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CO_2 Pricing Pass-Through to Electricity Prices Under Partial Regulations

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Abstract

With climate change becoming a growing concern, carbon trading has gained attention as a key solution to reducing carbon emissions. However, this raises a concern about whether polluters pass the cost of carbon to electricity prices. This study aims to assess the impact of CO_2 pricing on electricity prices in the PJM market where some areas are regulated by carbon trading while others are not. Our findings reveal a significant impact of CO_2 prices across all regulated areas, encompassing both real-time and day-ahead markets. Moreover, the impact extends to non-regulated areas, indicating a spillover effect within the PJM market. Interestingly, the electricity price increase in unregulated areas negatively correlates with their distance to regulated areas. The strongest impact is observed during peak hours. These findings highlight how carbon trading policies affect electricity prices, showing how regulations in one area can influence pricing across the energy market.

1 Introduction

Climate change poses an ever-increasing threat to our planet. This brings global efforts to mitigate carbon emissions and protect the environment. Among different strategies brought to prevent climate change is the implementation of cap-and-trade policies on carbon dioxide (CO_2) emissions which were originally used to regulate sulfur dioxide. This policy sets a cap on CO_2 emissions by assigning a certain number of permits, each allowing some quantity of emissions. Under this system, the government gradually reduces the emissions cap over time, motivating companies to look for renewable energy sources and minimize their carbon emissions. On the one hand, companies that produce higher emissions than their permit allows are taxed and may even be penalized for a violation. On the other hand, companies that reduce their emissions can sell their allowances to those companies that pollute more. This introduces the concept of carbon trading where companies engage in the buying and selling of carbon credits. Companies with renewable sources of energy have extra amounts of credits due to their reduced emission, providing them with the opportunity to sell extra credits to those companies that need additional allowance to meet their emission target.

The Cap-and-Trade policy has its pros and cons. On the positive side, it acts as a powerful incentive for companies to transition towards renewable energy sources as the cost of purchasing extra permits increases annually. Additionally, the government's decision to auction emissions credits to the highest bidder serves as a significant source of revenue. Conversely, critics argue that the adoption of renewable energy sources is expensive, leading companies to choose the purchase of permits and payment of taxes for excess emissions. Moreover, different emissions standards and maximum caps across different regions introduce further complexities, such as areas subject to the policy engaging in electricity trading with non-participating regions, creating a spill-over effect in the energy market. All these things raise concerns over the effectiveness of the cap-and-trade policy.

In the United States, several entities oversee the implementation of cap-and-trade policy. One such entity is the Regional Greenhouse Gas Initiative (RGGI), established in 2009. This initiative involves 11 northeastern states dedicated to reducing CO_2 emissions from power plants. Operating as a cap-and-invest emissions reduction program, it requires polluters to buy allowances equivalent to their emissions. RGGI decreases the regional cap over time which ensures a planned and predictable decrease in CO_2 emissions. Power plants that need to purchase allowances include this cost in their energy market bids, treating it as any other variable operational cost.

RGGI regulates some portion of the Pennsylvania-New Jersey-Maryland (PJM) interconnection, which serves as a central hub for coordinating wholesale electricity movement across 13 states (Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia), along with the District of Columbia. Among these states, Delaware, New Jersey, and Maryland fall under the regulation of RGGI. This unique blend of regulated and unregulated areas within the PJM market makes it an interesting subject for study, particularly in understanding the impact of RGGI on the broader electricity market. Given the presence of both regulated and unregulated areas, energy leakage undermines the effectiveness of the RGGI policy, as generation emissions shift from RGGI states to non-RGGI states within PJM due to PJM's least-cost energy dispatch mechanism. This study focuses on the PJM interconnection to examine the influence of RGGI CO_2 pricing on electricity prices in both regulated and unregulated areas, aiming to identify trends in its impact across various areas in the market.

To fulfill the study's objective, this paper conducts regression analysis on real-time market (RTM) and day-ahead market (DAM) prices within the PJM interconnection spanning from January 1, 2020, to December 31, 2022. We select this time frame due to the rising nature of prices of RGGI CO_2 and Natural Gas. The higher prices of CO_2 and Natural Gas in these years amplifies the impact of these variables on RTM and DAM electricity prices. Figures 1 and 2 illustrate the trend of CO_2 and Natural Gas prices over time, respectively. Notably, the price of CO_2 significantly exceeds the price floor during this period. We also see the similar rising behavior of price for Natural Gas during this period.

Figure 1 and 2

By analyzing the RTM and DAM prices alongside other variables, including RGGI CO_2 prices, this analysis aims to uncover the impact of all variables on prices. The analysis seeks to address the following questions:

1. Does the CO_2 price set by RGGI influence RTM and DAM prices across the regulated

areas in the PJM? A positive and significant impact would indicate the effectiveness of the cap-and-trade policy in transferring the cost of CO_2 emissions to electricity prices.

2. Is the impact of RGGI's CO_2 price significant only for regulated areas within PJM, or does it extend to unregulated areas? A positive and significant result across the entire PJM market would suggest RGGI's impact on both regulated and unregulated areas, implying a spill-over effect in the energy market.

3. Does the regression coefficient of RGGI's CO_2 price vary by time of the day for RTM and DAM prices? Varying coefficients would reflect peak periods of non-renewable energy use and subsequent CO_2 emissions in electricity generation.

4. Is there a correlation between the regression coefficient for RGGI's CO_2 prices and the average distance of unregulated areas from regulated areas within PJM? An increasing coefficient with a decreasing average distance would mean a heterogeneous nature of the spill-over effect on electricity prices due to partial regulation in the PJM market.

We summarize our findings to answer the above-mentioned questions. Firstly, our analysis reveals a significant and positive regression coefficient for the RGGI CO_2 price across the regulated areas in PJM market for both real-time market (RTM) and day-ahead market (DAM) electricity prices. This outcome supports the efficiency of the cap-and-trade policy within the regulated areas in the PJM market. The findings suggest the continued use of the cap-and-trade program as a means to advance decarbonization objectives.

Secondly, our regression analysis shows the significant and positive impact of RGGI CO_2 pricing on the entire PJM Real-Time and Day-Ahead electricity market prices. Furthermore, the coefficient of RGGI CO_2 pricing is positive and significant at 5% level for all the pricing nodes in different periods for RTM and DAM. This result supports the broad influence of the CO_2 pricing in the PJM market suggesting a spill-over effect.

Thirdly, the coefficient for RGGI's CO_2 price in our regression analysis shows a notably higher magnitude during the 06:00-10:00 period throughout the day. Moreover, we observe that the coefficient for the Day-Ahead Market consistently remains lower than that for the Real-Time Market across all periods of the day. This variation in coefficients reflects the peak periods of non-renewable energy utilization and consequent CO_2 emissions in electricity generation.

Finally, our analysis reveals a negative correlation between the regression coefficient of CO_2 price and the distance of unregulated areas from regulated areas within PJM. As the average distance of unregulated areas increases from regulated areas, the impact of CO_2 pricing decreases. This finding supports the heterogeneous nature of the spill-over effect in the PJM electricity market.

