impact on generators, through both generation and thermal efficiency, for those plants in RGGI and those in areas where RGGI-induced leakage is likely to occur relative to those plants not near the RGGI region and, thus, likely unaffected by the regulation. Second, we explore how RGGI has affected transmission flows out of the likely "leaker" region. Below we describe our strategy for both investigations.

3.1 Generator-level Models

To determine if RGGI impacted the production and heat rates of generators, we estimate a difference-in-differences (diff-in-diff) model using annual generator-level data. The more specific form of the estimation is given as:

$$Y_{it} = \sum_{j \in J} \alpha_j TREAT_{it}^{j} + \mathbf{X}_{it}'\beta + f(Z_{it}) + \gamma_t + \theta_i + \varepsilon_{it} \tag{1}$$

Y_{it} is either generator i's capacity factor, CF_{it} defined as the net generation (MWhs) in year t divided by nameplate capacity (MW) times the number of hours in t, or its heat rate, HR_{it} defined as the MMBtu's of fuel input in year t divided by i's net generation. $\mathbf{X}_{it}$ is a set of controls such as regional demand for electricity and other relevant environmental policies affecting generator i in period t. Z_{it} is the ratio of the generators' input fuel costs to regional fuel costs of competing generation technologies. The input price ratio enter (1) in the general functional form $f(Z_{it})$ because we consider specifications that allow input fuel prices to enter the model non-parametrically as well as polynomially.[7] Time and generator fixed effects are represented by γ_t and θ_i, respectively.

The variable $TREAT_{it}^{j}$ is the treatment dummy, with our base specification as $J = [RGGI, Leaker]$. The treatment dummies are then defined as $TREAT_{it}^{RGGI} = 1$ if plant i is in a RGGI-participating state and year t is 2009 or later (when RGGI is in effect) and $TREAT_{it}^{Leaker} = 1$ if plant i is in OH or PA during the years t when RGGI is in effect.[8] The estimation was run separately for coal and NGCC plants. Additionally, for all specifications, the set of control generators consists of all generators within the given generation technology (i.e., coal-fired or NGCC) that are not either in a RGGI state or in a leaker state.[9]

Standard theory about regulation-induced leakage and emissions pricing in general help us frame expectations about the sign of the treatment effects (the α_j's) across the different treatment groups and generation technologies. First, in the absence of leakage, we might expect emissions pricing to lead to a shift in generation share from higher emissions-intensive coal generation to relatively cleaner natural gas, suggesting a negative treatment effect for coal plants and a positive treatment for gas plants in RGGI. However, with trade exposure, one would expect a leakage effect whereby generation in RGGI is decreased and generation

---

[7] Considering non-linear and non-constant responses to input prices in the electricity sector has been suggested by, among others, Cullen and Mansur (2014). In Cullen and Mansur (2014), they consider non-parametrically modeled coal-to-gas price ratios when estimating price impacts on regional emissions from the electricity sector and show there is a highly non-linear relationship between electricity-sector emissions and input price ratios.

[8] We also considered specifications where only one treatment effect entered the model (i.e., the model would include *either* $TREAT_{it}^{RGGI}$ or $TREAT_{it}^{Leaker}$) and the control plants are the same as in our base specification. Treatment effect estimates from running the treatment effects separately are nearly identical to those presented below and were thus omitted from the text.

[9] We consider several other refinements of the set of control plants. These results are reviewed in more detail in our discussion of robustness checks.

in nearby unregulated regions increases. The leakage effect should therefore should create negative treatment effects for RGGI plants and a positive treatment effect for plants in the leaker states. Combined, this implies that we would expect $\alpha_{RGGI} < 0$ for coal generators in RGGI and α_{RGGI} to be ambigously signed for RGGI-NGCC generators. For the plants in the leaker region we would expect $\alpha_{Leaker} > 0$ given the leakage affect. However, whether or not both generation technologies examined, coal and NGCC, respond to this leakage affect in the leaker region will depend on their relative marginal costs (MCs) during the treatment period. Typically, we expect coal generators to have a lower MC than NGCC generators, but the near the time RGGI went into effect, natural gas prices dropped dramatically, particularly in PA due to fracking-induced supply expansions in the area. As such NGCC plants became more cost competitive with coal, so it is possible that the leakage effect in the leaker region could be felt most suggesting $\alpha_{Leaker} > 0$ for NGCC plants.

In terms of heat rate impacts, carbon pricing would increase the cost of burning fossil fuels so *apriori* expectations would suggest that carbon pricing would incentivize an increase the thermal efficiency (decrease in heat rate) of RGGI plants, leading to an expectation of $\alpha_{RGGI} < 0$. Because coal is more emissions intensive than natural gas, carbon pricing would cause the cost of burning coal to increase more than that of natural gas so we might also expect the treatment effect in the heat rate specifications to be larger for coal plant in RGGI than for NGCC plants in RGGI. For the leaker region generators, it would seem unlikely that RGGI would have any impact on their efficiency levels as it does not directly impact their effective operation costs.

3.2 Transmission Model

We estimate a model of inter-region electricity transmission to find out whether electricity exports from PJM to the RGGI region have increased *relative to exports to other regions*. A positive result would support the conclusion that an increase in gas generation in Pennsylvania and Ohio has indeed resulted in leakage into RGGI.

In our core specification, we use transmission between PJM and non-RGGI neighboring regions as a control for transmission from PJM to RGGI. If net exports from PJM increase uniformly, we will estimate a treatment effect of zero. However if net exports from PJM to RGGI increase relative to net exports to other regions, we will find an effect. The key identification assumption is that transmission in one region of an electricity grid (ISO or RTO) is a good control for transmission in another region. This is plausible because both non-policy determinants of generation and demand exhibit substantial spatial autocorrelation. If a weather system causes an increase in electricity demand, that happens at a regional scale. This increases transmission across the region.

This logic motivates the empirical specification in equation 2.

$$y_{it} = \beta Treat_{it} + \gamma_t + \theta_i + \varepsilon_{it} \tag{2}$$

y_{it} Transmission across an interface

$Treat_{it}$ Treatment s

We estimate several specifications of equation 2. First of all, we let y_{it} be gross flow in each direction and net flow in different regressions. For convenience, we will define exports to be flows from PJM to New York. Second, we estimate equation 2 for both all interfaces to NY and aggregating those interfaces to a single representative one. This is because there were several interfaces built during our study period. Reporting both specifications allows us to estimate both the average change in transmission across individual interfaces and the change in total transmission. Third, we consider two separate control groups. The first control group is all interfaces in PJM, whether they are to neighboring ISOs or between subunits of the PJM grid. The second control group consists of only interfaces between PJM and neighboring ISOs.

It is important to note that the electricity grid boundaries do not neatly line up with political jurisdiction boundaries. Several states in RGGI are also part of PJM - Delaware, Maryland, and (until its departure from RGGI) New Jersey. Thus an increase of electricity imports into those states will not be counted in our analysis. If leakage also occurs inside PJM, then our estimates (with respect to transmission) will underestimate the full effect.

