External Impacts of Local Energy Policy: The Case of Renewable Portfolio Standards

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Abstract

Renewable portfolio standards (RPSs) are state level policies that require in-state electricity providers to procure a minimum percentage of electricity sales from renewable sources. Using theoretical and empirical models, we show how RPSs induce out-of-state emissions reductions through inter-state trade of the credits used for RPS compliance. When one state passes an RPS, it increases demand for credits sold by firms in other (potentially non-RPS) states. We find evidence that increasing a state's RPS decreases coal generation and increases wind generation in outside states through this tradable credit channel. We perform a welfare simulation to evaluate the aggregate benefits of the reductions in local coal-fired pollutants induced by RPSs. Our estimates suggest that a 1 percentage point increase a state's RPS results in up to $100 million in gross benefits towards the United States as a whole. However, there is substantial heterogeneity in the total benefits caused by increases in different states' RPSs.

JEL: H70, Q40, Q53

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Policies that are local in scope are the dominant instrument used by regulators to reduce greenhouse gas and criteria pollution from electricity generation. This is particularly salient in the United States, which is home to the Regional Greenhouse Gas Initiative, the Cross-State Air Pollution Rule, Renewable Portfolio Standards, and other state level policies. Despite their local regulatory scope, it is possible for these policies to have significant external effects on the environment and economy. For example, energy economists have long been concerned that local regulation may displace fossil fuels generation into other regions rather than reducing it (Bushnell et al., 2008).[1] If local regulation alters external fossil fuel generation and emissions, there may be unanticipated, and unaccounted, external effects from changes in the spatial distribution of criteria pollutants. Quantifying these pollution effects is vital since the associated health consequences often make up the largest share of the gross benefits of energy policies.[2]

Renewable portfolio standards (RPSs) are one of the main renewable energy policies in the United States. RPSs are state level policies that mandate in-state electricity providers to procure a minimum percentage of retail electricity from renewable sources. 29 states and Washington D.C. have currently passed an RPS with stated goals of increasing renewable energy, improving local environmental quality, and creating additional in-state "green jobs." While RPSs only govern in-state electricity providers, their design allows them to also have out-of-state impacts. Under an RPS, electricity generators are awarded one renewable energy credit (REC) for each megawatt-hour (MWh) of renewable energy generation. Each year, electricity providers must retire a certain number of RECs, proportional to their annual retail electricity sales. State regulators generally allow for inter-state trade of RECs, opening the door for RPSs to have out-of-state impacts on generation and pollution.

In this paper we theoretically and empirically demonstrate how one state's RPS can influence fossil fuel and renewable electricity generation in another state. We develop a stylized model of electricity providers in separate states, where each electricity provider generates and sells both types of electricity to in-state consumers. Each state's electricity provider must comply with its state's RPS, but is eligible to trade RECs with electricity providers in other states. Using this model, we show that fossil fuel electricity generation decreases in response to more stringent out-of-state RPSs through REC market channels. A more stringent out-of-state RPS increases the demand for RECs in the stylized REC market. Greater demand for RECs increases the REC price, which in turn raises the implicit RPS tax on fossil fuel generation and reduces fossil fuel generation in every state in the REC market.

Using fixed effects and instrumental variables models, we empirically test our model's predic-

[1]There is a substantial literature on reshuffling and leakage in the electricity sector, e.g. Fowlie (2009), Bushnell et al. (2014), and Fell and Maniloff (2015). The phenomenon we analyze will not precisely fall within the traditional definitions of reshuffling or leakage.

[2]This is particularly applicable to the current Clean Power Plan, which has elements of local regulation since it gives each state significant flexibility in the design of its specific policy to satisfy the federal mandate. The Clean Power Plan has been estimated to avoid thousands of premature deaths annually (Driscoll et al., 2015), with annual benefits valued over $50 billion (EPA, 2015). Economists have also recently made calls for ex-post evaluations of existing, non-first best policies (Moss and Cisternino, 2009; Burke et al., 2016).

tions by estimating the impact of out-of-state demand for RECs (due to increases in out-of-state RPS stringency) on in-state electricity generation from fossil fuel and renewable sources. We estimate that a 1 terawatt-hour (TWh) increase in out-of-state REC demand reduces in-state coal generation by 1%, and total fossil fuel generation by 0.3% at the state level, with no discernible effect on natural gas.[3] state level wind generation increases by 13% in response to a 1 TWh increase in out-of-state REC demand, however we find no impact on solar. Our findings are robust across multiple specifications, including a plant level analysis, controlling for overall regional trends (e.g. declining prices for solar capacity), and using an instrument which addresses concerns about endogenous selection of REC trade eligibility between states, endogenous changes to existing RPSs, and endogenous changes in generation.

