Cap-and-trade, clean energy, and negative leakage: State-level evidence from the Regional Greenhouse Gas Initiative*

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Abstract

In this study I examine how the Regional Greenhouse Gas Initiative (RGGI) impacts long-term clean energy production. While prior work on RGGI has examined emission leakage, wherein a cap on emissions in one region leads to increased generation in another region, this paper focuses on clean energy production and explores the possibility of negative leakage. Negative leakage in this paper refers to a positive externality in which an emission cap may lead to a reduction in emissions beyond the geographic boundaries of regulation. I perform a state-level difference-in-difference analysis of generation data from 2001 to 2023 to determine the relationship between the implementation of RGGI and energy production. I categorize states as RGGI, leaker, or control and separately estimate the treatment effects of RGGI implementation on solar, wind, natural gas, and coal energy generation. RGGI implementation is associated with a substantial increase in solar energy generation in RGGI and leaker states, but the near absence of solar energy producers in these states prior to the implementation of the cap means the results offer limited causal insight. RGGI is also associated with a positive but not statistically significant increase in wind energy production in RGGI and leaker states. Coal and natural gas production both decrease in RGGI states, with leakage occurring in the form of increased natural gas production in leaker states.

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1 Introduction

RGGI is a market-based emissions reduction (cap-and-trade) program that was announced in 2005 and includes a handful of states in the northeast. RGGI establishes a regional cap on carbon emissions and issues a limited number of carbon allowances, each of which authorizes the emission of one ton of carbon dioxide. Emission leakage occurs when regulations aimed at reducing greenhouse gas emissions in a region increase emissions in a neighboring region. Leakage generally reduces the overall effectiveness of a regulation. My thesis seeks to investigate the possibility of negative leakage, wherein carbon emissions may decrease beyond the geographic and quantitative boundaries of a cap. This may occur through market forces, such that increased demand for energy is met by clean energy infrastructure development, since renewable energy plants tend to have a lower average cost than fossil-fuel plants. Negative leakage may also occur through the "abatement resource effect" as identified by Baylis, Fullerton, and Karney. The abatement resource effect suggests that if RGGI states drive increased demand for cleaner energy, substitution away from carbon-intensive energy production might shrink the sector overall. This study will observe energy production focusing specifically on clean energy. Although increased clean energy production across state lines is effectively the opposite of leakage in the traditional sense, it can be studied using a similar methodology.

The Regional Greenhouse Gas Initiative is one of several cap-and-trade programs worldwide. The European Union Emissions Trading System (EU ETS), implemented in 2005, is the world's first and largest greenhouse gas-focused cap-and-trade program, as well as the first cap-and-trade program, carbon-focused or otherwise, to be implemented internationally. Similar to RGGI, the EU ETS takes a phased approach, tightening its cap over time. Although the EU ETS covers over ten times as much emissions as RGGI does [1] and, unlike RGGI, covers multiple sectors, results of the EU ETS can help shape expectations for other climate-focused cap-and-trade programs. In their extensive review of the EU ETS, Colmer et al. (2020) observed significant emissions reduction and little evidence of carbon leakage.

[1] In 2024, the EU ETS covered 1.1 billion tons of CO_2 emissions. RGGI allocated 69.4 million carbon allowances, each corresponding to one metric ton of CO_2, totalling only 69.4 million tons, or about 6% the amount covered by the EU ETS.

They found that firms responded to carbon pricing by investing in clean energy technology. This firm-level evidence provides valuable context for understanding the potential for leakage in a cap-and-trade program.

The study most relevant to this project is "Leakage in regional environmental policy: The case of the regional greenhouse gas initiative" by Harrison Fell and Peter Maniloff which examines whether RGGI leads to emissions leakage based on the change in capacity factors[2] of individual plants. It finds that emission leakage occurs in the form of substitution toward leaker states increasing natural gas production, which is significantly less emission-intensive than coal production. This follows the line of reasoning that, among other drawbacks[3], coal is much more resource-constrained than natural gas, so coal plants are generally more expensive to operate. The study does not observe a switch from coal to natural gas within RGGI states as might be expected. Fell and Maniloff identify three types of firms: 1) Firms in RGGI states, 2) firms in leaker states Pennsylvania and Ohio, where the infrastructure enables cost-effective transmission into RGGI states, and 3) control states, which are purported not to be impacted by RGGI at all. These variable categories form the empirical basis of my study, as having a control group is necessary to understand leakage or negative leakage without spillover effects.

Much of the literature referenced in this work is conducted at the firm-level and often looks at capacity factors. While this is ideal for dispatchable fuels like coal and natural gas, capacity factors do not provide valuable information about solar and wind production since these plants produce proportionally to the amount of sun or wind available respectively. As such, this study focuses on solar and wind energy production aggregated at the state level, which accounts for the entry of new generators into the market.

Fell and Maniloff calculated that RGGI resulted in a net decrease of 4.3 million tons of CO_2 emissions, with the gross 8.8 million ton decrease being offset by 4.5 million tons of leakage in Pennsylvania and Ohio. The question remains whether this net decrease may be even greater or growing due to negative leakage, as ignoring negative leakage might lead

[2]For a given period of time, capacity factor is equal to a plant's total generation divided by the amount it is capable of producing at full capacity.

[3]These drawbacks are discussed in Section 4: Energy Production in the United States

to the overestimation of leakage. No previous studies appear to consider the possibility of negative leakage under RGGI. My study is an introduction to the possibility of negative leakage, with the intention that the concept be incorporated into future studies of emission reduction programs.

This study focuses on solar and wind energy as fuels of interest, and not hydropower or nuclear energy. This is because solar and wind power are scalable and productive at the margin, whereas hydroelectric expansion is limited by geographic constraints and necessitates substantial, upfront investments that cannot be scaled down (one cannot construct a fraction of a dam to meet capacity needs). Nuclear energy, while low-emission, faces similar barriers to hydropower. Although solar and wind plants, like all power generators, are subject to multi-year implementation lags[4], they remain suitable technologies for analyzing the response of clean energy to emission regulation.