Although the effectiveness of RGGI has been studied in the literature [1–3], its impact on electricity prices are still under-explored. Most previous research on the pass-through of carbon costs to electricity prices focuses on an area that is fully regulated by the policy [4–7]. The PJM provides a unique setting where the market is only partially regulated.

Our paper contributes significantly to ongoing policy discussions surrounding cap-and-trade policies and their efficacy. Through regression analysis of PJM's Real-Time Market (RTM) and Day-Ahead Market (DAM) electricity prices, incorporating various variables including the RGGI CO_2 price, we provide evidence of the effectiveness of cap-and-trade policy implementation within the regulated areas of PJM. Furthermore, our findings indicate a positive and significant impact of the RGGI CO_2 price on unregulated areas, highlighting the presence of a spill-over effect within the PJM market. Additionally, our study identifies specific times of the day when this impact is most pronounced. Finally, we introduce a unique methodology to conclude the heterogeneous nature of the spill-over effect within PJM.

The remainder of this paper is structured as follows: Section 2 provides an overview of the PJM Electricity Market, explaining price determination methodologies and introducing the regression equation used for analysis. Section 3 presents the regression results and additional data analysis. Finally, Section 4 concludes the paper.

2 Materials and Methods

2.1 The PJM Electricity Market and Price Bidding

The data of electricity prices from PJM Electricity Market is the main source of analysis for this research. The PJM Energy market operates in real-time and day-ahead modes to meet consumers' electricity needs. Real-time energy trading occurs within PJM's real-time (five minutes ahead) Energy market, while the Day-Ahead Market (one day ahead) calculates hourly locational marginal prices (LMP) based on predicted consumer demand. PJM's day-ahead market forecasts prices for the next day, while the real-time market procures energy for immediate delivery.

PJM calculates and determines the day-ahead market (DAM) and real-time market (RTM) prices based on the bid prices submitted by electricity suppliers in the area. Each supplier must submit a bid price indicating the amount of electricity they are willing to sell. If a supplier does not submit a bid price, it is assumed they will sell 0 MWh of electricity. The bid period for the day-ahead market closes at 11:00, after which PJM begins running the Day-ahead Market Clearing Engine to establish hourly commitment schedules and locational marginal prices (LMPs) for the Day-ahead Market. This scheduling process ensures that demand is met, and each supplier receives a price equal to or greater than their bid price.

When determining the clearing price, priority is given to bids with the lowest price, and the corresponding amount of electricity is assigned accordingly until the market demand for the day is met. Suppliers with renewable energy sources or lower-cost resources for electricity generation typically submit lower bid prices and can thus sell more units. This process continues until the demand for the day is satisfied. The fuel used for the final unit that determines the market electricity is the marginal fuel for that time period. Figure 3 illustrates a typical PJM Generation Stack, where suppliers with renewable energy sources can bid at lower prices and sell more units, while those relying on Natural Gas and Oil may have higher bid prices and supply fewer units. The final bid that meets the demand at any given time becomes the market clearing price.

Figure 3

For our research, we analyze both real-time and day-ahead market prices over a three-year period (2020-2022). Although the locational marginal prices for the real-time market may vary slightly, we aggregate 12 different prices within an hour to determine the locational marginal price for a location for that hour. Similar to [5], as day-ahead and real-time market prices may be similar during certain periods of the day, we divide the 24-hour period into 5 distinct periods (00:00-06:00, 06:00-10:00, 10:00-14:00, 14:00-18:00, and 18:00-24:00). Some portion of this paper uses Period 1, Period 2, Period 3, Period 4, and Period 5, respectively, to represent these different time-of-day for RTM and DAM electricity prices.

2.2 Regulated and Unregulated Areas in PJM

The PJM Interconnection plays a crucial role in coordinating electricity distribution across portions of 13 states, some of which are subject to regulation by RGGI. This aspect makes the PJM region a particularly compelling subject for examining the effects of RGGI regulations on both regulated and unregulated areas within the PJM market. Our research delves into this by analyzing data collected from 21 distinct pricing nodes within the PJM Electricity Market. These nodes represent a diverse mix of regulated and unregulated areas. Figure 4 illustrates the locations we've included in our analysis.

Figure 4

In our sample, we identify 7 regulated areas, including Atlantic City Electric Co. (AE), Jersey Central Power & Light (JCP&L), Delmarva Power & Light Co. (DP&L), PSEG (PSEG), Baltimore Gas and Electric Co. (BGE), Potomac Electric Power Co. (PEPCO), and Rockland Electric Co. (RECO). The remaining unregulated areas consist of American Electric Power (AEP), Allegheny Power Systems (AP), American Transmission Systems, Inc. (ATSI), Commonwealth Edison Company (ComEd), Dayton Power & Light Co. (DAY), Duke Energy Ohio and Kentucky Corp. (DEO&K), Duquesne Light Co. (DLCO), Dominion (Dominion), East Kentucky Power Cooperative (EKPC), Met-Ed (METED), Ohio Valley Electric Corp. (OVEC), PECO Energy Co. (PECO), Pennsylvania Electric Co. (PENELEC), and PPL Electric Utilities (PPL). Figure 5 illustrates the portion of regulated and unregulated areas in the PJM market. The green-shaded portion on the map indicates the regions within the PJM market subject to regulation by RGGI, with the rest representing unregulated areas.

Figure 5

This study aims to conduct regression analysis for RTM and DAM electricity prices for all these areas and study the impact of RGGI CO_2 price on them. The analysis result on both the regulated and unregulated areas adds emphasis on our finding for the spill-over effect.

2.3 Real-Time and Day-Ahead Price Regressions

Regression Analysis is employed to quantify the impact of various variables, including the RGGI price, on Real-Time and Day-Ahead Market Prices. The left-hand side of the equation represents P_{dt}, the Electricity Market Price for the Real-Time and Day-Ahead Market (d) at different periods t (=1 for 00:00-06:00, 2 for 06:00-10:00, 3 for 10:00-14:00, 4 for 14:00-18:00, and 5 for 18:00-24:00).

Using PJM's real-time and day-ahead market prices, we conduct regression analysis with the following specifications:

$$P_{dt} = \alpha_{dt} + \beta_d N_t + \gamma_d R_t + \theta_{1d} X_{1t} + ... + \theta_{8d} X_{8t} \tag{1}$$

As this equation 1 is a linear regression, each coefficient measures the marginal price effect of a right-hand side (RHS) variable on the left-hand side variable. The left-hand side of the equation represents the locational marginal price for the real-time or day-ahead market at time period t. The right-hand side of the equation consists of several variables considered to calculate their impact on the prices.

The linear function of constant α_{dt} in the equation accounts for six binary indicators for the day of the week, four binary indicators for the period of the day, and eleven binary indicators for the month of the year. Including these fixed constants helps to capture the impact of residual price variables not captured by other right-hand side variables.

The variable N_t represents the natural gas price, used as a resource for electricity generation. Its coefficient $\beta_d > 0$ provides the impact of the natural gas price for the day on electricity prices for both the Real-Time and Day-Ahead markets.

The next variable R_t represents the price for CO_2 emissions set by RGGI for the day. Its coefficient γ_d indicates the impact of the CO_2 price on electricity prices. With $\gamma_d > 0$, this suggests the effectiveness of the Cap-and-Trade policy, reflecting the pass-through of CO_2 prices to electricity prices.