4 Data

Our generation analysis uses generator-level data provided by the data aggregation firm Ventyx. This data is based on largely on publicly available data sets, though some aggregation was conducted by Ventyx. Finally, as noted above, we collect this data only on coal and NGCC generators. We use these technology types because they are the types most likely affected by the RGGI regulation.[10]

---

[10] Other technologies such as natural gas turbines or diesel generators are used more rarely for high demand cases and are likely to continue in that role regardless of emission constraints. Nuclear is another prevelant technology in the region around RGGI, but it is already running at near capacity so it is unlikely to respond to the policy. There is also considerable hydro generation capacity in and around RGGI. Responses from hydro may be more likely than that for nuclear, but a lack of consistent reservoir or river flow data

To form the dependent variables for the generator-level analysis, capacity factor and heat rate, we get monthly generation (MWh's) and fuel consumption (MMBtu's) data, based off of information provided in form EIA-923. This data is sufficient to form the heat rate variable HR_{it} (fuel consumption divided by monthly generation). However, to get capacity factor we also collect generator-level nameplate capacity measures, based on EIA-860 data. With generation and capacity measures we form CF_{it} as described above. In addition, because some generation plants have multiple generators of the same technology (e.g. some plants have multiple NGCC generators or multiple coal steam generators) and because some of our data are at the plant-level only (e.g. fuel prices), we aggregate all generation, fuel consumption, and capacity measures for generators of the same technology within a plant. This aggregated data is then treated as a single generator in our analysis.[11]

Table 1 shows capacity factors for coal and gas plants before and during RGGI, along with their standard deviations. For this table, plants in Pennsylvania and Ohio are considered potential leakers, and all plants outside of RGGI, Pennsylvania, and Ohio are in the control group. Figure 2 displays unconditional kernel density estimates which show this same information graphically. Note that coal use declined modestly in all regions under RGGI, and by a greater amount in RGGI states than in control states. Far more dramatically, note that while gas utilization increased modestly in control states and RGGI states, it increased by twenty-five percentage points in leaker states. This will form the core of our argument - natural gas generation in leaker states increased dramatically during RGGI, supplanting

---

prohibited a complete exploration of this technology.

[11] Beyond not having distinct fuel prices across same-technology generators within a given plant, this aggregation also makes sense within the fixed effects panel estimation undertaken here. More specifically, if the fixed effect picks up such generator-level heterogeneity as management quality, fuel terminal access, and/or transmission access these would be aspects shared by generators within the same plant.

RGGI coal generation.

Controls for the generator-level analysis, X_{it}, include load, input prices, and regulatory measures. Load is a measure of electricity demanded at a given time. As electricity is not storable and electricity generators are statutorily required to meet demand, load acts to shift the quantity supplied along the supply curve. Long-distance electricity transmission is costly and constrained by capacity, so we use the total load in the "transmission zone" for each plant.[12]

Plant-level fuel prices, the primary variable cost for power plants, are derived from monthly delivered fuel costs reported on EIA-923 forms and are measured in cents per MMBtu.[13] We also control for the price of substitutes. For coal plants, we include the natural gas price at the nearest natural gas price hub. For NGCC plants, we include the generation-weighted mean cost of coal for coal plants in the NGCC plant's transmission zone.[14]

Electricity generators also face a variety of regulations unrelated to RGGI. Thus for coal plants we include indicator variables for SO_2 control equipment and NO_X phase as well as a NO_X budget plan indicator for gas plants. We additionally include the log of NERC-region renewable generation (including hydroelectricity).

---

[12] Transmission zones are defined by Ventyx. According to the Ventyx documentation, transmission zones "represent load pockets and these load pockets are derived through extensive analysis of FERC 714 data, ISO reports in ERCOT, WECC transmission cases and Multiregional Modeling Working Groups (MMWGs) in the Eastern interconnect." Load for these areas is reported via data provided by the ISO's.

[13] The fuel cost data in the EIA-923 forms is reported for utilities in traditional cost of service regulated regions and other regulated power providers. Where the cost data is not available publicly, Ventyx assigns a fuel cost to the plant based on regional fuel prices and prices at similar plants.

[14] Coal is primarily transported by rail instead of by pipeline, so there is not a single public regional price.

4.1 Transmission data

Our transmission analysis uses interface-level data available from the PJM Regional Transmission Organization (RTO). PJM is one of a number of Independent System Operators (ISOs) and RTOs which manage the regional subgrids comprising the national electricity grid. PJM covers Pennsylvania and Ohio as all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia. Figure 1 illustrates the extent of ISOs and RTOs in the United States.

ISOs and RTOs in turn have sub-sub grids. Connections between these units are referred to as "interfaces". We use monthly transmission across individual PJM interfaces.[15] Transmission can occur in either direction across an interface, and over the course of a month will typically occur in both directions. Thus for each interface-month observation we have three data values: transmission in each direction, plus the net transmission. The data period is January 2004-Dec 2012, the same period of study as our generation analysis. We tag all interfaces between PJM and New York.[16] We additionally aggregate all transmission from PJM into New York into a single representative observation. Table 3 summarizes net transmission across control interfaces and New York interfaces before and during the RGGI period. Standard deviations are large because of substantial variation in both typical use of different interfaces and intra-interface variation. However, the key difference-in-difference result that transmission from PJM into New York increased relative to transmission across other interfaces is readily apparent.

---

[15] Available in Monitoring Analytics' annual "PJM State of the Market", downloaded from `http://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2012.shtml`.

[16] NYISO, Linden, Neptune, and Hudson

5 Results

5.1 Generator-level Results

We begin by presenting the estimation results from the generator-level analysis, equation (1). As noted above, this analysis was conducted for coal and NGCC plants separately and using two different dependent variables (capacity factors and heat rates). In each specification, $f(Z_{it})$ is modeled nonparametrically with a rule-of-thumb bandwidth. We also consider two different specifications of the time trend, a cubic time trend and annual fixed effects. Generally, one would consider annual fixed effects to be a preferred specification in controlling for common time-varying unobservables. However, out of concern that annual fixed effects for annual data might effectively soak up the variation in other control variables, and in particular in our flexible specification of the input price ratio, we additionally include specifications with a cubic time trend.

Table 4 gives the treatment effect parameter estimates for the specifications with capacity factor as the dependent variable. The first two columns give the results for the case where the sample is restricted to NGCC generators and across the two different time trend specifications and the final two columns are the results using only coal generators. The "RGGI" line gives the treatment effects estimate for α_{RGGI} and the "Leaker" line gives the parameter estimates for α_{Leaker}. Additional controls for this specification, beyond the nonparametric input price ratio, include the NO_X phase well as an indicator for the presence of SO_2 control equipment. Parameter estimates associated with these controls are included in the appendix in Table 10.

For RGGI generators, we see that NGCC generators' capacity factors have a small and statistically insignificant response to RGGI, but RGGI coal generators did have a RGGI-induced reduction in capacity factors of about 7 to 10 percentage points. Conversely, in the leaker region, we estimate that RGGI led to 10 to 11 percentage point increase in capacity factors for NGCC generators, but had effectively no impact on coal generators.[17]

Together, these results suggests that there was no significant within-RGGI fuel switching from coal to NGCC plants. Rather, it appears that a primary compliance mechanism was to turn down coal plants in RGGI. This, as the parameters describe, did lead to leakage whereby the reduced coal-fired generation in RGGI was compensated for by increased generation in the leaker regions of PA and OH. However, instead of the displaced coal generation in RGGI be made up for by increased coal generation in surrounding regions, it appears that NGCC generation in the leaker regions was the substituting generation form. This substitution pattern leads us to our notion of "beneficial leakage". Yes, RGGI appears to have created a leakage situation as generation from NGCC plants in the leaker region were higher than they otherwise would have been and thus emissions in the leaker region are higher than they would have been. But, RGGI induced a substitution pattern whereby RGGI coal generators' production was at least partially offset by relatively cleaner leaker-region NGCC generation, creating a situation where, *ceteris paribus*, combined emissions from the leaker and RGGI regions were lower than they otherwise would have been.