I examine solar and wind production from 2001 to 2023 aggregated at the state level. I conduct a difference-in-difference analysis comparing net generation in leaker states and RGGI states to net generation in control states before and after the cap to determine whether the implementation of a cap is associated with a change in energy production. I find that RGGI is associated with an increase in wind energy production in leaker and RGGI states relative to control states, but this result is not statistically significant. I also find that RGGI is associated with a 392% increase in solar energy production in RGGI states and a 226% increase in solar energy production in leaker states; however, these results can be attributed to the fact that there were no commercial solar generators in RGGI or leaker states prior to 2007, just two years before RGGI was implemented.

[4]Implementation lags are discussed in greater detail in Sections 5.3 and 8.2

2 Conceptual framework

2.1 Energy Substitution

Economic theory tells us that carbon pricing will shift demand in the PJM[5] auction toward the least-cost alternative, non-regulated energy sources[6], but it doesn't predict which types of energy will see the greatest increase—that's something we need to determine empirically. To elucidate these predictions, I will present the theoretical and highly simplified supply and demand functions for different energy sources. In the context of RGGI, electricity generation can be placed into categories:

1. **Within-RGGI dirty energy:** This carbon-intensive energy production falls within the boundaries of the cap. It is the only category of energy production that is explicitly regulated. The upward sloping supply function for regulated energy production becomes vertical at the point of the fixed, maximum quantity cap.

2. **All Other Energy:** All other energy (AOE) includes all energy production outside of RGGI boundaries. Intuitively, AOE should experience a positive demand shock upon the implementation of RGGI. It is ambiguous, however, what categories of AOE will experience what share of this shock. Clarifying this ambiguity through empirical research is key to understanding the extent to which leakage or negative leakage occur as a result of RGGI.

    (a) **Within-RGGI clean energy:** One key expected outcome of RGGI is ostensibly to increase the production of clean energy within the regulatory boundaries. **A positive demand shock for this category is the intended effect of RGGI.**

    (b) **Non-RGGI dirty energy:** Emission-intensive energy produced in leaker states, states that can easily transmit to RGGI states, are not bound by the regulation.

[5]The PJM (originally Pennsylvania-New Jersey-Maryland) Interconnection is a regional transmission organization that coordinates electricity movement across the eastern United States.

[6]Non-regulated fuels are only least-cost alternatives within the electricity grid. Higher electricity prices might lead consumers to replace electric heaters, powered by different fuel types across the electricity grid, with a natural gas heater independent of the electricity grid. This concept is clarified in Section 5.3.

A positive demand shock for this category constitutes emissions leakage, wherein a cap on emissions leads to increased emissions elsewhere.

(c) **Non-RGGI clean energy:** If clean energy produced in leaker states experiences a positive demand shock fueled by RGGI states, **we may see an expansion of clean energy infrastructure that results in negative emissions leakage**, a decrease in emissions beyond the cap.

A notable distinction between the supply functions of dirty and clean energy is that coal and natural gas plants have relatively upward sloping marginal cost curves, since they have significant operating costs and their marginal cost increases as their output increases. Solar and wind farms, which have no fuel input cost, have relatively flat marginal cost curves. While there is a significant fixed cost to building a renewable energy plant, the operating costs are close to zero. A solar plant produces a quantity of energy roughly proportional to the amount of sun that is available. That is to say, a demand shock is unlikely to change the output of a solar farm in the short run, but in the long run, more solar farms may enter the market. To see whether RGGI incentivizes an increase in the supply of clean energy, I look at long-term data at the state level. In this way, I account for changes in clean energy, including generation by plants that may enter or exit the market in the long-run and estimate the extent to which clean energy production is stimulated by the RGGI demand shock.

2.2 Negative Leakage

In this paper, the term "negative leakage" refers to a reduction in emissions or an increase in clean energy production in non-regulated regions as an indirect result of a cap-and-trade program. Negative leakage can be considered a "positive" externality of regulation. This is a variation on the Baylis et. al. definition of negative leakage, where substitution away from carbon in regulated areas causes shrinkage in the carbon-intensive sector at large, even outside of the regulated area. It is unlikely that decreasing coal, oil, or natural gas dispatch in RGGI states would have any impact on wider high emission energy production.

Rather, I suspect that negative leakage might occur as a result of a shift away from the regulated energy toward alternative sources. Since solar and wind energy are rapidly proliferating, partly because of their cost-effectiveness, it is reasonable to suspect that a shift in demand for alternative energy could incentivize solar and wind firms to enter the market, leading to negative leakage.

3 Policy Background

3.1 Carbon Abatement strategies

In the absence of government intervention, the private sector need not respond to the externalities posed by greenhouse gas emissions, including costs to human welfare and the environment. That is, emitters do not account for the social cost of carbon, the marginal cost to society of each ton of carbon dioxide emitted. Without intervention, the market does not operate at the equilibrium point of production determined by accounting for the social marginal cost of emissions. When the private sector fails to internalize an externality, the government can act in three ways:

1. **Quantity-based Instruments:** In the short run, a quantity cap ensures that the market immediately operates efficiently considering the social marginal cost of carbon emissions. However, the price of energy production will increase due to the limited supply and the government will not accumulate any revenue. In the long run, firms face an incentive to innovate to reduce emissions until the quantity cap is reached, but no incentive to innovate further. A quantity cap is not sensitive to supply shocks, leading to deadweight loss.

2. **Price-based Instruments:** A government can regulate emissions through a Peguvian tax or subsidy. In the short run, the demand for energy is inelastic, so there will not be much substitution away from electrical energy usage. Substitution between high-carbon and low-carbon forms of energy production in the electricity grid is minimal in the short run, since it takes time for power generators to enter the market.