The subsequent variable X_{1t} represents the average hourly demand for electricity in the location at the given time of day. Its coefficient θ_{1d}, expected to be positive, reflects the impact of electricity demand on prices.

The next four variables, X_{2t}, X_{3_t}, X_{4t}, and X_{5t}, represent the PJM area's generation from Wind, Solar, Nuclear, and Hydro sources (MWh) respectively. Their coefficients $\theta_{2d}, \theta_{3_d}, \theta_{4d}$, and θ_{5d} indicate how electricity market prices change with shifts in generation from renewable sources such as Wind, Solar, Nuclear, and Hydro-power. We anticipate the coefficients for these variables to be negative.

The remaining three variables, X_{6t}, X_{7_t}, and X_{8t}, represent the PJM area's generation from Coal, Gas, and Oil (MWh) respectively. Their coefficients $\theta_{6d}, \theta_{7_d}$, and θ_{8d} reflect the impact of generation units from non-renewable sources - Coal, Gas, and Oil - respectively. We expect the coefficients for these variables to be positive.

Additionally, we introduce another variable, X_{9t}, with its coefficient θ_{9d}, representing the percentage of Marginal fuel as Natural Gas for market declaration in a period on electricity prices.

2.4 Data

The primary data sources are PJM, RGGI, and the U.S. Energy Information Administration (EIA). Equation (1) serves as the foundation for much of the research. In some instances, we also incorporate additional variables to enhance the analysis. Table 1 presents the descriptive statistics of RTM and DAM Prices along with the variables impacting the prices. The table illustrates mean, standard deviation, minimum, and maximum of all the variables for different periods of the day.

Table 1

We include several variables to understand how they affect RTM and DAM electricity prices. Using these variables helps minimize errors in our results. In the summary table, we find that the Natural Gas Price and RGGI Price stay the same all day long, so we only need one row of information for these variables. Another variable we look at is forecast demand, which tells us how much electricity is demanded in a specific area during a specific time of day. We also examine electricity generation from renewable sources like wind, solar, nuclear, and hydro power. Additionally, we consider electricity generation from coal, gas, and oil. These are the main variables we use for our regression analysis. However, we also include other dummy variables that provide more details about the time of day, day of the week, and month of the year.

Table 2 shows the correlations between the time-of-day periods for RTM and DAM prices and their main drivers. While we don't directly rely on this data for our main results in the results section, these correlations give us an early indication of whether our regression-based method is effective for understanding how RTM and DAM prices behave in PJM.

Table 2

The summary table and correlation results lay the groundwork for our further analysis to understand how different factors affect RTM and DAM electricity prices. This initial work helps us dig deeper into how various factors impact electricity prices

3 Results

3.1 Impact of RGGI CO_2 Pricing in Regulated Areas of PJM

Table 3 presents the results of regression analysis for RTM and DAM market prices in regulated areas within PJM. Initially, the analysis considers only two variables: the price of Natural Gas and RGGI CO_2 Price, to assess their impact on electricity prices. Subsequently, additional variables such as forecasted electricity demand, electricity generation from various sources (wind, solar, nuclear, hydro, coal, gas, and oil), and marginal fuel weight are included to enhance the analysis. Marginal fuel weight represents the percentage of marginal fuel used during periods of energy generation. Furthermore, dummy variables reflecting period-of-day, day-of-week, and month-of-year are incorporated. This progressive addition of variables allows for a comprehensive evaluation of the regression results.

Table 3

The focus of the analysis is on the coefficient for the RGGI price, aiming to study its impact on RTM and DAM electricity prices. Across all cases, with and without additional variables, the coefficient (γ_d) for RGGI CO_2 price is consistently positive and significant at the 5% level for both RTM and DAM prices. In the final regression model incorporating all variables and dummy variables, the coefficients for RGGI CO_2 price for RTM and DAM electricity prices are 3.685 and 2.692, respectively. This implies that a $1/metric ton increase in CO_2 price increases the RTM electricity price by $3.685 per MWh and the DAM electricity price by 2.692 per MWh.

The positive coefficient for the RGGI CO_2 price underscores the effectiveness of the cap-and-trade policy implemented by RGGI in the regulated areas of PJM. It indicates that RTM and DAM electricity prices in these areas contain the CO_2 price set by RGGI. As the emission cap decreases over time, permits for CO_2 emission gets expensive resulting in the impact of RGGI CO_2 price becoming higher. This requires generation units to explore renewable energy sources to mitigate costs or adopt alternative strategies to reduce costs and remain competitive in electricity price bidding.

3.2 Impact of RGGI CO_2 Pricing in entire PJM

As the PJM market consists of both regulated and unregulated areas, we delve deeper into regression analysis to examine the entire PJM market. Table 4 presents the regression analysis of the entire PJM market for RTM and DAM electricity prices, including various variables. Initially, the regression considers only two variables: Natural Gas price and RGGI CO_2 price. Subsequently, additional variables impacting RTM and DAM prices are included, gradually adding dummy variables representing period-of-day, day-of-week, and month-of-year. This step-wise addition of variables enhances the quality of the results at each stage.

Focusing on the coefficient of RGGI CO_2 price, we observe it to be consistently positive and significant at the 5% level across all regression analyses. In the final regression model, which includes all variables and dummy variables, the coefficient is 2.893 for RTM electricity price and 1.972 for DAM electricity price. This implies that if CO_2 price increases by $1/metric ton, the RTM electricity price will increase by $2.893/MWh and the DAM electricity price will increase by $1.972/MWh. These results indicate the impact of RGGI CO_2 price across the entire PJM market, encompassing both regulated and unregulated areas. This suggests a spill-over effect in the PJM market.

Table 4

To further validate our findings, we conduct individual regression analyses for all areas within PJM across different periods of the day. Table 5 summarizes the results, indicating the significance of the coefficient of RGGI CO_2 price for both RTM and DAM prices in various periods. Notably, out of 21 areas comprising 7 regulated and 14 unregulated areas, the coefficient of RGGI CO_2 price is significant for all 21 areas in the Day-Ahead Market across all periods. Similarly, in the Real-Time Market, the coefficient is significant for all areas in Periods 1, 2, 3, and 4. Additionally, 12 out of 21 areas exhibit significant RGGI coefficients for Period 4 in the Real-Time Market.

Table 5

The consistent significance of the RGGI CO_2 price coefficient across all areas in PJM, including unregulated areas, underscores its impact beyond regulatory boundaries. This further emphasizes the heterogeneous nature of the spill-over effect in the PJM electricity market.

3.3 RGGI CO_2 Coefficient Variation by Time of Day

In this study, we segment the entire day into five distinct periods and conduct regression analyses for both Real-Time (RTM) and Day-Ahead (DAM) electricity prices across these periods. Our focus is to examine the variation in the coefficient of the RGGI CO_2 price across different periods. Table 5 displays the minimum, maximum, and average coefficients of the RGGI CO_2 price obtained from regression analyses conducted on 21 different areas within PJM for both RTM and DAM electricity prices. Notably, the average coefficient reaches its peak for both RTM and DAM electricity prices during period 2 (06:00-10:00).