---

[17] These results are qualitatively robust to $f(Z_{it})$ being a lower order polynomial or a natural logarithm of Z_{it}. However, some fully parametric specifications yield substantially larger treatment effect estimates for Leaker NGCC plants. This result is consistent with Cullen and Mansur (2014)'s argument that a parametric price specification may not fully capture fuel switching behavior, and that instead there is a kink at the price ratio where NGCC generation becomes inframarginal to coal on the dispatch curve. If the parametric specification under-predicts fuel switching at high coal-gas price ratios (which would be consistent with Cullen and Mansur (2014)), then due to collinearity between Leaker treatment and low gas prices, the Leaker treatment effect would be overestimated. The semi parametric specification is therefore our preferred specification.

One may also question why leaker region NGCC increased instead of coal. Throughout much of our sample, coal and gas prices were such that on average coal generators had lower MC's than NGCC's. However, the dramatic drop in gas prices near the time RGGI went into effect did make NGCC's much more cost competitive with coal generators, so that is the likely reason these NGCC generators increased their production in response to RGGI. In addition, many of the NGCC plants in PA happen to be on northern and eastern edges of PJM and are thus physically closer to the RGGI regions than the coal plants in PA. This proximity difference may have made it easier for NGCC plants to transmit their power to RGGI regions. Finally, one may also note that NGCC plants in the leaker regions had plent of spare capacity pre-RGGI, as can be seen in Figure 2 and thus had a larger margin to respond to RGGI. While this may be true, the concurrent drop in gas prices also significantly lowered the capacity factors of coal plant, so relative spare capacity pre-treatment would not appear to be a primary driver for NGCC being the technology that responded to RGGI in the leaker regions.

To further assess the magnitudes of these estimated treatment effects we calculate a rough back-of-the-envelope estimate of the scale of leakage. We multiple our estimated treatment effects of an 11.9 percentage point increase in Leaker NGCC capacity factor and a 12.1 percentage and a 12.1 percentage point decrease in RGGI coal capacity factor (specifications 1 and 3 of Table 4, respectively) times the average annual generation capacities to find the estimated generation leakage. Per these estimates, we find that Leaker NGCC generation increased by approximately 11 million megawatt hours per year, whereas RGGI coal generation decreased by approximately 9.3 million megawatt hours per year. A t-test cannot reject the null that the Leaker NGCC generation increase and RGGI coal generation decrease are equal (p-value=0.67 for the test that their difference is different from zero). These generation changes imply that production leakage increased Leaker CO_2 emissions by 4.5 million tons per year and decreased RGGI CO_2 emissions by 8.8 million tons per year, for an aggregate decrease of 4.3 million tons per year.[18] Total RGGI + Leaker region emissions were approximately 296 million tons in 2012[19], so while generation leakage has been substantial, it has actually acted to reduce emissions by approximately 1.4%.

Treatment effects for the specifications using heat rate as the dependent variable are given in Table 5. As with the capacity factor specifications, additional controls of NO_X phase, presence of SO_2 control equipment, annual fixed effects, log of NERC-wide renewable generation, input price ration, and capacity factor were included in the regressions from which these treatment effects are derived and these estimates are given in Table 11 of the appendix. Capacity factor is instrumented with logged load. Here we generally find that RGGI did not induce signficant heat rate changes for RGGI or leaker region generators. This is somewhat expected given the relatively small carbon price and the ease in which emission-intensive generation in RGGI can be replaced by generation from the leaker region.

The identification of the treatment effect in this diff-in-diff setting hinge on several key assumptions. First, we must assume the treatment is exogenous. Given that the formation was a largely political process among geographically close states it seems reasonable to assume that the the decision to start RGGI was largely exogenous to generator behavior. The decision of a state to join RGGI may however have been a function of the state's generation profile which may prompt concerns of selection bias, but even if this was true it

---

[18] Based on an average RGGI coal heat rate of 11,184 BTU/KwH and coal CO_2 content of 205 lbs/mmbtu and average Leaker NGCC heat rate of 6722 BTU/KwH and gas CO_2 content of 117 lbs/mmbtu.

[19] Authors' calculation based on data from http://www.eia.gov/environment/emissions/state/.

seems unlikely that the participation decision was driven by the operations (capacity factors and heat rates) of the given plants. Second, we must also assume that RGGI dies not affect generators beyond the RGGI region and adjacent leaker region. This too seems plausible as states farther away than the leaker region have less direct access to RGGI and are therefore not likely places for leakage and given the relatively small geographic regin of RGGI it is unlikely its passage had noticeable impacts on input prices or other important electricity supply determinants. We also need to assess whether or not our control generators have similar pre-treatment trends as the treatment regions. To explore this more thoroughly we estimate the following equation:

$$Y_{it} = \sum_{j \in J} \alpha_{jt} D_t TREAT_i^j + \mathbf{X}'_{it}\beta + f(Z_{it}) + \gamma_t + \theta_i + \varepsilon_{it} \tag{3}$$

where D_t is a year dummy with $D_t = 1$ in year t and 0 otherwise, $TREAT_i^j = 1$ if generator i is *ever* in treatment j, and, thus, α_{jt} are estimated parameters that pick up a treatment group specific time trend. We do this for both polynomial and nonparametric specifications of $f(Z_t)$. A plot of the α_{jt} terms, along with 95% confidence bands, are given in Figures 3-6. These plots show that for both the RGGI and Leaker treatments the pre-treatment period time fixed effects are not statistically different from zero, indicating they have similar pre-treatment trends as the control group.

We additionally perform a variety of robustness checks for the capacity factor specifications to further show the consistency of the treatment effect. In particular, because the control group includes plants from all across the contiguous U.S., we estimate Equation (1) with two different sets of control generators. First, because RGGI and the leaker regions are in states that have deregulated their electricity markets, moving from integrated, regulated monopolistic utility structures to more competitive wholesale electricity market structures, we limit the control group to generators also in states that have also deregulated. Results from this specification have the control group designated as "Deregulated States".[20] Second, because plants in the western United States may be poor controls for unobserved common time effects in the northeastern U.S., we limit the control group to plants on the Eastern Interconnection.[21]

Treatment effect estimates under the various control group specifications are presented in Table 9. Each of the columns in Table 9 gives the treatment effect under either the RGGI or Leaker treatment specifications. All estimations are considered using a non-parametric specification of the coal-to-gas price ratio and using a parametric time trend.[22] The results using these control specification are quite similar to those presented under the broader control group specification. Namely, we again find RGGI states had an approximately 10 percentage point decline in coal capacity factors and a smaller decline in NGCC capacity factors, while Pennsylvania had an approximately 10 percentage point increase in NGCC capacity factors.