To estimate the welfare and distributional impacts of the fossil fuel reductions, we use the APEEP integrated assessment model (Muller and Mendelsohn, 2012) in conjunction with our empirical results. The APEEP model allows us to simulate where the avoided coal-fired emissions would have been transported, and the corresponding spatial distribution of welfare increases. We find that welfare gains in 2011–2012 from the emissions reductions solely from this external, out-of-state effect can be over tens of millions of dollars for a 1 percentage point increase in some states' RPSs.

This paper makes several contributions to the economics of energy and environmental policy. We argue that these are the most credible estimates to date of RPSs' effects on fossil fuel and renewable generation.[4] We do so by leveraging plausibly exogenous out-of-state variation in the demand for RECs, and by instrumenting to handle any remaining concerns about endogeneity. The trade off of improving the identification of RPS effects is that we are unable to quantify the full impact of RPSs. To conduct a full policy analysis we would need to address non-random RPS adoption, which available evidence suggests is a function of the in-state environmental, energy and economic landscape. Non-random RPS adoption by policymakers induces bias in standard fixed effects and differences-in-differences identification strategies.[5] Consequently, the previous literature, which primarily investigates in-state effects with these methods, has reported inconsistent results. Estimates of the effect of RPSs on in-state renewable generation and capacity range from no effect (Carley, 2009), a positive effect (Menz and Vachon, 2006; Yin and Powers, 2010), or even a negative effect (Shrimali and Kniefel, 2011; Shrimali et al., 2012). Analyzing out-of-state responses allows us to circumvent this selection problem, and obtain better-identified estimates.

To correctly capture out-of-state REC demand, we construct a novel dataset of the inter-state REC trade network in each year. Having an accurate dataset of the possible ways to trade RECs from state to state is vital for determining which renewable and fossil fuel plants are responding to a given state's RPS. Others have acknowledged the potential for out-of-state RPS impacts, but

[3]1 TWh of REC demand is approximately the amount of RECs electricity providers in Oregon retired for RPS compliance in 2012 (Heeter et al., 2015).

[4]Other aspects of RPSs have been studied, such as their effect on electricity prices (Fischer, 2010), and their implied CO_2 abatement cost (Johnson, 2014).

[5]Lyon and Yin (2010) provide evidence as to which state level characteristics are correlated with RPS adoption.

have solely focused on the effects of RPSs of bordering states (Yin and Powers, 2010; Shrimali et al., 2012; Fremeth and Shaver, 2014).[6] Sharing a border is neither a necessary nor sufficient condition for two states to be able to trade RECs. In reality, trade eligibility between any pair of states differs across time and is determined by both constraints written into the actual RPS legislation, and incompatibilities in the regional electronic systems used to track REC trading in the US.

Our final contribution is to model the magnitude, and spatial distribution of the external effects of RPSs. The large benefits we estimate from the out-of-state RPS effect is critical for policy evaluation. Our findings show that RPS states are bearing the costs of a policy that is providing millions of dollars of benefits in outside regions. This highlights the importance of understanding the potential for similar external impacts of other local environmental policies.

This paper is organized as follows. In Section 1 we discuss the institutional background of RPSs and REC markets. Section 2 outlines our theoretical model, which provides our testable hypotheses. In Section 3 we discuss the data, the empirical framework, and show the estimation results. Section 4 uses the empirical results and the APEEP integrated assessment model to analyze spatial welfare implications of pollution changes from REC trade. Section 5 concludes.