This means both the amount of energy consumed and carbon emitted are expected to remain stable in the short run. During this time, the government will accumulate tax revenue. In the long run, however, households may be incentivized to substitute away from reliance on the power grid, for example choosing a natural gas water heater over an electrical one. In regional transmission organizations like PJM, substitution between high-carbon and low-carbon methods of energy production becomes elastic during this time, and it is likely that clean energy producers will enter the market, causing a reduction in overall emissions, hopefully toward the equilibrium point of production.

3. **Cap and Trade:** Cap-and-trade emerged from Coasean theory in the 1960's, was first put into practice in the 1980's and 1990's, and matured into a global climate policy tool by the 2000's. A regulating body places a quantity cap on emissions and issues tradable emissions allowances, essentially assigning property rights to a public good, in this case the atmosphere. Put simply, an emissions allowance is a license to pollute. These allowances are either allocated freely (grandfathered) or auctioned off and then traded, ensuring that abatement occurs where it is most cost-efficient. In other words, allowances are allocated to the firms that have the highest need to emit. Allowances are granted in a uniform price auction, where the price and quantity of emissions sold is determined by the intersection of the government-determined supply curve and the demand curve based on prices posed at the auction.

3.2 History of RGGI

In 2003, Governors from Connecticut, Delaware, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont first considered a regional cap-and-trade program. In 2005, these governors, with the exception of those from Massachusetts and Rhode Island, signed the Memorandum of Understanding (MOU), officially agreeing to implement RGGI. Massachusetts and Rhode Island later signed on to the MOU as well. Each RGGI state implements a CO_2 budget trading program based on the RGGI Model

Rule, which is the standardized template developed by participating states. Legally, each state maintains control over RGGI implementation. Operationally, however, the states participate in a single regional carbon market where allowances are tradable across states. A state's carbon cap determines the number of allowances it consigns to the regional auction, and the state receives the revenue for the allowances it auctions off. RGGI began its first implementation period on January 1, 2009. New Jersey withdrew in 2011 and resumed participation in 2020. Virginia joined RGGI in 2021 but withdrew in 2023. A Virginia judge ruled that the withdrawal was unconstitutional in 2024, but the return to RGGI has been delayed due to the Virginia Governor's appeal. Pennsylvania joined RGGI in 2022, but has been enjoined from participation pending a ruling by its state supreme court.

3.3 Mechanics of RGGI

RGGI requires that electric power generators with a capacity of 25 megawatts or greater must hold allowances corresponding to their carbon emissions. Allowances can be allocated for free or purchased through the regional auction or secondary markets. A carbon allowance represents one ton of CO_2 emissions.

In 2025, the RGGI cap was 151,879,674 allowances and the adjusted cap was 137,118,499 allowances. The cap has gradually tightened over time, with the most dramatic tightening taking place in 2014, where the cap was reduced from 165 million allowances to 91 million allowances[7]. Prior to this reduction, RGGI permits were arguably overallocated, and carbon producers faced little incentive to decrease emissions other than anticipatory pressures. As such, it is critical to examine net generation not just upon implementation of RGGI but also before, during, and after the cap tightening in 2014.

3.4 Companion Policies

Companion policies, such as renewable portfolio standards and energy efficiency programs, are usually passed along with the adoption of RGGI. Although these policies can reduce emissions locally, they can also lead to the waterbed effect, wherein increased carbon

[7] 82,702,336 allowances, adjusted

efficiency decreases demand for emission allowances, lowering allowance prices and yielding no net reduction. The Emissions Containment Reserve aims to mitigate this issue by adjusting the allowance supply in response to a decrease in prices. While companion policies can encourage emissions reductions, they can paradoxically weaken the effectiveness of cap-and-trade if not properly accounted for.

4 Energy Production in the United States

EIA data demonstrate that among certain energy types of primary focus, mainly coal, solar, and wind, there are notable instances of entry and exit. Specifically, no solar plants existed in RGGI or leaker states prior to 2007, and there has been significant entry of solar and wind plants across the United States. Coal plants across the United States have been shutting down due to the supremacy of natural gas, the decreasing cost of renewable energy, aging infrastructure, policy pressures, and inefficiency relative to their market clearing dispatch price[8].

Coal generation has also been steadily declining since 2008 when the Great Recession, which decreased industrial production and electricity demand, coincided with the shale gas boom which caused significant growth in natural gas reserves. These simultaneous events resulted in a negative shock to the demand for coal generation. A decline in coal generation is not always a result of coal plants shutting down, but instead often means that a coal plant is producing less relative to its total factor production, meaning its capacity factor is declining due to decreased demand.

Unlike dispatchable fuels like coal and natural gas, an increase in solar, wind, or hydro energy production usually necessitates the entry of new generators, since these plants produce roughly proportionally to the amount of sun, wind, or waterflow available respectively. As we see in Figure 3, solar energy generation has been steadily and dramatically increasing across the United States since the time RGGI was implemented. We see in Figure 4 that wind generation, while not increasing as dramatically as solar generation, is still trending

[8]When coal plants operate at a lower capacity factor, their average costs are often prohibitively high due to fixed costs.

upward. Wind generation, notably, has occupied a significant position in the energy grid for longer than solar generation has.