Finally, given that near the time RGGI was introduced, natural gas prices dropped dramatically due to fracking-induced supply expansions, some discussion of the coal-to-gas price ratio impacts is warranted. We display the marginal effect of the coal-to-gas price ratio from our generator-level analysis on NGCC capacity factors over a range of price ratios and using the nonparametric price ratio specification. The plot of the effects of the price

---

[20] The control group for the "Deregulated States" includes generators in the following state: IL, MI, OR, and TX. This group of states was based on EIA (2010) PA and OH are omitted from the control group.

[21] The control group for the "Eastern" states includes plants in the FRCC, MRO, NPCC, RFC, SERC, and SPP NERC regions.

[22] Though not shown, results using the linear specification of the log of coal-to-gas price ratios and time fixed effects are similar to what we show here.

ratio Z_{it} is given in Figure 7.[23][24] As shown in Figure 9, the coal-to-gas price ratio is well below one for the majority of the sample, but during periods of very low gas prices the fuels were price equivalent, and occasionally coal was more expensive than gas. Table 1 shows that Leaker NGCC capacity factors increased by approximately 25 percentage points during our treatment period while non-Leaker NGCC capacity factors increase by approximately 3 percentage points. Figure 7 shows that an increase in the coal-gas price ratio from 0.4 to 1 would increase NGCC capacity factors by approximately 7 percentage points while a smaller price ratio increase (gas price decrease) would cause a smaller increase in capacity factor. This implies that the non-Leaker region NGCC capacity factor increase was largely driven by low gas prices, but that low gas prices accounted for somewhat less than half of the increase in Leaker NGCC capacity factors.

5.2 Transmission Results

Our transmission results in Tables 6-8 show an economically substantial and statistically significant increase in electricity transmission from PJM into New York during the RGGI program. Table 6 shows the increase in gross exports from PJM to New York during RGGI, relative to other interfaces. Columns 1 and 3 estimate transmission across all interfaces to New York, whereas columns 2 and 4 replace these interfaces with a single representative observation who's value is the sum of all gross exports to New York. We see that gross electricity exports from PJM to New York increased by 2451.95 gigawatt-hours per month

---

[23] Figure 8 shows f(Z) for coal plants. We see that coal generation is less sensitive to prices than NGCC generation, consistent with Linn et al. (2014)'s finding that coal generation is much less responsive to gas prices than gas generation.

[24] Both Figures 7 and 8 have wide confidence intervals for very high and very low coal-gas price ratios. This is because there are few observations with very high or low price ratios, as can be seen in Figure 9. Estimating regions with few observations nonparametrically yields wide confidence intervals.

during RGGI (Column 2). Gross exports increased significantly and substantially for given interfaces (Columns 1 and 3), for the aggregate total (Columns 2 and 4), and whether the control group is all PJM interfaces (columns 1 and 2) or just interfaces to other regions (columns 3 and 4).

In Table 7, we see that gross electricity imports to PJM from New York also increased - by 1088.431 gigawatthours per month in Column 2. Column 1 shows that gross imports across the average interface increased by 155.802 gigawatthours per month. We have a smaller and insignificant average effect and smaller but significant aggregate effect when we restrict the control group to external interfaces (Columns 3 and 4). This could suggest a general increase in gross imports. An increase in flow in each direction is consistent with the general reshuffling due to low gas prices.

Table 8 shows the change in net electricity exports from PJM to New York. The large increase in net exports from PJM to New York relative to exports to other regions as shown in Table 8 is consistent with the hypothesis that the increase in Pennsylvania and Ohio NGCC generation was indeed policy-induced. Specification 2 of Table 8 shows a monthly net transmission increase of 1497.852 gigawatthours or an annual transmission increase of approximately 18,000 GwH, or 18 million MwH. This is comparable to, albeit somewhat larger than, the leakage estimate based on the generation model. Using external interfaces as controls we find a somewhat larger effect of 1707.409 gigawatthours per month. Treating all interfaces individually we still find positive and significant effects in specifications 1 and 3. In all specifications, the net effect is approximately the difference between the gross exports and imports.

6 Conclusions

Sub-global and sub-national climate policies have been, and continue to be, the primary mechanisms of regulating GHG's. Unfortunately, as has been well documented, these regional programs can often lead to emission leakage whereby regulated regions' abatement is offset by increase in emissions in unregulated cases. In the worst case scenario, aggregate emissions may even increase if regional regulations induce production to move to more emissions intensive areas.

While the possibility and severity of leakage has been explored thoroughly in theory and simulation modeling, very few empirical estimations of leakage exist in the literature. We add to the empirical evidence of leakage by exploring the case of the RGGI. More specifically, we use electricity generator-level data to estimate how the RGGI policy affected those plants directly regulated by the program and those geographically near the regulation region relative to plants further away and therefore less affected by the policy. We also use generation transmission flow data to identify how the policy has affected electricity trade around the region most likely impacted by the regulation.

Our generator-level analysis implies that RGGI induced coal plants in the RGGI region to reduce their capacity utilitization by approximately 10 percentage points. This reduced generation in the RGGI region was not compensated for by increase in gas-fired generation in the area, but rather RGGI led to an increase in generation from the areas surrounding RGGI, the deemed leaker region. However, the RGGI-induced increase in generation from the leaker region came from relatively cleaner NGCC generators. This result leads us to our notion of "beneficial leakage" - the policy did induce leakage (emissions in the unregulated regions were higher than they otherwise would have been), but the policy motivated a reduction of emissions-intensive generation in the regulated region and an expansion of relatively cleaner generation in the unregulated region leading to an aggregate reduction of emissions across the regulated and neighboring unregulated regions. The electricity transmission further supports this generation substitution pattern.

This type of leakage pattern, where the policy forces a reduction of production from emissions-intensive sources in the regulated regions and moves production to a region with relatively cleaner production, is not often discussed, but appears possible in other settings. In particular, we might see this type of leakage in regulation-induced movement of production from capital-intensive, and hence emissions-intensive, generation in developed countries to production in more labor-intensive production in developing regions. Overall, further empirical analyses are necessary to evaluate possible severity of regional-policy-related leakage.

References

Aichele, R. and G. Felbermayr (2015). Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade. *Review of Economics and Statistics 97*(1), 104–115.

Aldy, J. E. and W. A. Pizer (2011). The competitiveness impacts of climate change mitigation policies. NBER Working Paper No. 17705.

Bushnell, J. and Y. Chen (2012). Allocation and leakage in cap-and-trade markets for co2. *Resources and Energy Economics 34*, 647–668.

Bushnell, J., Y. Chen, and M. Zaragoza (2014). Downstream regulation of co2 emissions in california's electricity sector. *Energy Policy*.

Carbone, J. C. and N. Rivers (2014). Climate policy and competitiveness: Policy guidance and quantitative evidence. Colorado School of Mines Division of Economics and Business Working Paper 2014-05.

Caron, J., S. Rausch, and N. Winchester (2015). Leakage from sub-national climate policy: The case of california's cap-and-trade program. *Energy Journal 36*(2).