The distribution of coefficients for all areas is better depicted in the box plots shown in Figure 6 and Figure 7. These box plots provide a visual representation of the five-number summary, including the minimum, first quartile, median, third quartile, and maximum values of the RGGI CO_2 price coefficient. The number line below the box plot displays the coefficients of RGGI CO_2 price obtained from the regression analysis. The box in the box plot extends from the first quartile to the third quartile, with a vertical line marking the median. The whiskers in the box plot extend from each quartile to the minimum (to the left) and maximum (to the right).

Figure 6 compares the RGGI coefficient for RTM and DAM across different periods. Here we observe that, on average, the RGGI CO_2 price coefficient for RTM is higher than that for DAM across all periods. The difference in the coefficient between RTM and DAM is particularly notable during periods 2 (06:00-10:00) and 3 (10:00-14:00), whereas it remains relatively consistent for the remaining periods. The spread in the coefficient is consistent between RTM and DAM across all periods.

Figure 6

Figure 7 further compares the RGGI coefficient across different periods for both RTM and DAM electricity prices. In both the Real-Time and Day-Ahead markets, the coefficient is notably higher during period 2 (06:00-10:00), indicating the maximum impact of RGGI CO_2 pricing during this period of the day. These findings underscore the variability in the impact of RGGI CO_2 pricing across different periods, with period 2 demonstrating the highest impact of RGGI coefficient on both RTM and DAM electricity prices within the PJM market.

Figure 7

Hence, we note that RGGI has a greater effect on RTM prices compared to DAM prices, with the most significant impact occurring during period 2 (06:00-10:00) of the day.

3.4 Trend of RGGI Regression Coefficients for Unregulated Areas with Average Distance from Regulated Areas

The positive and significant coefficient of the RGGI CO_2 price on both Real-Time Market (RTM) and Day-Ahead Market (DAM) electricity prices in the unregulated areas of PJM suggests a spill-over effect within the PJM market. To find the nature of this spill-over effect, we conduct a detailed analysis. Initially, we calculate the average distance between each unregulated area and all the regulated areas within the PJM. This is achieved by determining the geographical coordinates of the pricing nodes in each unregulated area and computing the distances to the pricing nodes of regulated areas. The average distance is then calculated across all unregulated areas. Subsequently, we examine the relationship between the RGGI CO_2 price coefficient and the average distance for both the RTM and DAM electricity markets to identify any trends.

Table 6 presents the average distance (in miles) and the corresponding RGGI coefficients for RTM and DAM. To visualize the trend in the spill-over effect, we plot the data from Table 6 on a graph, with distance on the x-axis and RGGI coefficients on the y-axis. Figure 8 illustrates the resultant graph, showcasing the heterogeneous nature of the spill-over effect within the PJM market.

Table 6

Our analysis reveals a negative correlation between distance and the regression coefficient of the RGGI CO_2 price. Specifically, as the distance from unregulated areas to regulated areas increases, the impact of the RGGI CO_2 price on RTM and DAM electricity prices tends to decrease. This observation suggests that generation units in regulated areas may initially seek to purchase additional electricity from nearby unregulated areas before sourcing from more distant unregulated areas. The strong negative correlation between distance and the RGGI coefficient underscores the heterogeneous nature of the spill-over effect in the PJM market.

Figure 8

This spill-over effect could potentially hinder the effective implementation of the cap-and-trade policy for the regulated areas within PJM. Understanding and addressing these spill-over effects is crucial for ensuring the success of carbon pricing initiatives in reducing emissions across the entire PJM market.

4 Conclusion

In summary, this paper offers a detailed analysis of Real-Time and Day-Ahead market prices in PJM from January 1, 2020, to December 31, 2022. The regression analysis reveals a significant positive impact of RGGI CO_2 prices on both RTM and DAM electricity prices in both regulated and unregulated areas of PJM, indicating a spill-over effect. Notably, this impact is most seen during period 2 (06:00-10:00) of the day. Moreover, the effect is stronger for unregulated areas closer to regulated ones, demonstrating a varied spill-over effect in PJM.

These findings raise concerns about the effectiveness of RGGI's cap-and-trade policy in PJM. While the positive impact of RGGI CO_2 prices in regulated areas suggests policy efficacy, the spill-over effect may undermine its overall effectiveness. Generation units in regulated areas may opt to purchase electricity from nearby unregulated areas to avoid CO_2 emission costs, potentially hindering efforts to promote renewable energy sources. However, expanding RGGI's policy to include additional areas may enhance its efficiency in the market.

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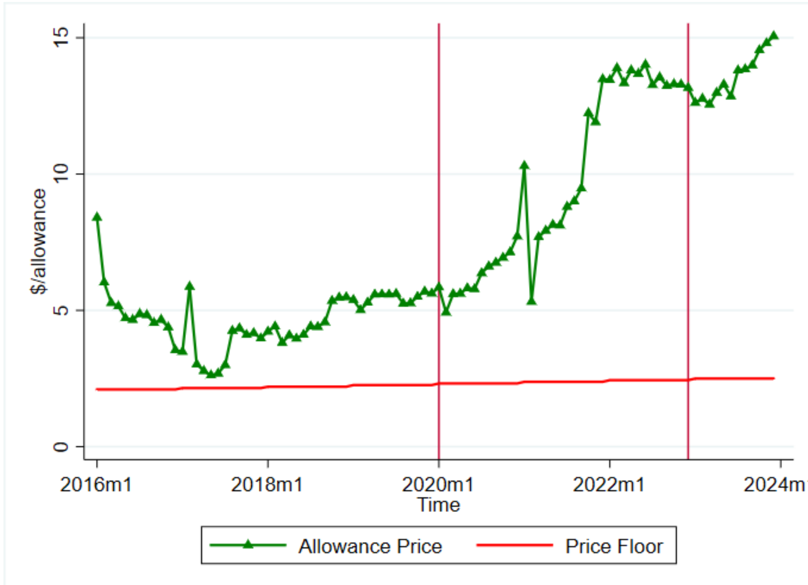