1 RPS Policies and REC Trading

Figure 1: RPS states and REC tracking systems, 2011

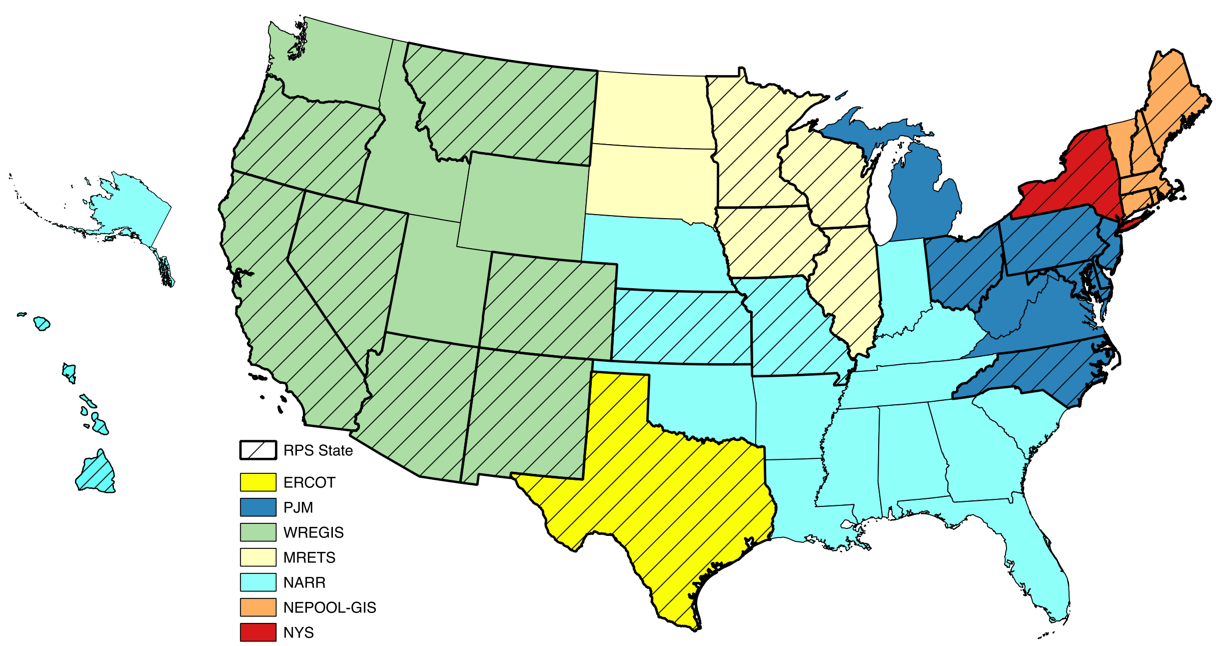


Figure 1 displays a map of all states that had implemented a mandatory RPS in 2011. The

[6] Fremeth and Shaver (2014) interpret their result as being due to forward looking utilities foreshadowing passage of RPSs in their area of operation. The other papers do not provide a clear foundation for limiting the analysis to border states.

29 RPS states are primarily located in the northeast, midwest, and the western US. Several other states, such as Vermont, have passed voluntary RPS goals. We ignore these in our analysis. Iowa implemented the first RPS over 30 years ago in 1983, yet over half of RPSs have been enacted in the 2000s. The stated reasons for passing RPS legislation vary from state to state, but the majority of states specifically mention anticipated in-state employment gains from the green power industry, strengthening of the in-state renewable sector, local environmental improvements, and local emissions reductions as primary goals in the initial statement of the policy (Holt and Wiser, 2007).[7]

Most states have implemented an RPS by setting a schedule that ramps up in stringency over ten to twenty years. Each RPS policy is unique, beginning in different years and increasing at different rates.[8] This is illustrated in Figure 2 which displays each state's primary RPS: the RPS requirement for each state's largest type of electricity provider.[9]

To reduce compliance costs, states have allowed for firms to trade the RECs used for RPS compliance. Moreover, a majority of states allow RECs to be traded across state borders. Industry stakeholders have noted that REC trade is critical for the viability of renewable energy projects as it allows for the environmental attributes of renewables to be sold separately from the actual energy.[10] The importance of RECs has been recognized by renewable energy developers as early as 2004, with one developer stating that "most utility-scale wind power projects in the East are fundamentally uneconomic without REC premiums" (Holt et al., 2011).

All RECs, including those sold across state borders, are monitored by one of the regional electronic REC tracking systems. In 2013, the final year of our sample, there were 7 operational tracking systems, ERCOT, MRETS, NARR, NEPOOL-GIS, NYS, PJM and WREGIS.[11] Figure 1 indicates the tracking system each state belonged to in 2011. Most tracking systems cover the same region as a preexisting independent system operator (ISO) or regional transmission organization, for example: NEPOOL-GIS aligns with ISO New England; NYS aligns with New York ISO; MRETS aligns with MISO; and ERCOT and PJM are named identically to the regional ISOs. In the western US, WREGIS effectively covers the entire western interconnection. The remaining states

[7]Theoretically, an RPS is a second-best instrument for attaining both the emission reduction and increased renewable generation goals. As an intensity standard, an RPS simultaneously subsidizes renewables and taxes non-renewables (Helfand, 1991; Holland et al., 2009; Lemoine, 2016). But, the renewable subsidy and non-renewable tax are decided by only one instrument: the minimum percentage of renewables.