Cullen, J. A. and E. T. Mansur (2014). Inferring carbon abatement costs in electricity markets: A revealed preference approach using the shale revolution. Working Paper 2014.

EIA (2010). Electricity restructuring by state. `http://www.eia.gov/electricity/policies/restructuring/restructure_elect.html`. Accessed: 04/19/2015.

Jacobsen, M., L. Goulder, and A. van Benthem (2012). Unintended consequences from nested state and federal regulations: The case of the pavley greenhouse-gas-per-mile limits. *Journal of Environmental Economics and Management 63*(2), 187–208.

Kahn, M. E. and E. T. Mansur (2013). Do local energy prices and regulation affect the geographic concentration of employment? *Journal of Public Economics 101*, 105–114.

Kindle, A. and D. Shawhan (2012). An empirical test for inter-state carbon-dioxide emissions leakage resulting from the regional greenhouse gas initiative. In *Presented at USAEE 2012*. `http://www.usaee.org/usaee2012/submissions/Presentations/Kindle_USAEE_2012_RGGI_Presentation.pdf`.

Levinson, A. and M. S. Taylor (2008). Unmasking the pollution haven effect. *International Economic Review 49*(1), 223–254.

Linn, J., L. Muehlenbachs, and Y. Wang (2014). How do natural gas prices affect electricity consumers and the environment? *Resources for the Future Discussion Paper* (14-19).

Wing, I. S. and M. Kilodziej (2008). The regional greenhouse gas initiative: Emission leakage and the effectiveness of interstate border adjustments. Harvard Kennedy School Regulatory Policy Program Working Paper No. RPP-2008-03.

Figure 1: Map of Independent System Operators and Regional Transmission Organizations

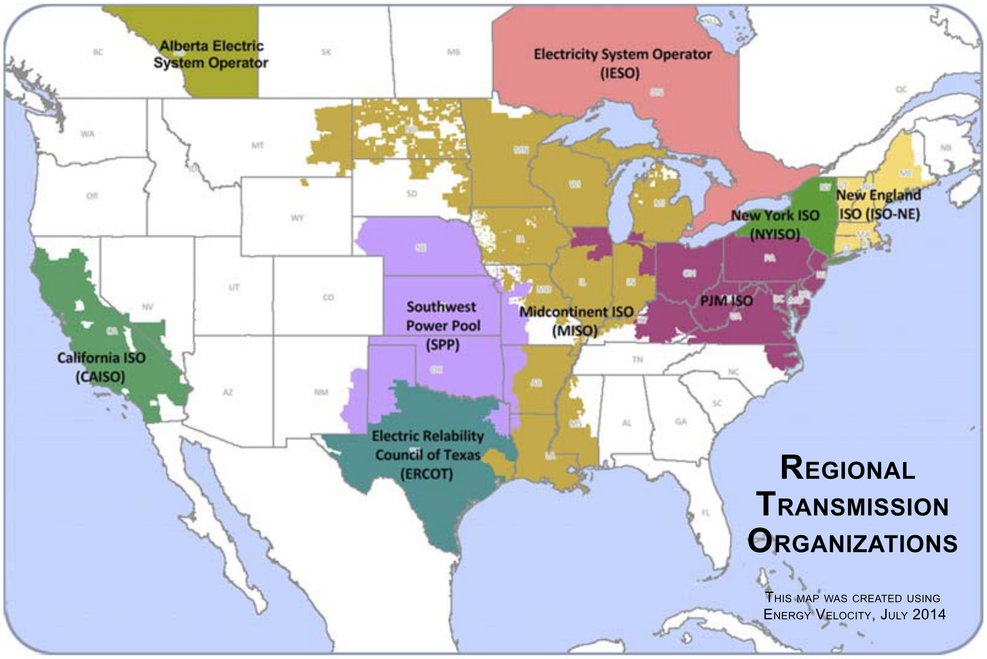
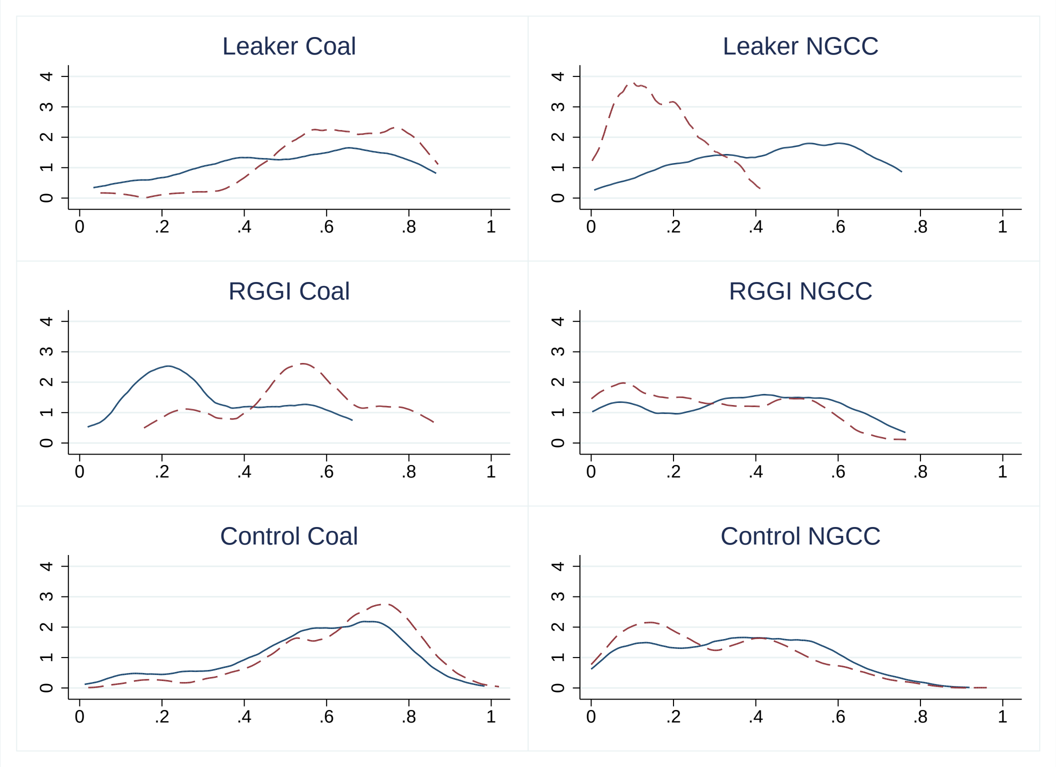
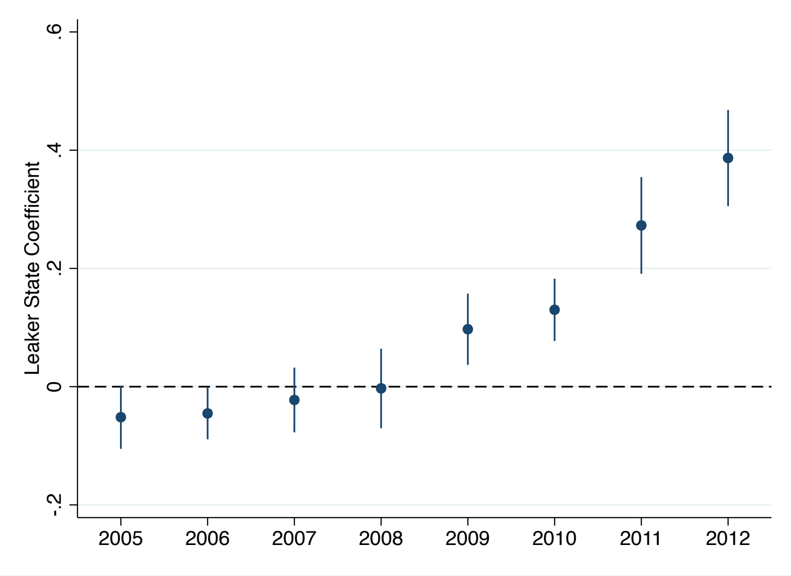