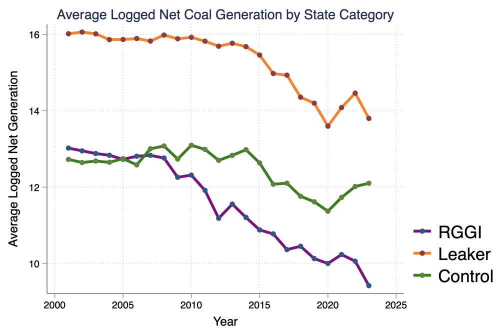

Figure 1: Coal generation

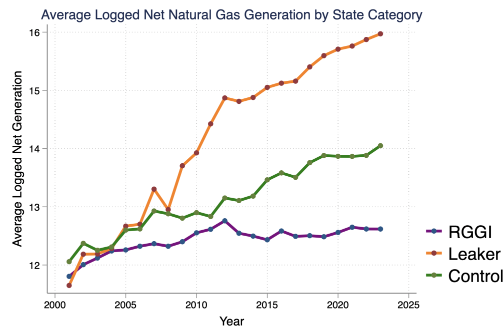

Figure 2: Natural Gas Generation

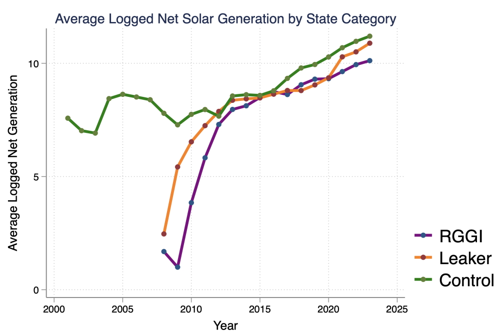

Figure 3: Solar generation

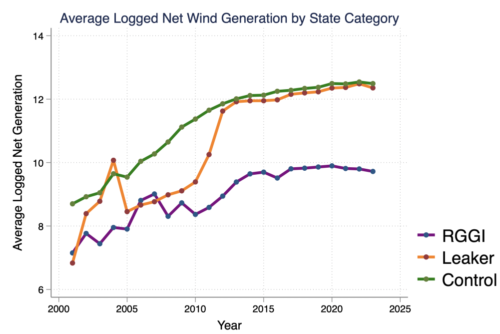

Figure 4: Wind generation

5 Production Analysis

5.1 Defining State Types

RGGI is made up of the nine consistent members: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont. As discussed in Section 3.2, New Jersey, Virginia, and Pennsylvania are important edge cases.

Pennsylvania and Ohio are likely leaker states based on the connectivity of their electricity grids to RGGI states. These states are part of the PJM interconnection, and their primary interfaces to transmit energy into the RGGI region enter RGGI through New York, based on findings by Fell and Maniloff. All other states are designated as the control group.

5.2 Difference-in-difference Framework

The study estimates the impact of RGGI on net generation. Specifically, does a state being a leaker or RGGI state make it more likely to experience a change in either clean or dirty energy production relative to a control state after the implementation of RGGI?

In the model below, I classify firms into three categories: **1) RGGI states, 2) leaker states, and 3) control states**, to estimate how energy production by a given fuel (solar, wind, natural gas, or coal) changes in a given state i at a given time t (before or after the implementation of RGGI). The model absorbs state and year fixed effects, in order to control for state and time-specific variations respectively. Possible confounding factors are natural gas prices, which vary across years due to market fluctuations, and heating and cooling degree days, which vary across states due to differences in climate. Standard errors are clustered at the state level to account for arbitrary correlation of error terms within states.

$$\log(\text{NetGen}_{st}) = \beta_1 \cdot \text{RGGI}_s \times \text{Post}_t + \beta_2 \cdot \text{Leaker}_s \times \text{Post}_t + \alpha_s + \gamma_t + \varepsilon_{st} \tag{1}$$

Where:

- $\log(\text{NetGen}_{st})$ is the natural log of aggregate net generation in state s at time t.
- $\text{RGGI}_s \times \text{Post}_t$ is an interaction term indicating whether the plant is in an RGGI state post-policy.
- $\text{Leaker}_s \times \text{Post}_s$ is an interaction term for leaker states post-policy.
- α_s are state fixed effects.
- γ_t are year fixed effects.

- ε_{st} is the error term, clustered at the state level.

I separately analyze each plant type of interest WND (wind), SUN (solar), NG (natural gas), and COL/BIT (coal). Using a difference-in-difference framework, the model estimates the causal impact of RGGI on aggregate clean energy production of a respective category (hydropower, wind, or solar) in RGGI and leaker states, relative to control states.

For a regression run for a given fuel type, a statistically significant, positive coefficient on β_1 indicates that the implementation of RGGI is associated with larger energy production increase by that fuel type in RGGI states than in control states. A similar coefficient on β_2 would indicate that the implementation of RGGI is associated with a higher solar energy production increase for leaker states than for control states. If β_2 has a positive coefficient when running a regression for a clean fuel, and causal inference assumptions are satisfied, this is evidence of negative leakage.

5.3 Identification Assumptions

This analysis relies on a set of assumptions to isolate the research question and ensure tractability.

1. I assume that under a binding emissions cap, demand for electricity is inelastic and there is very low substitution between electric and non-electric appliances. This is a significant assumption, because, in the long-run, rising electricity prices incentivize consumers to shift away from electricity usage. For example, higher electricity prices may compel a homeowner to prefer a natural gas water heater over an electric one, which would increase fossil fuel usage without reflecting on industrial energy production data.

2. I qualitatively consider the effects of companion policies that are passed in RGGI states, but do not control for each one econometrically. Companion policies can mitigate emissions leakage and enhance overall emissions reductions; however, they may also inadvertently decrease pressures to reduce emissions due to the waterbed effect.

As such, I cannot easily anticipate or control for their impact, and move forward with the assumption that they are minimally effective.

3. The difference-in-difference methodology relies on the parallel trends assumption, which requires that, in the absence of RGGI, energy production trends in RGGI, leaker, and control states would have evolved similarly. I assess the parallel trends assumption for wind energy through an event study. I also visualize average production levels by energy type over time to identify any differential pre-RGGI trends that could violate this assumption. Based on data tabulation and event studies, I cannot infer causality in our study of solar energy production, since there was no solar energy produced in RGGI or Leaker states until 2007.