Figure 1: RGGI CO_2 Price Trend over Time

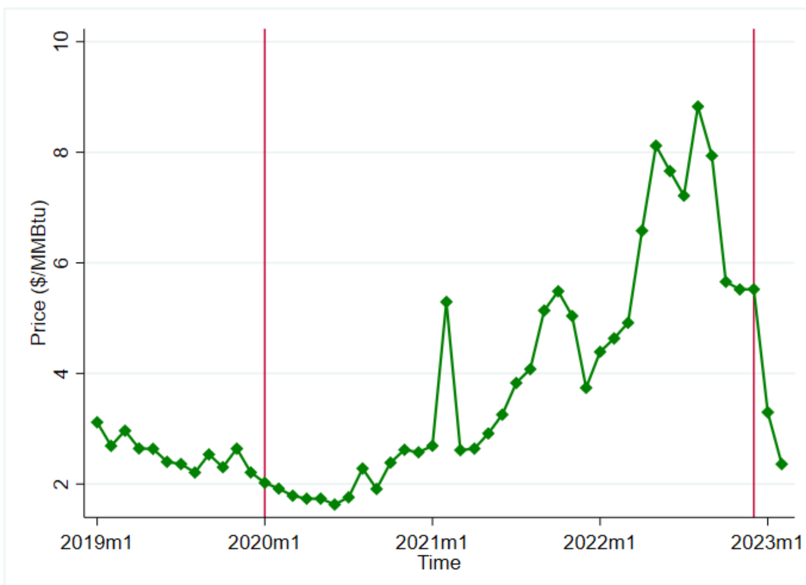

Figure 2: Natural Gas Price Trend over Time

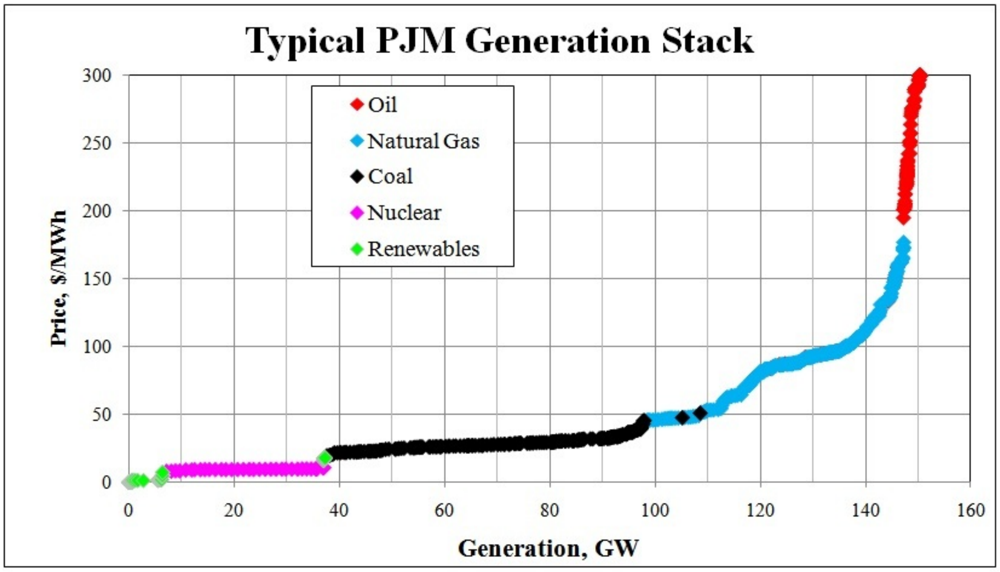

Figure 3: PJM Generation Stack

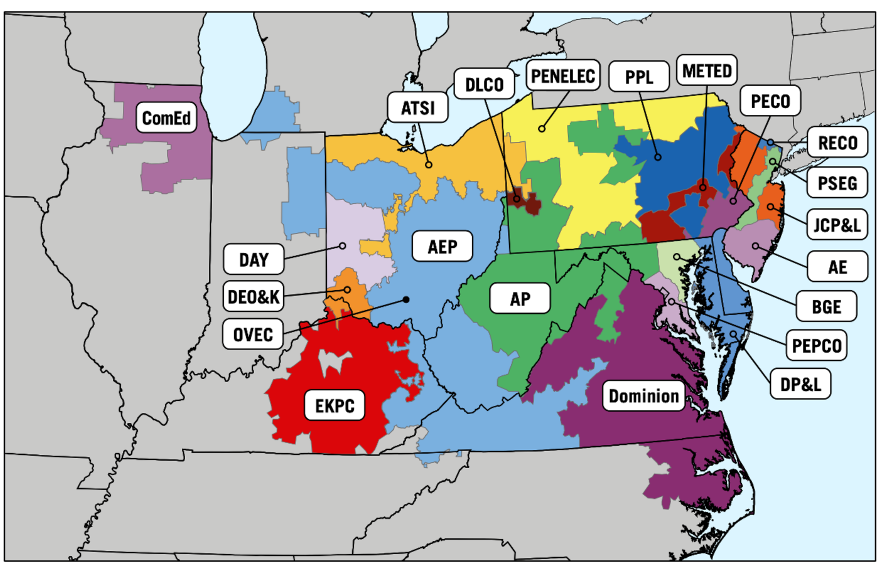

Figure 4: PJM Electricity Market Areas

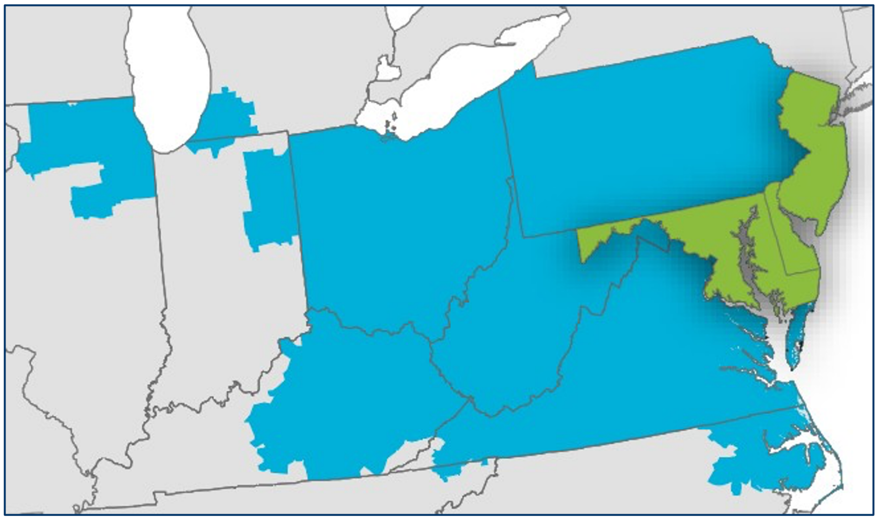

Figure 5: Regulated and Unregulated Areas in PJM

Note: Green-shaded region shows the areas regulated by RGGI, while other regions are unregulated.