Figure 2: Capacity Factor Kernel Densities



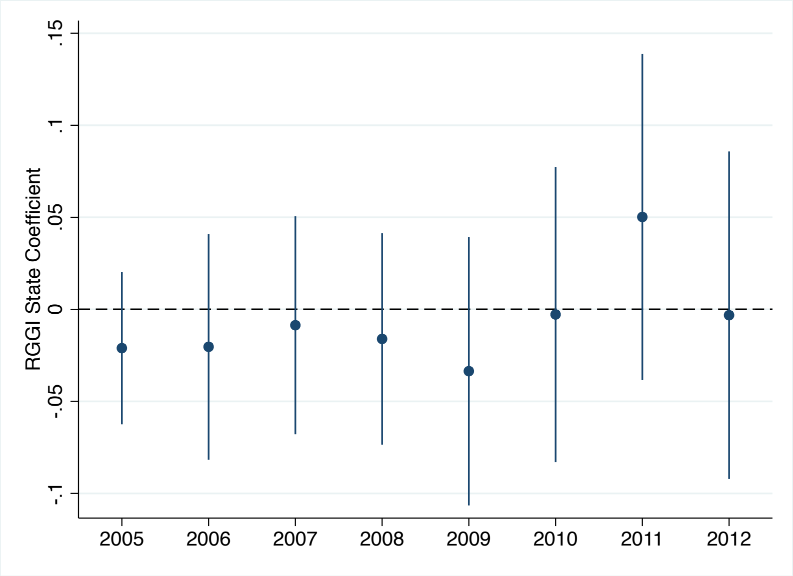
Dash line: Pre-treatment. Solid line: Post-treatment.

Figure 3: Semiparametric NGCC Treatment Effects, Leaker States



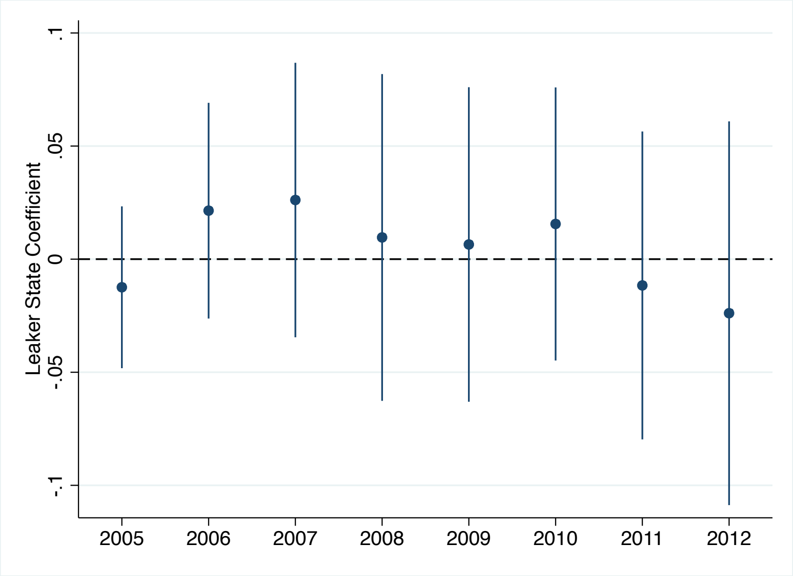
Vertical lines represent 95% confidence intervals.

Figure 4: Semiparametric NGCC Treatment Effects, RGGI States



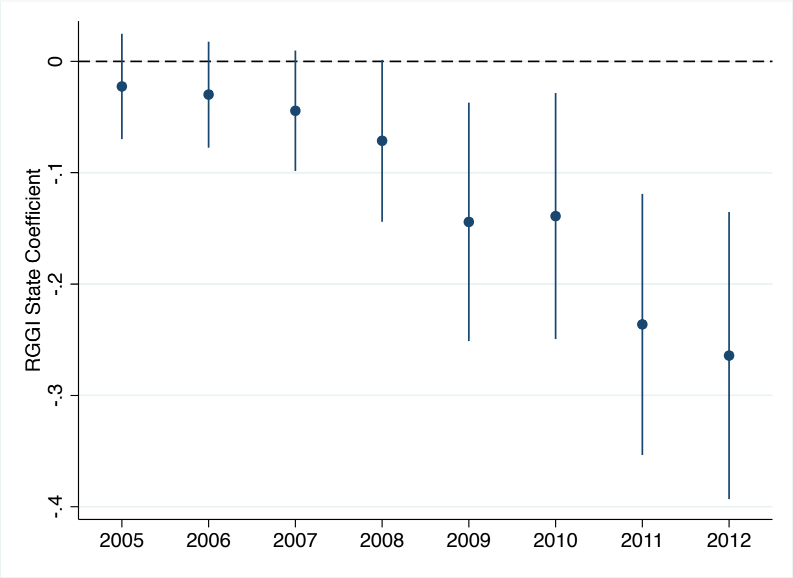
Vertical lines represent 95% confidence intervals.

Figure 5: Semiparametric Coal Treatment Effects, Leaker States



Vertical lines represent 95% confidence intervals.

Figure 6: Semiparametric Coal Treatment Effects, RGGI States



Vertical lines represent 95% confidence intervals.