4. Before a new energy plant enters the PJM, project developers must first enter a queue for a period of around five years, and will not decide whether to build until they receive an estimate of anticipated costs from the PJM two years after their original submission. While there is some anticipation of future actions by RGGI, many changes in generation will likely be observable some years after a RGGI action. For the purposes of this analysis, I assume some difference is observable at the time of implementation.

6 Results

I run regressions using state-level energy production data. The results show the relationship between RGGI implementation (and the 2014 cap reduction), and net generation in RGGI states and leaker states relative to control states.

Table 1: Effect of RGGI on Net Generation by Fuel Type

Fuel	**RGGI (With Spillover)**	**Leaker (With Spillover)**	**RGGI (No Spillover)**
Wind	0.1298	0.5302	0.1363
	(0.3348)	(0.6552)	(0.3361)
Solar	3.9247***	2.2646***	3.9247***
	(0.4603)	(0.4603)	(0.4605)
Natural Gas	-0.6697**	1.5400***	-0.6697**
	(0.2706)	(0.3529)	(0.2707)
Coal	-1.1054***	-0.0927	-1.1029***
	(0.3159)	(0.3058)	(0.3155)

Note: Standard errors in parentheses. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

I find a 13% and 53% increase in wind energy production associated with RGGI implementation in RGGI and leaker states respectively relative to control states, but these results are not statistically significant. Since wind energy is rapidly expanding across the United States, it is not surprising that there is not a significant difference between treatment and control states in the change in wind energy production after RGGI. I find a 392% and 226% increase in solar energy production in RGGI and leaker states respectively. These results are statistically significant at the $p < 0.01$ level. However, these results can be attributed to the complete absence of solar plants in RGGI or leaker states prior to 2007. Due to the scarcity of pre-treatment data, the parallel trend assumption is not met and therefore I cannot make a causal inference about RGGI's impact on solar energy. If parallel trends were satisfied and results were statistically significant, an increase in clean energy production in leaker states would strongly suggest the presence of negative leakage.

As expected, both natural gas and coal production decrease in RGGI states relative to control states. Generation by coal plants slightly decreases in leaker states, while generation by natural gas, which is a relatively low-emission fuel compared to coal, increases. So, while there is no evidence of leakage in the form of increased coal production, there is evidence of leakage in the form of increased natural gas production in leaker states.

Table 2: Effect of 2014 RGGI Cap Reduction on Net Generation by Fuel Type

Fuel	**RGGI Coefficient**	**Leaker Coefficient**
Wind	0.4917	0.8257
	(0.3178)	(0.8535)
Solar	0.2412	-1.3625***
	(0.8381)	(0.3343)
Natural Gas	-0.7064**	1.2124***
	(0.2699)	(0.3576)
Coal	-1.1052***	-0.1545
	(0.3091)	(0.3875)

Note: Standard errors in parentheses. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Similar to the the 2009 implementation of RGGI, the 2014 cap reduction is associated with a 49% and 83% increase in wind production in RGGI and leaker states respectively relative to control states, but these results are not statistically significant. The cap reduction is associated with a 24% increase in solar energy production in RGGI state, but not at any serious level of significance. This statistic may be more informative than the 2009 statistic, since there were five years additional years to establish pre-treatment trends in solar production, and the reduced cap is much more likely to impact demand.

Interestingly, the 2014 tightening of the cap is associated with a statistically significant 136% decrease in solar energy production in leaker states. This is contrary to what might be expected if leaker states were expecting an increased demand for energy from RGGI states.

As with the original implementation of RGGI, the 2014 cap reduction is associated with a decrease in natural gas and coal production in RGGI states. Once again, there is no leakage in the form of coal production, and coal production decreases in leaker states in 2014 as in 2009. Further investigation is necessary to investigate whether this could be an instance of the Baylis et. al. definition of negative leakage, where a carbon-intensive sector shrinks as a whole due to regulation. However, given the decline of coal energy as described in Section 4, this seems unlikely. As with 2009, the 2014 cap reduction is associated with leakage in the form of increased natural gas production.

As discussed in Sections 5.3 and 8.3, the effects of RGGI regulations are scattered due to the amount of time a generator spends in the PJM queue, although the 2014 cap tightening was anticipated in the years preceding it. Rigorous event study of this cap in the future may prove fruitful.

Table 3: Effect of RGGI on Solar Energy Production (log net generation)

	Coefficient	Std. Error	t-stat	95% CI
RGGI State × Post-RGGI	3.9247	0.4603	8.53	[2.9993, 4.8501]
Leaker State × Post-RGGI	2.2646	0.4603	4.92	[1.3392, 3.1900]
Constant	8.5027	0.1074	78.77	[8.2857, 8.7198]
Observations		6,460		
Clusters (State)		49		
R-squared		0.8117		
Adjusted R-squared		0.8096		
Fixed Effects		State, Year		

7 Discussion

7.1 Takeaways

Since solar energy experienced massive growth at the same time as the initial implementation of RGGI, detailed study of carbon pricing and cap reduction across time will be necessary to search for conclusive signs of negative leakage. There is no existing data that could establish a causal relationship in a difference-in-difference model for solar production where the treatment year is 2009 (the year of RGGI implementation) because solar production does not date back far enough to establish pre-trends. Based on visual investigation, it appears that while solar energy production spiked in RGGI and leaker states around the time of RGGI implementation, production trends for RGGI, leaker, and control states begin to converge soon after.

Parallel pretreatment trends are similarly hard to establish for wind energy generation, although production rates appear to have leveled out as wind energy has gained popularity. The impact of any future regulations on clean energy production will be much more readily available now that solar and wind energy have entered the market at a large scale.