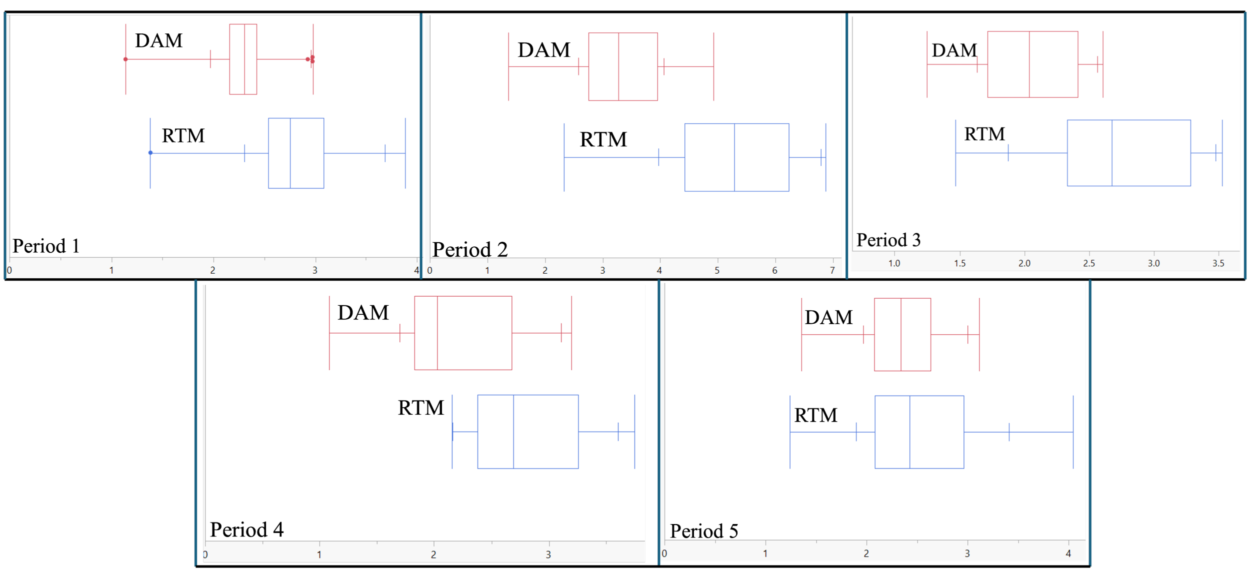

Figure 6: Box-Plot Comparing RGGI Coefficient for RTM and DAM in different Periods

Note: Period 1 (00:00-06:00), Period 2 (06:00-10:00), Period 3 (10:00-14:00), Period 4 (14:00-18:00), and Period 5 (18:00-24:00)

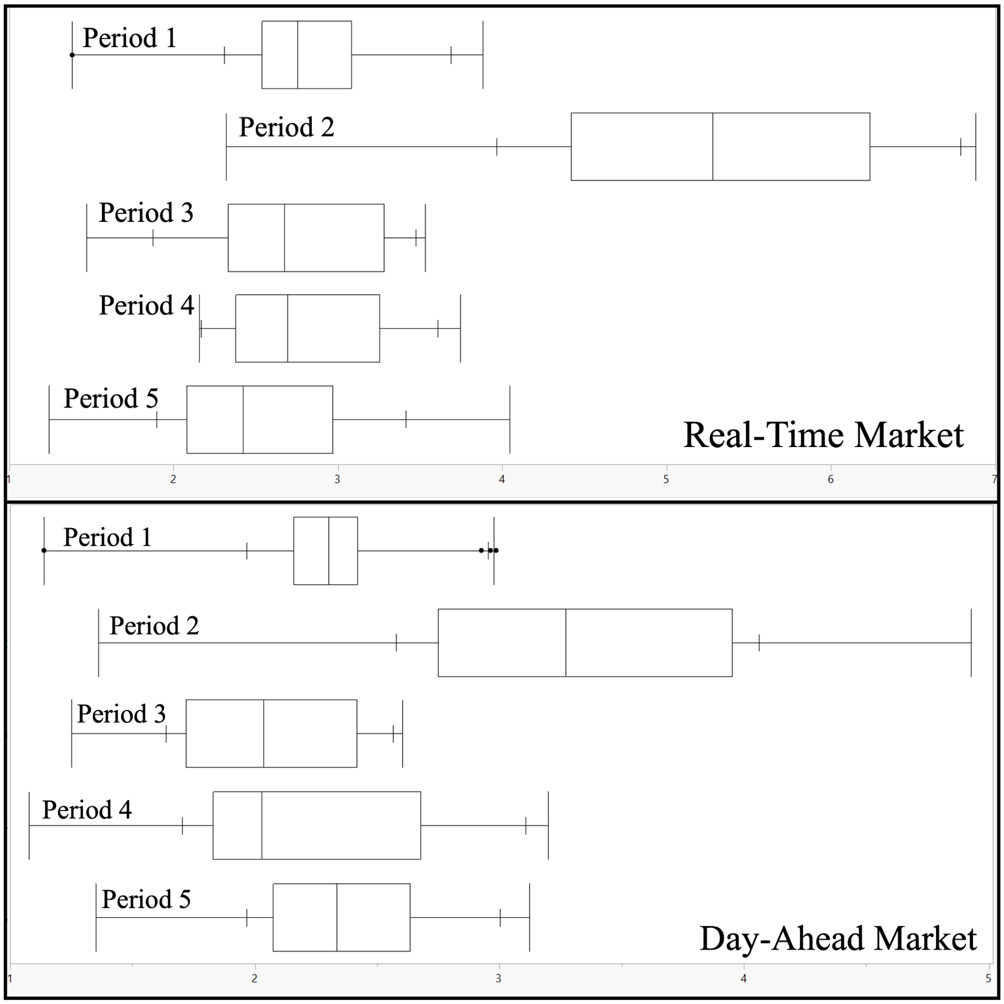

Figure 7: Box-Plot Comparing RGGI Coefficient for different Periods in RTM and DAM

Note: Period 1 (00:00-06:00), Period 2 (06:00-10:00), Period 3 (10:00-14:00), Period 4 (14:00-18:00), and Period 5 (18:00-24:00)

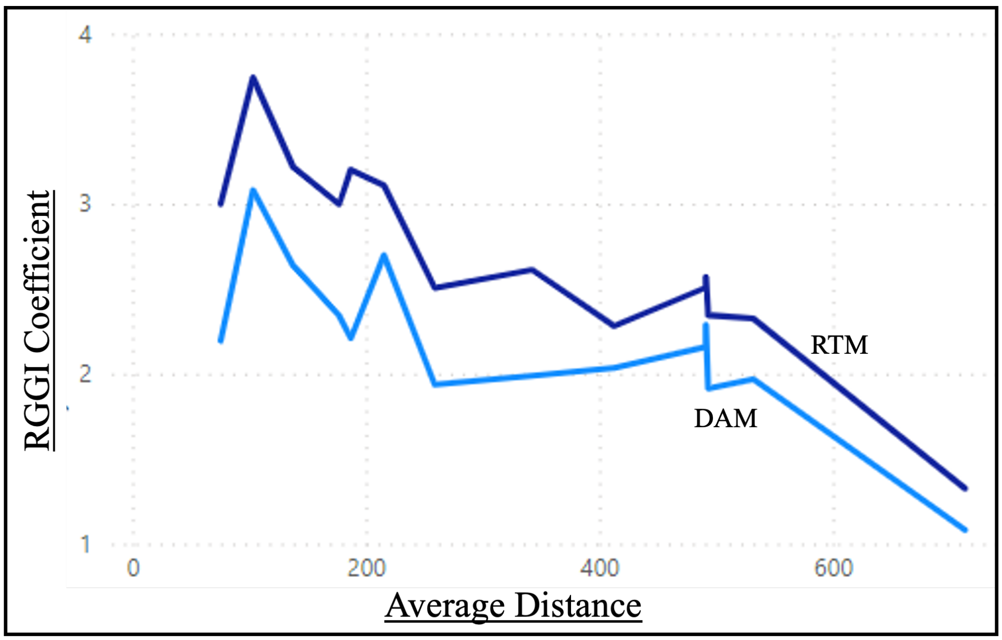

Figure 8: RGGI Coefficient for RTM and DAM correlation of Unregulated Areas with distance from Regulated areas