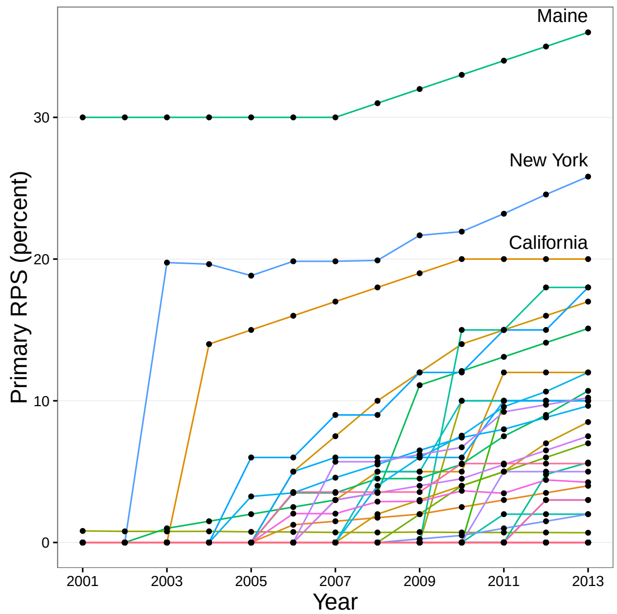
[8]RPSs also diverge along other dimensions such as what energy sources qualify as renewable. For example, Michigan counts energy generated by burning waste from the paper production process as renewable, but Arizona does not. States also differ on how long RECs can be banked over time however for simplicity in our reduced form framework we abstract away from this.

[9]In some years, New York's RPS declines since it is adjusted based off hydroelectric generation forecasts. Some states also have a secondary RPS that regulates smaller electricity providers, for example electricity cooperatives, at a different RPS stringency than those regulated by the primary RPS. RPS states also diverge on whether electricity providers can use generation from renewable capacity build before RPS passage to obtain RECs. We demonstrate how we account for these policy features in Section 3.1.

[10]Some states do require RECs to be bundled with the energy and we control for this policy feature in our analysis.

[11]During our sample, Nevada, Michigan, and North Carolina have their own state level tracking systems in place as well, but they are also a part of the 7 larger systems. Some states, such as Montana, may be split into two by different REC tracking systems. We assign states to the tracking system which covers a majority of its area.

Figure 2: The primary RPS for each state.



Note: The primary RPS is the RPS requirement for each state's largest type of electricity provider.

not covered by these REC systems are largely located in the southeast and do not have RPSs. The NARR tracking system launched in 2009 to allow firms in these states to trade RECs.

Theoretically, RECs can be traded between any two states since RECs are separate electronic commodities from the actual renewable energy. However, there are two limitations that restrict REC trade between states. The first limitation is a trade constraint written into the actual RPS legislation. Some states require their RPS to be met solely with RECs generated either in-state in an approved set of states. For example, Nevada, Iowa, and Texas each require that the RECs retired to meet their respective RPSs be generated in-state. This restriction can create asymmetric trade eligibility between states. One such example is the trade relationship between North Carolina and Texas. North Carolina allows for its RPS to be met using RECs generated in Texas, but firms in Texas cannot purchase RECs generated in North Carolina since Texas utilities cannot use RECs generated outside of the state.

The second limitation on inter-state REC trade is due to incompatibilities between the regional REC tracking systems. A REC generated on one tracking system cannot necessarily be transferred to another tracking system. An electricity generator, e.g. a wind turbine, is registered for the REC tracking system that covers the area where it's located, and the RECs created by this generator are tracked on this specific system. If an electricity provider covered by different tracking system wishes to purchase RECs created by this wind turbine, the purchaser's REC tracking system must have the technological capability to accept RECs that were created on the seller's REC tracking system. For example, the WREGIS system is incapable of accepting RECs generated in states governed by other tracking systems. Hence, states covered by WREGIS are incapable of purchasing RECs that were created in states outside of WREGIS.[12]

We use the REC trade constraints written into the RPS legislation, the constraints imposed by the incompatibilities between tracking systems, and information on when REC tracking systems became operational, to determine each state's potential REC trading partners in each year. REC tracking systems have become operational at different times over the past 15 years, beginning with ERCOT in 2002, and most recently NARR in 2009 (Heeter and Bird, 2011). This changes a firm's potential set of inter-state trade partners over time.

Correctly accounting for potential REC trade relationships is critical for RPS evaluation since inter-state trade comprises a large portion of all REC transactions. Heeter et al. (2015) find that over half of all RECs retired to meet RPSs in 2012 were generated in an outside state.[13] Half of the states in the Northeast and Mid-Atlantic obtained a majority of RECs from out-of-state. Delaware and Rhode Island are extreme examples, importing 94 percent and 77 percent of the RECs that were retired for RPS compliance in 2012. Schmalensee (2011) provides additional evidence that many states obtained a majority of their RECs from out-of-state even in 2007. Conversely, states in the West and Midwest engage in far less inter-state REC trade, with only two states (Illinois and Missouri) obtaining a majority of their RECs from out-of-state in 2012.