Figure 7: $f(Z_{it})$ for NGCC plants with 95% confidence interval

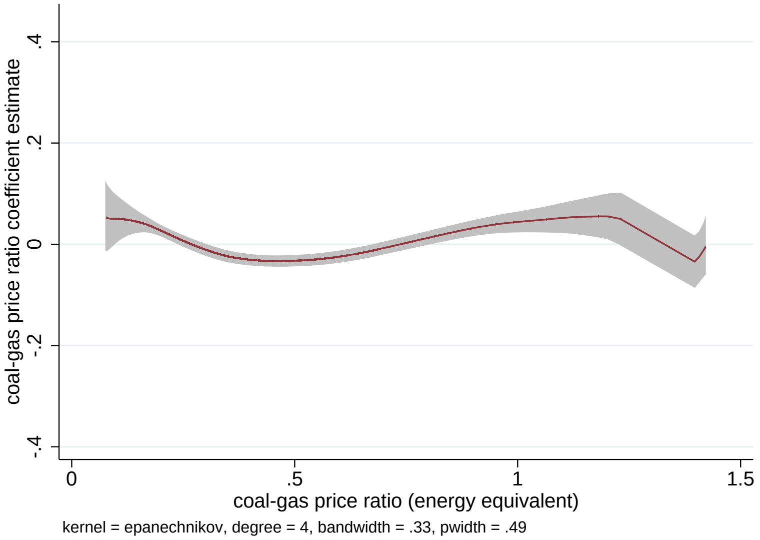


Figure 8: $f(Z_{it})$ for coal plants with 95% confidence interval

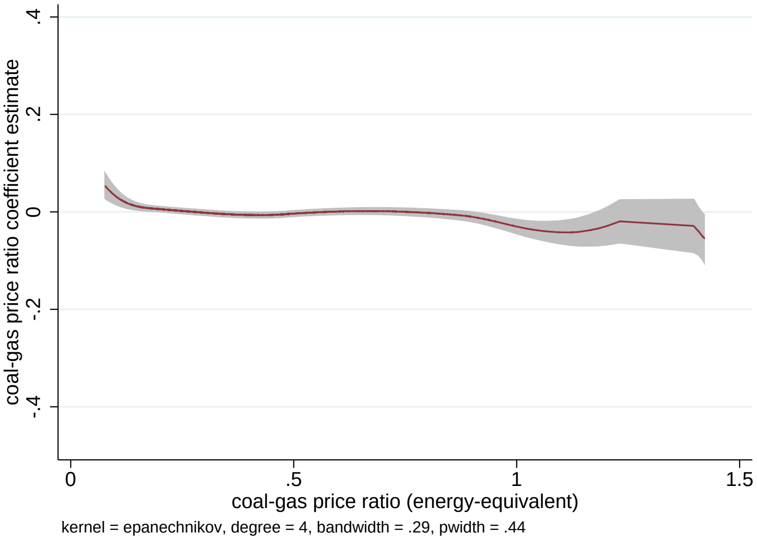


Figure 9: Histogram of the coal-gas price ratio

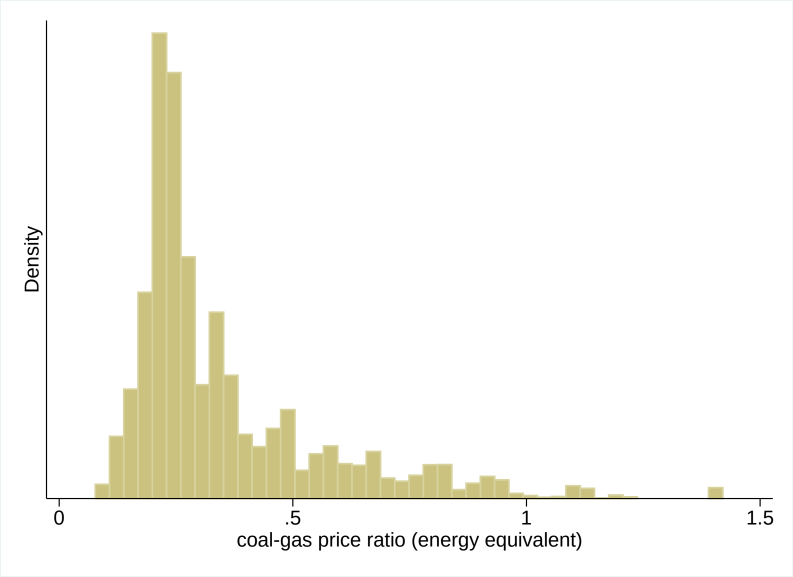


Table 1: Capacity factors before and during RGGI

	Coal Pre Treatment	Coal Post Treatment	Gas Pre Treatment	Gas Post Treatment
Control	0.61	0.51	0.31	0.35
	(0.19)	(0.22)	(0.20)	(0.20)
RGGI	0.50	0.30	0.31	0.36
	(0.21)	(0.18)	(0.23)	(0.21)
Leaker	0.60	0.45	0.15	0.41
	(0.20)	(0.25)	(0.11)	(0.22)

Notes: Standard deviations listed below means. Gas is NGCC only.

Table 2: Heat rates before and during RGGI

	Coal Pre Treatment	Coal Post Treatment	Gas Pre Treatment	Gas Post Treatment
Control	11553.95	12063.52	8284.36	8411.753
	(4308.041)	(10068.17)	(1863.569)	(5844.631)
RGGI	11193.34	11193.34	8244.687	8380.452
	(1637.399)	(2392.743)	(1294.103)	(1831.118)
Leaker	12756.08	12497.33	9317.186	9909.831
	(6273.784)	(5082.53)	(5323.853)	(14128.42)

Notes: Standard deviations listed below means. Gas is NGCC only.

Table 3: PJM Transmission before and during RGGI

	Before Treatment	After Treatment
Control	21.932	-13.452
	(314.809)	(339.903)
New York	488.557	756.505
	(351.886)	(740.943)

Notes: Standard deviations listed below means. Units are GwH.

Table 4: Treatment Effects - Capacity Factor

	(1) NGCC	(2) NGCC	(3) Coal	(4) Coal
isUnderRGGI	-0.015	-0.026	-0.121***	-0.090**
	(0.016)	(0.017)	(0.040)	(0.040)
isLeaker	0.119***	0.100***	-0.014	0.009
	(0.028)	(0.029)	(0.025)	(0.025)
Observations	1,716	1,716	1,930	1,930
Time	Cubic Trend	FE's	Cubic Trend	FE's

*Notes: *, **, *** denote statistical significance at at least the 10, 5, and 1 percent levels, respectively. Robust standard errors, clustered at the plant level, are given in parentheses below the parameter estimates. "Time Trend" denotes the manner in which time effects are accounted for where "Cubic" means a cubic time trend was included and "FE's" mean the model includes year fixed effects.*

Table 5: Treatment Effects - Heat Rate

	(1) NGCC	(2) NGCC	(3) Coal	(4) Coal
isUnderRGGI	0.024	0.011	-0.030	-0.040
	(0.022)	(0.019)	(0.022)	(0.033)
isLeaker	-0.131	-0.069	0.015*	0.014
	(0.104)	(0.080)	(0.008)	(0.010)
Observations	2,069	2,069	2,263	2,263
Time	Cubic Trend	FE's	Cubic Trend	FE's

*Notes: *, **, *** denote statistical significance at at least the 10, 5, and 1 percent levels, respectively. Robust standard errors, clustered at the plant level, are given in parentheses below the parameter estimates. "Time Trend" denotes the manner in which time effects are accounted for where "Cubic" means a cubic time trend was included and "FE's" mean the model includes year fixed effects.*

Table 6: PJM gross exports to NY

	(1)	(2)	(3)	(4)
RGGI	263.314***	2,451.950***	361.097***	2,538.127***
	(26.362)	(38.593)	(41.279)	(69.206)
Observations	2,404	2,244	748	588
NY Interface	Distinct	Aggregated	Distinct	Aggregated
Control	All	All	External	External

*Notes: *, **, *** represent 10, 5, and 1 percent confidence levels. All specifications include interface and monthly fixed effects. ”NY Interfaces” refers to whether interfaces between PJM and New York are included individually (”Distinct”) or are aggregated into a single measure of transmission between PJM and New York (”Aggregated”). ”Control” refers to whether the control group is all PJM interfaces (”All”) or only interfaces with other ISOs/RTOs (”External”).*