While my results do not provide causal evidence for negative leakage, they also largely do not present any evidence to the contrary. A notable exception to this is the negative relationship between the 2014 cap reduction and solar energy generation in leaker states. The tightening of the RGGI cap in 2014 was associated with a statistically significant 136% decrease in solar energy generation in leaker states relative to control states. This outcome begs further research.

Overall, RGGI is associated with decreased production of coal and natural gas energy, with evidence of leakage in the form of increased natural gas production in leaker states. That is to say, coal generation is on the decline nationwide while natural gas, solar, and wind generation grow.

7.2 Limitations

In order to understand and qualify these results, we must consider the delayed response of energy generation. This delay can be around five years, unless regulations are previously anticipated, in which case it may be shorter. In addition to these delays, we must consider non-RGGI factors that can impact clean energy generation, including federal tax credit policies, which may make renewable energy more profitable around the same time regulations of interest are passed. For instance, the anomalous result of decreased solar generation in leaker states in response to the 2014 cap tightening could be related to any number of occurrences five years before, including a shifting policy environment toward the end of the 2000's. Dynamics and concurrent events are critical to determining methodology and interpreting results.

Furthermore, although I designate Pennsylvania and Ohio to be leaker states, and hope to accommodate most leakage through this designation, it is important to mention that Illinois contributes greatly to wind generation in PJM, as does Indiana to solar generation. Future studies might benefit from considering these states, which were designated as control states in my methodology.

8 Future Work

8.1 Financial Transmission Rights

Financial transmission rights (FTRs) are a financial instrument auctioned off in energy markets including PJM. FTRs hedge against high transmission costs, which occur when the line of transmission between two nodes of energy production is overly congested. The owner of an FTR is entitled to the difference in locational marginal price between two locations on the transmission grid. FTRs can be used as a measure of congestion. Specifically, future work could aim to understand whether the implementation of RGGI caused an increase in congestion expectations in principal power lines across state lines. This could help explain the transmission economics behind where new energy produced is being allocated, and the extent to which new plants might continue to supply energy across the RGGI boundary.

8.2 PJM Queue Applications

Any developers hoping to add a new plant to the PJM Interconnection must remain in a queue for around five years. Two years into this waiting period, the PJM will give project developers an estimate of the infrastructure costs necessary to support the project. As these costs can vary greatly based on plant type, size, and grid location, a developer may then decide not to go through with the construction.

Examining the PJM queue will be necessary to understand market response to cap-and-trade policy. Compounding factors threaten any conclusions based solely on generation. Most important among these factors are staggered and delayed responses preventing the precise examination of any treatment date. There is also value in investigating trends in new interconnection requests for energy projects, even for those plants eventually not built due to anticipated costs. For this reason, announced investments in solar and wind energy as well as the rate at which firms enter the PJM queue should be foundational in future causal studies of RGGI. PJM queue data is available for use in such a study.

9 Data Overview

The data used in this analysis is sourced from the U.S. Energy Information Administration, specifically page 1 on files from each year labeled `EIA923_Schedules_2_3_4_5`. The EIA-923 schedules can found at `www.eia.gov/electricity/data/eia923/`. There are slight variations in naming and data collection conventions from year to year.

10 Bibliography

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11 Appendix

11.1 State Categories

RGGI	**Leaker**	**Control**
Connecticut (CT)	Pennsylvania (PA)	Alabama (AL)
Delaware (DE)	Ohio (OH)	Alaska (AK)
Maine (ME)		Arizona (AZ)
Maryland (MD)		Arkansas (AR)
Massachusetts (MA)		California (CA)
New Hampshire (NH)		Colorado (CO)
New York (NY)		Florida (FL)
Rhode Island (RI)		Georgia (GA)
Vermont (VT)		Hawaii (HI)
		Idaho (ID)
		Illinois (IL)
		Indiana (IN)
		Iowa (IA)
		Kansas (KS)
		Kentucky (KY)
		Louisiana (LA)
		Michigan (MI)
		Minnesota (MN)
		Mississippi (MS)
		Missouri (MO)
		Montana (MT)
		Nebraska (NE)
		Nevada (NV)
		New Jersey (NJ)
		New Mexico (NM)
		North Carolina (NC)
		North Dakota (ND)
		Oklahoma (OK)
		Oregon (OR)
		South Carolina (SC)
		South Dakota (SD)
		Tennessee (TN)
		Texas (TX)
		Utah (UT)
		Virginia (VA)
		Washington (WA)
		West Virginia (WV)
		Wisconsin (WI)
		Wyoming (WY)