Figure 3 shows a set of six maps illustrating, for certain states, the sets of potential REC trade partner states, and the percentage of RECs used for RPS compliance in 2012 that were purchased from those states. In each map the REC purchasing state is highlighted in red. The set of states shown on each map are states from where firms in the red state could feasibly buy RECs. The shade of blue indicates the percentage of the total number of RECs retired in the red state in 2012 that originated in that state. For example, if a state is colored in dark blue this indicates that more than 10% of the RECs retired for compliance in 2012 in the purchasing (red) state originated in the dark blue state. The top left map shows the set of states from where Illinois electricity providers can purchase RECs. Electricity providers in Illinois can purchase RECs created in three tracking systems; MRETS, PJM, or NYS. However, the actual trades occur only with a subset of the potential states. The bottom left map indicates that Maryland, located in PJM, can trade with PJM states, New York, and a subset of MRETS states. The middle two maps indicate that Oregon and Colorado are limited to trading solely in WREGIS, and only purchase RECs from a subset of these states. The right two maps indicate that Maine and Rhode Island, located in NEPOOL, are only eligible to trade with other NEPOOL states and NYS.

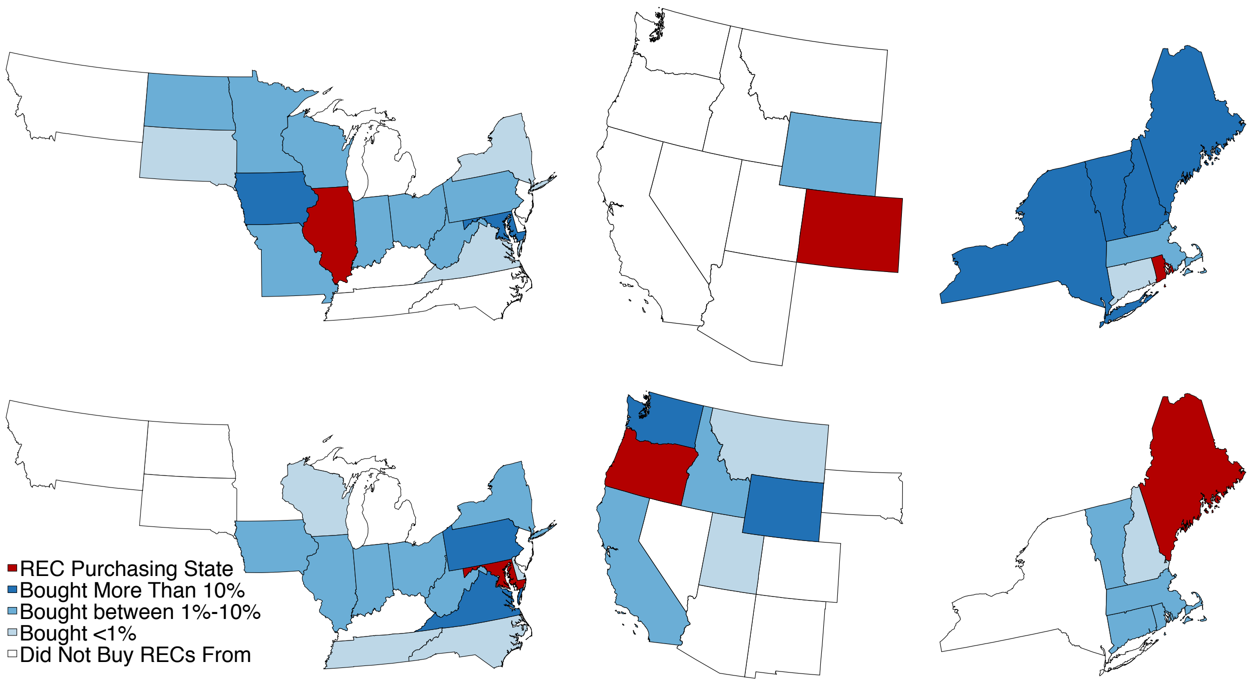
2 Theoretical Model

To analyze inter-state RPS impacts and to generate testable hypotheses for our empirical analysis, we develop a stylized static model of an electricity provider. Consider a cost-minimizing,

[12]Heeter et al. (2015) provides REC trade data for 2012 and 2013 which confirms this assertion. See Heeter and Bird (2011) for a listing of REC tracking system compatibilities.