Table 1: Summary Table for all the Variables

Variable	Time of day Period	Mean	Standard deviation	Minimum	Maximum
RTM Price	00:00-06:00	33.639	79.234	-40.498	3762.614
	06:00-10:00	42.118	63.948	-33.234	2557.652
	10:00-14:00	44.757	43.458	-171.541	982.616
	14:00-18:00	54.251	90.949	-221.964	4263.155
	18:00-24:00	39.647	53.134	-33.375	2812.690
DAM Price	00:00-06:00	32.020	22.981	-14.009	430.377
	06:00-10:00	42.117	31.217	-0.124	517.731
	10:00-14:00	44.537	31.964	3.781	363.703
	14:00-18:00	52.508	40.981	3.234	492.521
	18:00-24:00	39.672	28.044	6.027	469.731
Natural Gas Price	00:00-24:00	4.111	2.250	1.330	23.860
RGGI Price	00:00-24:00	9.742	3.198	4.300	14.225
Forecast Demand	00:00-06:00	20045.6	16500.99	826.000	117463.000
	06:00-10:00	23112.293	19025.503	828.000	130048.000
	10:00-14:00	24738.775	20637.946	945.000	145040.000
	14:00-18:00	26197.694	21822.442	1072.000	149945.000
	18:00-24:00	23500.377	19415.792	996.000	130342.000
Wind Energy (MWh)	00:00-06:00	3429.328	2135.692	26.000	9189.000
	06:00-10:00	3147.752	2111.597	15.000	9364.000
	10:00-14:00	3052.938	2210.367	13.000	9244.000
	14:00-18:00	3286.380	2223.062	12.000	9371.000
	18:00-24:00	3476.049	2215.213	67.000	9137.000
Solar Energy (MWh)	00:00-06:00	8.039	10.761	0.000	153.000
	06:00-10:00	620.970	750.148	0.000	3339.000
	10:00-14:00	1705.825	793.966	20.000	3486.000
	14:00-18:00	661.064	810.293	0.000	3343.000
	18:00-24:00	8.522	11.712	0.000	152.000
Nuclear Energy (MWh)	00:00-06:00	31256.760	2154.629	25315.000	45630.000
	06:00-10:00	31275.589	2112.095	25204.000	34151.000
	10:00-14:00	31248.967	2096.873	25192.000	34133.000
	14:00-18:00	31233.312	2089.402	25316.000	34116.000
	18:00-24:00	31230.578	2100.131	25321.000	34119.000
Hydro power Energy (MWh)	00:00-06:00	870.518	450.807	169.000	4380.000
	06:00-10:00	1834.062	1285.914	213.000	5935.000
	10:00-14:00	1776.310	1024.157	205.000	5881.000
	14:00-18:00	3189.219	1367.846	207.000	6768.000
	18:00-24:00	1319.012	720.065	173.000	6091.000
Coal Generation (MWh)	00:00-06:00	16945.410	6027.855	5737.000	39959.000
	06:00-10:00	18610.603	6395.219	5838.000	40907.000
	10:00-14:00	20208.785	7003.928	6641.000	42008.000
	14:00-18:00	20929.748	7363.796	6779.000	42678.000
	18:00-24:00	20053.938	6923.798	7177.000	42185.000
Gas Generation (MWh)	00:00-06:00	30282.090	5653.144	16062.000	48358.000
	06:00-10:00	35305.648	6717.960	14494.000	55199.000
	10:00-14:00	38895.746	9106.589	18906.000	68719.000
	14:00-18:00	41518.531	10401.191	20200.000	69663.000
	18:00-24:00	37177.744	7638.605	20300.000	65466.000
Oil Generation (MWh)	00:00-06:00	225.111	362.921	53.000	10911.000
	06:00-10:00	270.029	467.520	40.000	11621.000
	10:00-14:00	280.732	409.099	34.000	11451.000
	14:00-18:00	324.637	532.027	36.000	11841.000
	18:00-24:00	254.611	392.246	33.000	8122.000

Table 2: Real-Time and Day-Ahead Market Price's Correlation with other variables

	Real-Time Market					Day-Ahead Market				
Variables	**Period 1**	**Period 2**	**Period 3**	**Period 4**	**Period 5**	**Period 1**	**Period 2**	**Period 3**	**Period 4**	**Period 5**
Natural Gas Price	0.2212	0.3167	0.5541	0.3626	0.4117	0.6769	0.6399	0.7758	0.7385	0.7701
RGGI Price	0.2133	0.3313	0.4697	0.3035	0.3734	0.6774	0.6560	0.6602	0.6307	0.7018
Forecast Demand	0.0311	0.0403	0.0623	0.0513	0.0292	0.0655	0.0570	0.0684	0.0924	0.0565
Wind Energy	0.0402	0.0534	-0.0528	-0.0167	0.0020	0.0425	0.0789	-0.0623	-0.0756	-0.0215
Solar Energy	0.0019	0.0175	0.2820	0.1208	0.0407	0.0726	0.1096	0.4503	0.2500	0.0984
Nuclear Energy	0.0332	0.0028	0.0286	0.0480	0.0349	0.0404	-0.0221	0.0356	0.0592	0.0390
Hydro power Energy	0.0766	0.0975	0.1739	0.2478	0.1514	0.0153	0.2045	0.2085	0.3971	0.0903
Coal Generation	0.1523	0.1478	0.1860	0.1285	0.1449	0.3119	0.2330	0.2200	0.2372	0.2201
Gas Generation	0.1293	0.1963	0.3308	0.2420	0.1980	0.3033	0.3459	0.4007	0.4449	0.3336
Oil Generation	0.8030	0.6714	0.4679	0.4631	0.5043	0.4736	0.4815	0.3100	0.3757	0.4014

Note: Period 1 (00:00-06:00), Period 2 (06:00-10:00), Period 3 (10:00-14:00), Period 4 (14:00-18:00), and Period 5 (18:00-24:00)

Table 3: Regression Analysis with Varying Variables for Regulated Areas in PJM

	(1) RTM Price	(2) DAM Price	(3) RTM Price	(4) DAM Price	(5) RTM Price	(6) DAM Price	(7) RTM Price	(8) DAM Price
Natural Gas Price	6.990***	6.869***	3.682***	5.417***	3.755***	5.461***	3.712***	5.723***
	(0.223)	(0.086)	(0.176)	(0.066)	(0.178)	(0.066)	(0.194)	(0.071)
RGGI Price	2.784***	2.556***	3.728***	3.102***	3.728***	3.102***	3.685***	2.692***
	(0.157)	(0.061)	(0.124)	(0.046)	(0.124)	(0.046)	(0.138)	(0.051)
Forecast Demand			0.001***	0.002***	0.001***	0.002***	0.001***	0.002***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Wind Energy (MWh)			0.000	-0.000***	-0.000	-0.001***	0.000**	-0.001***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Solar Energy (MWh)			-0.002***	-0.001***	-0.002***	-0.001***	-0.002***	0.002***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
Nuclear Energy (MWh)			-0.000	-0.001***	0.000	-0.001***	-0.000	-0.001***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Hydro power Energy (MWh)			0.004***	0.003***	0.004***	0.003***	0.004***	0.003***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Coal Generation (MWh)			-0.001***	-0.000***	-0.001***	-0.000***	-0.001***	-0.000***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Gas Generation (MWh)			0.000***	-0.000***	0.000***	-0.000***	0.001***	-0.000*
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Oil Generation (MWh)			0.089***	0.023***	0.088***	0.023***	0.088***	0.022***
			(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
Marginal Fuel Weight					-3.096**	-1.845***	-3.492***	-1.628***
					(1.229)	(0.459)	(1.245)	(0.459)
Constant	-12.922***	-11.393***	-60.187***	-39.758***	-59.192***	-39.165***	-61.454***	-42.904***
	(1.025)	(0.395)	(3.941)	(1.470)	(3.960)	(1.477)	(7.329)	(2.703)
N	38325	38325	38325	38325	38325	38325	38325	38325

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: To maintain brevity, this table excludes estimates for intercepts and the effects of the period of the day, day-of-week, and month-of-year, which are mostly significant at the 5% level.