Table 4: Categorization of States as RGGI, Leaker, and Control

11.2 Event Study

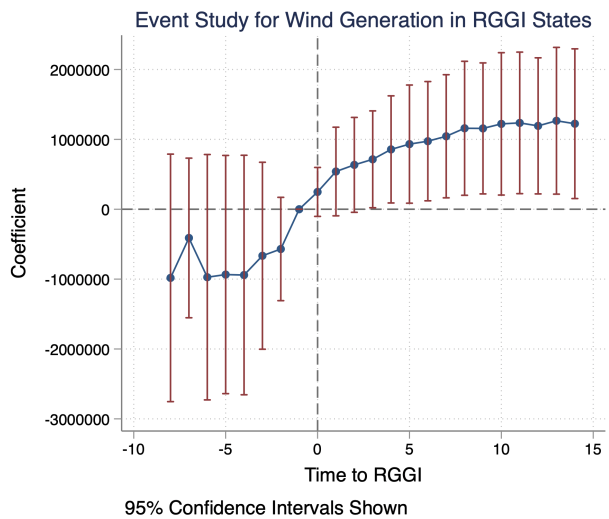

Figure 5: Event Study for Wind Generation in RGGI States

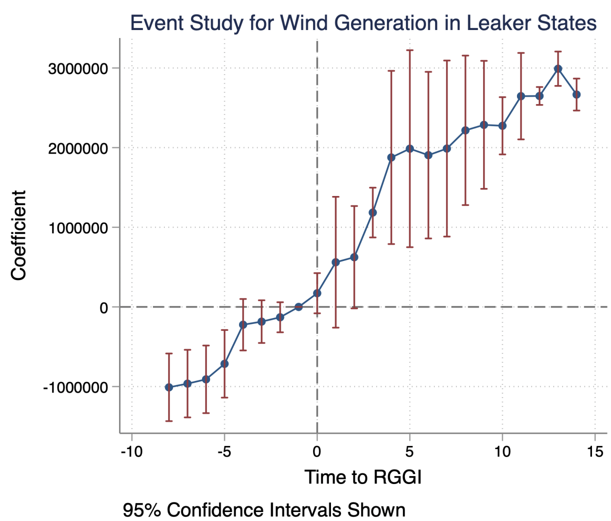

Figure 6: Event Study for Wind Generation in Leaker States

Table 5: Event Study Regression: Wind Generation in RGGI States

Year	**Coefficient**	**t-statistic**	**p-value**	**95% Confidence Interval**
2001	-982474	-1.09	0.284	[-2810215, 845267.3]
2002	-410962.8	-0.71	0.485	[-1589772, 767846.6]
2003	-972795.5	-1.09	0.284	[-2784928, 839337.4]
2004	-934903.7	-1.07	0.289	[-2694017, 824210.1]
2005	-941572.5	-1.08	0.288	[-2710316, 827170.6]
2006	-665781	-0.98	0.335	[-2046393, 714831.3]
2007	-569268	-1.51	0.139	[-1332371, 193835.3]
2009	247687.2	1.39	0.174	[-113701, 609075.4]
2010	539887.1	1.67	0.103	[-114543.2, 1194317]
2011	634842.9	1.83	0.075	[-66048.53, 1335734]
2012	714424	2.02	0.050	[-851.7432, 1429700]
2013	856365.6	2.19	0.035	[65266.11, 1647465]
2014	932137.7	2.16	0.037	[59446.67, 1804829]
2015	973865.7	2.24	0.031	[93067.23, 1854664]
2016	1044321	2.32	0.025	[134952.5, 1953689]
2017	1158512	2.37	0.023	[169047.5, 2147977]
2018	1156663	2.42	0.020	[189183.8, 2124143]
2019	1221747	2.35	0.024	[170521.9, 2272973]
2020	1235738	2.39	0.022	[190485.1, 2280990]
2021	1193230	2.40	0.021	[188316.5, 2198144]
2022	1266167	2.36	0.023	[182441.6, 2349892]
2023	1223976	2.24	0.031	[118399.3, 2329553]

Table 6: Event Study Regression: Wind Generation in Leaker States

Year	Coefficient	t-statistic	p-value	95% Confidence Interval
2001	-1009445	-4.66	0.000	[-1450555, -568335.3]
2002	-962850.8	-4.45	0.000	[-1403960, -521741.1]
2003	-909098	-4.20	0.000	[-1350208, -467988.3]
2004	-714307.1	-3.30	0.002	[-1155417, -273197.5]
2005	-223500	-1.36	0.185	[-559313.8, 112313.8]
2006	-184500	-1.35	0.187	[-462951.7, 93951.68]
2007	-129871.6	-1.35	0.187	[-326096.2, 66352.94]
2009	172196.5	1.34	0.191	[-90121.49, 434514.6]
2010	561049.4	1.34	0.190	[-292644.8, 1414743]
2011	624199.5	1.90	0.066	[-43599.33, 1291998]
2012	1184817	7.43	0.000	[860013, 1509621]
2013	1876717	3.38	0.002	[746803.8, 3006631]
2014	1986820	3.15	0.004	[701507.4, 3272132]
2015	1905586	3.57	0.001	[818449.7, 2992721]
2016	1988537	3.53	0.001	[839864.9, 3137209]
2017	2217308	4.63	0.000	[1242011, 3192605]
2018	2286215	5.58	0.000	[1451124, 3121306]
2019	2274452	12.40	0.000	[1900860, 2648043]
2020	2646419	9.56	0.000	[2082351, 3210486]
2021	2648708	46.23	0.000	[2532011, 2765405]
2022	2990872	27.16	0.000	[2766599, 3215144]
2023	2666568	26.05	0.000	[2458023, 2875113]