[13]We cannot use these data in our empirical analysis as they are not available for every RPS state and are only reported by Heeter et al. (2015) in 2012 and 2013.

Figure 3: Potential and actual REC trade partners for six states in 2012.



Note: In each map the REC purchasing state is highlighted in red. The set of states shown on each map is the set that the REC purchasing state could purchase RECs from in 2012. This data is obtained from Holt (2014), the DSIRE database, and state legislative documents. Data on the percentage of RECs used for RPS compliance that were purchased from each potential trade partner are collected from Heeter et al. (2015). For example, if a state is colored in dark blue this indicates that the purchasing (red) state bought more than 10% of the RECs it used for 2012 RPS compliance from the dark blue state.

representative electricity provider that supplies electricity to in-state consumers who have perfectly inelastic demand.[14] The provider for state i generates electricity from two sources, renewable q_i^r, and non-renewable q_i^n. Here, generation is interchangeable with the provider purchasing electricity in a wholesale market. Suppose the provider faces inelastic demand for electricity of quantity Q_i. The cost of generating electricity is $C_i^r(q_i^r)$ for renewable electricity and $C_i^n(q_i^n)$ for non-renewable electricity and both cost functions are continuous, increasing, convex, and twice differentiable.

The representative electricity provider for state i faces an RPS, $\alpha_i \in [0,1]$, which mandates the minimum percentage of electricity generation that must be renewable. Each unit of renewable generation yields the electricity provider a REC, which can be retired to meet the RPS. Since total generation in state i is constrained to be equal to Q_i, the intensity standard also maps directly into a quantity standard that the electricity provider retires $\alpha_i \times Q_i$ RECs.

The electricity provider is a part of a REC trading market consisting of N total electricity providers, each in a different state.[15] For simplicity, each electricity provider is eligible to buy and

[14]Retail electricity demand and electricity prices change infrequently, suggesting this assumption is a close approximation to a short-run outcome.

[15]This model is similar to that of Rudik (2016) who characterizes credit trading under intensity standards where

sell RECs with every electricity provider in the market. The REC price that clears the market is ξ, and each electricity provider takes the REC price as given. Let x_i be the net number of RECs sold by electricity provider i, so that if $x_i > 0$ the electricity provider is selling RECs and if $x_i < 0$ the electricity provider is purchasing RECs. The RPS constraint is then $(q_i^r - x_i)/(q_i^r + q_i^n) \geq \alpha$. This constraint will always bind. If it is slack, the electricity provider can reduce costs by selling its excess RECs until the constraint binds. We solve the binding constraint for $x_i = (1 - \alpha_i)\, q_i^r - \alpha_i q_i^n$ and enter it into the electricity provider's cost function. This eliminates the RPS constraint and x_i from the electricity provider's cost minimization problem which can be written as,

$$\max_{q_i^r, q_i^n} \; -C_i^r(q_i^r) - C_i^n(q_i^n) + \xi \left[(1 - \alpha_i)\, q_i^r - \alpha_i q_i^n\right] \tag{1}$$

$$\text{subject to:} \quad q_i^r + q_i^n = Q_i \tag{2}$$

$$\sum_{i=1}^{N} (1 - \alpha_i)\, q_i^r - \alpha_i q_i^n = 0, \tag{3}$$

where the expression in square brackets in equation (1) is the net quantity of RECs sold, and equation (3) is the market clearing condition for the REC market. The first order conditions that govern the equilibrium quantities of each type of electricity are,

$$-\frac{\partial C_i^r(q_i^r)}{\partial q_i^r} + \xi(1 - \alpha_i) + \lambda_i = 0 \tag{4}$$

$$-\frac{\partial C_i^n(q_i^n)}{\partial q_i^n} - \xi\, \alpha_i + \lambda_i = 0, \tag{5}$$

where λ_i is the positive shadow cost of the electricity demand constraint in equation (2). The first order conditions demonstrate that intensity standards implicitly subsidize the clean (renewable) good, and implicitly tax the dirty (non-renewable) good. The subsidy and tax are functions of state i's RPS, but also of the prevailing price in the REC market. The REC price component of the implicit RPS tax and subsidy is the channel through which an RPS in one state can affect generation in another. The theoretical yields two propositions and a corollary.