Table 7: PJM gross imports from NY

	(1)	(2)	(3)	(4)
RGGI	155.802***	1,088.431***	59.772*	964.989***
	(25.783)	(33.604)	(30.474)	(43.082)
Observations	2,416	2,256	748	588
NY Interfaces	Distinct	Aggregated	Distinct	Aggregated
Control	All	All	External	External

*Notes: *, **, *** represent 10, 5, and 1 percent confidence levels. All specifications include interface and monthly fixed effects. “NY Interfaces” refers to whether interfaces between PJM and New York are included individually (“Distinct”) or are aggregated into a single measure of transmission between PJM and New York (“Aggregated”). “Control” refers to whether the control group is all PJM interfaces (“All”) or only interfaces with other ISOs/RTOs (“External”).*

Table 8: PJM net exports to NY

	(1)	(2)	(3)	(4)
RGGI	133.029***	1,497.852***	326.420***	1,707.409***
	(35.064)	(46.875)	(45.805)	(68.788)
Observations	2,416	2,256	748	588
NY Interfaces	Distinct	Aggregated	Distinct	Aggregated
Control	All	All	External	External

*Notes: *, **, *** represent 10, 5, and 1 percentt confidence levels. All specifications include interface and monthly fixed effects. ”NY Interfaces” refers to whether interfaces between PJM and New York are included individually (”Distinct”) or are aggregated into a single measure of transmission between PJM and New York (”Aggregated”). ”Control” refers to whether the control group is all PJM interfaces (”All”) or only interfaces with other ISOs/RTOs (”External”).*

Table 9: Control sample sensitivity analyses

	(1) NGCC	(2) Coal	(3) NGCC	(4) Coal
isUnderRGGI	-0.014	-0.133***	-0.014	-0.122***
	(0.017)	(0.040)	(0.016)	(0.040)
isLeaker	0.121***	-0.026	0.113***	-0.015
	(0.028)	(0.026)	(0.028)	(0.025)
Observations	673	714	1,161	1,568
Control Group	Deregulated	Deregulated	Eastern	Eastern

*Notes: *, **, *** denote statistical significance at at least the 10, 5, and 1 percent levels, respectively. Robust standard errors, clustered at the plant level, are given in parentheses below the parameter estimates. All specifications account for time effects with a cubic time trend and for price effects non parametrically. "Control Group" describes whether the control group is non-treatment deregulated states ("Deregulated"), or non-treatment plants in the Eastern Interconnection ("Eastern").*

Table 10: Control Variables - Capacity Factor

	(1) NGCC	(2) NGCC	(3) Coal	(4) Coal
lnload	-0.032	0.016	0.519***	0.214***
	(0.068)	(0.074)	(0.064)	(0.069)
lnrenewable	-0.062***	-0.043***	-0.036**	-0.021
	(0.016)	(0.016)	(0.014)	(0.014)
year==2005		0.031***		0.009
		(0.008)		(0.006)
year==2006		0.035***		-0.010*
		(0.009)		(0.006)
year==2007		0.063***		-0.000
		(0.011)		(0.007)
year==2008		0.059***		-0.013*
		(0.012)		(0.007)
year==2009		0.089***		-0.073***
		(0.013)		(0.009)
year==2010		0.109***		-0.068***
		(0.015)		(0.011)
year==2011		0.114***		-0.099***
		(0.017)		(0.012)
year==2012		0.188***		-0.164***
		(0.018)		(0.014)
trend	0.161***		-0.053**	
	(0.033)		(0.026)	
trend2	-0.021***		0.008**	
	(0.004)		(0.003)	
trend3	0.001***		-0.000***	
	(0.000)		(0.000)	
noxphase1			0.003	0.006
			(0.020)	(0.019)
noxphase2			0.021	0.025
			(0.016)	(0.015)
noxphase3			-0.004	0.003
			(0.017)	(0.017)
noxphase4			0.180***	0.190***
			(0.044)	(0.044)
noxphase5			0.007	0.011
			(0.017)	(0.017)
so2controlequip			0.008	0.003
			(0.010)	(0.011)
Observations	1,716	1,716	1,930	1,930
Time	Cubic Trend	FE's	Cubic Trend	FE's

*Notes: *, **, *** denote statistical significance at at least the 10, 5, and 1 percent levels, respectively. Robust standard errors, clustered at the plant level, are given in parentheses below the parameter estimates. "Time Trend" denotes the manner in which time effects are accounted for where "Cubic" means a cubic time trend was included and "FE's" mean the model includes year fixed effects.*

Table 11: Control Variables - Heat Rate

	(1)	(2)	(3)	(4)
	NGCC	NGCC	Coal	Coal
cap_factor_annual	0.443	0.164	-0.502**	-0.636*
	(0.429)	(0.328)	(0.213)	(0.336)
coal_gas	-0.689	-0.127	-0.476	-0.495
	(1.496)	(1.369)	(0.592)	(0.661)
coal_gas2	3.960	0.552	2.801	3.388
	(9.704)	(9.037)	(3.443)	(3.880)
coal_gas3	-10.867	-2.589	-8.565	-10.281
	(31.140)	(29.478)	(9.811)	(11.100)
coal_gas4	15.556	6.427	13.643	15.800
	(54.644)	(52.273)	(14.892)	(16.815)
coal_gas5	-13.574	-9.137	-11.761	-13.181
	(53.293)	(51.159)	(12.328)	(13.892)
coal_gas6	7.154	6.585	5.179	5.671
	(26.888)	(25.798)	(5.236)	(5.897)
coal_gas7	-1.668	-1.792	-0.909	-0.981
	(5.442)	(5.211)	(0.890)	(1.003)
lnrenewable	0.016	0.005	0.000	0.001
	(0.018)	(0.015)	(0.006)	(0.007)
trend==5		0.000		0.012
		(0.015)		(0.008)
trend==6		0.023		0.004
		(0.015)		(0.006)
trend==7		0.014		0.016**
		(0.021)		(0.007)
trend==8		0.021		0.013**
		(0.018)		(0.005)
trend==9		0.046**		-0.013
		(0.019)		(0.013)
trend==10		0.034		-0.013
		(0.023)		(0.012)
trend==11		0.027		-0.019
		(0.021)		(0.017)
trend==12		0.018		-0.023
		(0.034)		(0.019)
trend	-0.060		0.045**	
	(0.079)		(0.022)	
trend2	0.010		-0.005*	
	(0.010)		(0.003)	
trend3	-0.000		0.000	
	(0.000)		(0.000)	
noxphase1			0.019*	0.019*
			(0.010)	(0.011)
noxphase2			0.022*	0.025*
			(0.012)	(0.015)
noxphase3			0.022**	0.022*
			(0.011)	(0.013)
noxphase4			0.090	0.118
			(0.058)	(0.082)
noxphase5			0.024**	0.025**
			(0.011)	(0.012)
so2controlequip			0.008	0.006
			(0.007)	(0.009)
Observations	2,069	2,069	2,263	2,263
Time	Cubic Trend	FE's	Cubic Trend	FE's

*Notes: *, **, *** denote statistical significance at at least the 10, 5, and 1 percent levels, respectively. Robust standard errors, clustered at the plant level, are given in parentheses below the parameter estimates. "Time Trend" denotes the manner in which time effects are accounted for where "Cubic" means a cubic time trend was included and "FE's" mean the model includes year fixed effects.*