11.3 Exploratory Data Visualizations

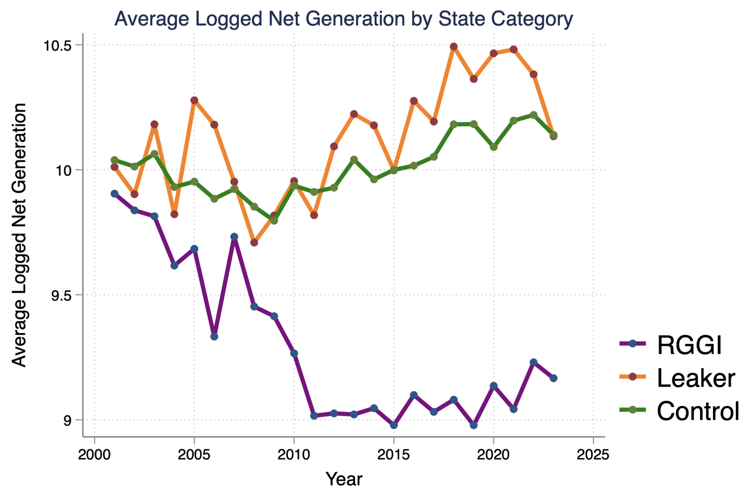

Figure 7: Average Logged Net Generation

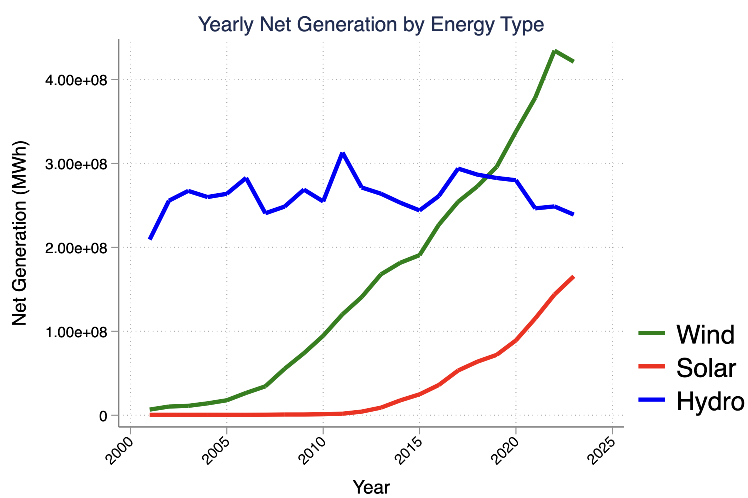

Figure 8: Net Generation by Renewable Fuels

11.4 Detailed Regression Results

Table 7: RGGI Impact on Wind Energy Production (log(Net Generation)) (with Spillover)

Variable	Coefficient	Std. Error	t-Statistic	p-Value	95% Confidence Interval
RGGI X Post	0.1298	0.3348	0.39	0.700	[-0.5464, 0.8060]
Leaker X Post	0.5302	0.6552	0.81	0.423	[-0.7930, 1.8535]
Constant	11.0112	0.0656	167.85	0.000	[10.8787, 11.1437]
F-statistic	0.33			0.7175	
R-squared	0.8857				
Adjusted R-squared	0.8849				

Table 8: RGGI Impact on Wind Energy Production (log(Net Generation)) (without Spillover)

Variable	Coefficient	Std. Error	t-Statistic	p-Value	95% Confidence Interval
RGGI X Post	0.1363	0.3361	0.41	0.687	[-0.5435, 0.8161]
Constant	11.0450	0.0559	197.57	0.000	[10.9319, 11.1581]
F-statistic	0.16			0.6873	
R-squared	0.8908				
Adjusted R-squared	0.8900				

Table 9: RGGI Impact on Solar Energy Production (log(Net Generation)) (with Spillover)

Variable	Coefficient	Std. Error	t-Statistic	p-Value	95% Confidence Interval
RGGI X Post	3.9247	0.4603	8.53	0.000	[2.9993, 4.8501]
Leaker X Post	2.2646	0.4603	4.92	0.000	[1.3392, 3.1900]
Constant	8.5027	0.1079	78.77	0.000	[8.2857, 8.7198]
F-statistic	9.69			0.0003	
R-squared	0.8117				
Adjusted R-squared	0.8096				

Table 10: RGGI Impact on Solar Energy Production (log(Net Generation)) (without Spillover)

Variable	Coefficient	Std. Error	t-Statistic	p-Value	95% Confidence Interval
RGGI X Post	3.9247	0.4605	8.52	0.000	[2.9978, 4.8516]
Constant	8.6319	0.0882	97.85	0.000	[8.4543, 8.8095]
F-statistic	72.64			0.0000	
R-squared	0.8143				
Adjusted R-squared	0.8121				

Table 11: RGGI Impact on Natural Gas Energy Production (log(Net Generation)) (with Spillover)

Variable	Coefficient	Std. Error	t-Statistic	p-Value	95% Confidence Interval
RGGI X Post	-0.6697	0.2706	-2.47	0.017	[-1.2135, -0.1259]
Leaker X Post	1.5400	0.3529	4.36	0.000	[0.8309, 2.2491]
Constant	13.0901	0.0352	371.78	0.000	[13.0193, 13.1608]
F-statistic	15.45			0.0000	
R-squared	0.8789				
Adjusted R-squared	0.8783				

Table 12: RGGI Impact on Natural Gas Energy Production (log(Net Generation)) (without Spillover)

Variable	Coefficient	Std. Error	t-Statistic	p-Value	95% Confidence Interval
RGGI X Post	-0.7064	0.2699	-2.62	0.012	[-1.2487, -0.1641]
Constant	13.0864	0.0335	390.97	0.000	[13.0190, 13.1537]
F-statistic	10.31			0.0002	
R-squared	0.8776				
Adjusted R-squared	0.8770				

Table 13: RGGI Impact on Coal Energy Production (log(Net Generation)) (with Spillover)

Variable	Coefficient	Std. Error	t-Statistic	p-Value	95% Confidence Interval
RGGI X Post	-1.1054	0.3159	-3.50	0.001	[-1.7418, -0.4691]
Leaker X Post	-0.0927	0.3058	-0.30	0.763	[-0.7087, 0.5233]
Constant	12.6544	0.0358	353.70	0.000	[12.5824, 12.7265]
F-statistic	8.90			0.0006	
R-squared	0.8265				
Adjusted R-squared	0.8253				

Table 14: RGGI Impact on Coal Energy Production (log(Net Generation)) (without Spillover)

Variable	Coefficient	Std. Error	t-Statistic	p-Value	95% Confidence Interval
RGGI X Post	-1.1052	0.3091	-3.58	0.001	[-1.7277, -0.4828]
Constant	12.5007	0.0297	420.28	0.000	[12.4407, 12.5607]
F-statistic	12.22			0.0026	
R-squared	0.8146				
Adjusted R-squared	0.8133				

11.5 Notes

For clarity, I have combined observations of coal (COL) and bituminous cole (BIT) production, the latter of which only occurs in 2001. All generation is in megawatt hours (MWh), or one megawatt of energy generated continuously over an hour.