Proposition 1 *The optimal quantity of renewable energy generated in state i, q_i^r, is increasing in the RPS of state j, α_j, and the optimal quantity of non-renewable energy generated in state i, q_i^n, is decreasing in the RPS of state j, α_j. This holds for $\forall\, i \neq j$.*

Proof: See appendix. □

Proposition 2 *The optimal quantity of renewable energy generated in state i, q_i^r, is increasing in the level of RECs demanded in state j, $\alpha_j \times Q_j$, and the optimal quantity of non-renewable energy generated in state i, q_i^n is decreasing in the level of RECs demand in state j, $\alpha_j \times Q_j$. This holds for $\forall\, i \neq j$.*

the credits are units of the clean good, and also of McKitrick (2005) who develops a model where firms trade permits in units of emissions intensity of overall production.

Proof: See appendix. □

Corollary 3 *ξ is increasing in α_i. This is strict if $q_i^r + q_i^n > 0$.*

Proof: See appendix. □

Proposition 1 states that the optimal level of non-renewable generation by provider i is decreasing in the RPS stringency of all other states. This result relies on several key features of RPSs and REC markets. First, a more stringent RPS in state j increases costs for electricity provider j as it forces the provider to move its generation bundle further towards renewables and away from the unconstrained optimum. As provider j's RPS becomes more stringent, provider j must retire more RECs to satisfy the policy. This increases the net demand for RECs in the REC market, regardless if provider j was previously a REC buyer or seller. Proposition 2 demonstrates that increasing the quantity of RECs required for RPS compliance increases renewable generation and decreases non-renewable generation in other states.

Corollary 3 shows that this effect comes about due to how higher RPSs increase the equilibrium REC price ξ. The increase in the REC price increases the renewable subsidy faced by providers $i \neq j$, which increase their renewable generation. These states must also decrease non-renewable generation in order to satisfy the inelastic demand for electricity. In addition, a higher REC price also increases the implicit non-renewable tax induced by their own RPS policy α_i as shown in Equation (5).

The results of our theoretical model suggest that generation of renewables and non-renewables respond to out-of-state RPSs and the quantity of RECs demanded for RPS compliance in outside, trade-eligible states. We use this insight to inform our empirical model and construct our variable of interest as the quantity of RECs required for RPS compliance in outside, REC trade eligible states.

3 Empirical Model

Our goal is to measure the causal effect of out-of-state RPS policies on in-state fossil fuel and renewable electricity generation through REC market channels. An ideal approach to estimating generation responses to out-of-state RPSs would leverage REC market prices. However, renewable energy and RECs are often bundled in long-term power purchase agreements to help finance construction (Holt and Bird, 2005; Heeter et al., 2014). Since these transactions occur outside of traditional REC markets, the REC prices negotiated within the agreement are typically not publicly available.

To estimate the effect of interest, we first calculate the aggregate number of RECs that must be retired by electricity providers in a given state to meet that state's RPS. We use these calculations to quantify the out-of-state REC demand and in-state REC demand to match the insights from our theoretical model. Once we have constructed the key variables in our model, we describe our empirical framework. We then discuss threats to identification and our instrument we use to address these concerns. Finally, we present the data we use to estimate our model and report our results.

3.1 Construction of the Measures of REC Demand

We first construct a variable denoting the quantity of RECs required for RPS compliance in a given state s in year t, $\textit{In-State REC Demand}_{st}$. Following from our stylized model in Section 2, this would simply be the product of the total electricity sales and the RPS in a given year. However, regulators often designed RPSs to allow RECs to come from renewable capacity that existed before the RPS was implemented. To more accurately capture the demand for RECs driven by RPSs, we must identify the amount of generation coming from renewable capacity that existed before the RPS, and reduce the quantity of RECs demanded by that amount. For example, consider a state with 1,000,000 MWh of electricity sales, and a 30% RPS. Suppose this state had 20% of its electricity coming from wind before the RPS was implemented and this generation can be used to create RECs for RPS compliance. Not accounting for the existing wind generation would result in an estimate of 300,000 RECs demanded for RPS compliance even though only 100,000 MWh of additional renewable generation must be brought online. Not making this adjustment would lead to overestimates of RPS stringency and biased coefficient estimates. Noting this adjustment, the variable is constructed as:

$$\textit{In-State REC Demand}_{st} = \sum_{r=1}^{N_s^r} \left(\textit{Nominal RPS}_{rst} \cdot \textit{Coverage}_{rst} \cdot \textit{Sales}_{st} - \textit{Existing}_{rsT_s} \right)$$