Table 4: Regression Analysis with Varying Variables for Entire PJM

	(1) RTM Price	(2) DAM Price	(3) RTM Price	(4) DAM Price	(5) RTM Price	(6) DAM Price	(7) RTM Price	(8) DAM Price
Natural Gas Price	8.305***	7.692***	5.254***	6.931***	5.237***	6.910***	4.967***	6.733***
	(0.564)	(0.201)	(0.450)	(0.142)	(0.455)	(0.143)	(0.488)	(0.151)
RGGI Price	2.141***	2.212***	2.832***	2.122***	2.830***	2.120***	2.893***	1.972***
	(0.397)	(0.142)	(0.319)	(0.100)	(0.319)	(0.100)	(0.348)	(0.107)
Forecast Demand			0.001**	0.002***	0.001**	0.002***	0.001**	0.002***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Wind Energy (MWh)			-0.001*	-0.002***	-0.001	-0.002***	-0.000	-0.002***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Solar Energy (MWh)			-0.001	-0.002***	-0.001	-0.002***	-0.001	0.000
			(0.001)	(0.000)	(0.001)	(0.000)	(0.002)	(0.000)
Nuclear Energy (MWh)			-0.001	-0.002***	-0.001	-0.002***	-0.001	-0.002***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
Hydro power Energy (MWh)			0.003***	0.001***	0.003***	0.001***	0.004***	0.001***
			(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
Coal Generation (MWh)			-0.001***	-0.002***	-0.001***	-0.002***	-0.001***	-0.002***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Gas Generation (MWh)			0.000	-0.002***	0.000	-0.002***	0.000	-0.002***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Oil Generation (MWh)			0.085***	0.017***	0.085***	0.017***	0.085***	0.016***
			(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
Marginal Fuel Weight					0.803	0.946	0.441	0.405
					(3.079)	(0.969)	(3.118)	(0.962)
Constant	-11.334***	-10.513***	-51.257***	-40.554***	-51.542***	-40.890***	-55.799***	-54.242***
	(2.586)	(0.924)	(9.832)	(3.094)	(9.894)	(3.113)	(18.457)	(5.695)
N	5475	5475	5475	5475	5475	5475	5475	5475

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: To maintain brevity, this table excludes estimates for intercepts and the effects of the period of the day, day-of-week, and month-of-year, which are mostly significant at the 5% level.

Table 5: RGGI Coefficient Summary for Real-Time and Day-Ahead Market for entire PJM

	Real-Time Market					Day-Ahead Market				
RGGI Price	**Num Sig**	**Min Coeff**	**Max Coeff**	**Avg Coeff**	**Std Dev**	**Num Sig**	**Min Coeff**	**Max Coeff**	**Avg Coeff**	**Std Dev**
00:00-06:00	21	1.3826	3.8810	2.8007	0.5396	21	1.1376	2.9755	2.3211	0.3924
06:00-10:00	21	2.3200	6.8796	5.2834	1.1584	21	1.3621	4.9271	3.3138	0.7641
10:00-14:00	21	1.4699	3.5295	2.7179	0.5781	21	1.2486	2.6031	2.0553	0.3770
14:00-18:00	12	2.1538	3.7450	2.8095	0.5171	21	1.0771	3.1964	2.2357	0.5567
18:00-24:00	21	1.2374	4.0447	2.5603	0.6422	21	1.3495	3.1195	2.3653	0.4031

Num Sig - Number of Significant Results

Min Coeff, Max Coeff, Avg Coeff - Minimum, Maximum, and Average Coefficient from the Results

Std Dev - Standard Deviation

Table 6: Average Distance and RGGI Coefficient for Unregulated Areas

Unregulated Areas	**Average Distance**	**RGGI Coefficient RTM**	**RGGI Coefficient DAM**
PECO	75.753	2.997	2.192
METED	103.384	3.743	3.079
PPL	137.757	3.216	2.638
AP	177.147	2.996	2.342
Dominion	187.059	3.199	2.209
PENELEC	215.539	3.107	2.697
DLCO	259.011	2.505	1.936
ATSI	342.533	2.610	1.988
OVEC	412.674	2.281	2.034
DEO&K	491.021	2.506	2.157
EKPC	491.379	2.570	2.287
DAY	493.330	2.344	1.914
AEP	531.940	2.326	1.967
COMED	713.431	1.326	1.081

Note: Average Distance is calculated in miles. All the coefficients for RTM and DAM are significant at 5% level.

OURE Reflection

Name: Love Gami

Faculty Advisor: Yishu Zhou

I had a wonderful experience during a two-semester research project with Professor Yishu. The research focused on energy economics, specifically examining the effectiveness of cap-and-trade policy in PJM. Over the course of these two semesters, I acquired various new skills and gained exciting insights.

Initially, I delved into different statistical techniques for data analysis. I was introduced to regression analysis and correlation, which were fundamental to our research objectives. Additionally, I familiarized myself with several other statistical terms and their implications in data analysis. Moving forward, I explored cap-and-trade policy and the Regional Greenhouse Gas Initiative (RGGI), a regional effort to implement the policy in northeastern states. I also studied carbon tax and its distinctions from cap-and-trade policy, while considering the various pros and cons associated with these policies and their intended impact on reducing carbon emissions. This exploration deepened my understanding of energy economics.

Building upon this foundational knowledge, I then learned to utilize STATA software for statistical analysis. Mastering this new software, starting from scratch, proved invaluable for our research. While the use of software was initially challenging, with consistent practice, I became proficient in using STATA, which significantly facilitated our statistical analysis. Subsequently, I engaged in data cleaning and the incorporation of missing data from relevant sources, a crucial aspect of our research. This process provided me with a comprehensive understanding of our research objectives and what we aimed to achieve.

Following the acquisition of these skills and completion of data cleaning, I delved into literature review of a paper that guided our research direction. Although challenging initially, through repeated reading, I gained clarity on the paper's content, which greatly informed the subsequent stages of our project. I then familiarized myself with our research objectives and methodologies, ultimately utilizing STATA to derive conclusions from our findings.

In addition to STATA, I also learned to use LaTeX (overleaf.com) for paper writing, starting from scratch. Overleaf provided with an amazing experience with paper formatting. Along with these, I also used JMP and Power BI tools to add visual aids to the paper.

Overall, this research experience has been immensely enriching, allowing me to develop a diverse skill set and deepen my understanding in the field of cap-and-trade.