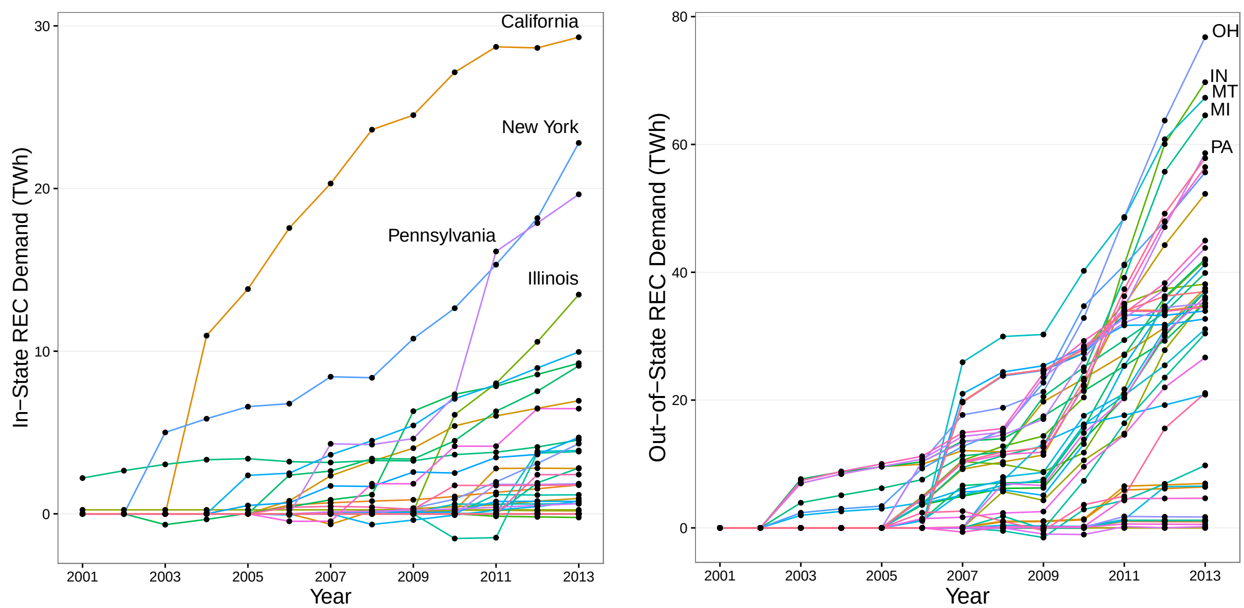
RPS types r differentiate between types of electricity providers, i.e. a state may set a different RPS for investor owned utilities (IOUs) vs municipal providers. $\textit{Nominal RPS}_{rst}$ is the stated RPS level for type r electricity providers in state s in year t.[16] State s has a total of N_s^r types for the entire sample period. Therefore, the number of RECs required for compliance for a given electricity provider type r, is just the product of RPS governing that type, $\textit{Nominal RPS}_{rst}$, the percent of the total electricity load satisfied that type, $\textit{Coverage}_{rst}$, and the state level of electricity sales, $\textit{Sales}_{st}$. Summing this quantity over types within a given state-year yields the gross number of RECs required for RPS compliance in that state-year.

$\textit{Existing}_{rsT_s}$ is the amount of electricity generation in the year prior to RPS enactment, T_s, that would be eligible to meet the RPS in future years. If generation from renewable capacity installed prior to the enactment of the RPS is not allowed for RPS compliance, then $\textit{Existing}_{rsT_s}$ is zero.[17] Once we account for generation from existing renewable capacity, this variable captures

[16] Types are further differentiated into tiers, which require a certain percentage of generation to come from specific sources. Since these are additive, we sum them into the type-level nominal RPS and omit them from the description to maintain clarity.

[17] By using this existing generation measure for all years after RPS passage, we are implicitly assuming that the existing renewable capacity will still exist and generate the same electricity throughout our sample. Since most

Figure 4: The in-state (a) and out-of-state (b) REC demand for each state.



(a) In-state demand for RECs

(b) Out-of-state demand for RECs

the additional required quantity of RECs relative to the amount of RECs obtained from renewable capacity build prior to the RPS being enacted. The left panel of Figure 4b displays this variable for each state over our sample period.

Our variable of interest is the quantity of RECs demanded by electricity providers in outside, REC trade-eligible states. This is simply the sum of the quantity of RECs demanded by all states, c, eligible to trade with state s in year t,

$$\textit{Out-of-State REC Demand}_{st} = \sum_{c \in TP_{st}} \textit{In-State REC Demand}_{ct}$$

where TP_{st} is the set of states eligible to trade RECs with state s in year t. Figure 4b displays $\textit{Out-of-State REC Demand}_{st}$ for each state and year of our sample. Out-of-state REC demand has on average increased over time as RPS requirements have surpassed existing eligible renewable capacity. However, out-of-state REC demand is neither strictly positive nor strictly increasing. A negative number of RECs demanded by state c in year t indicates that the state has a surplus of RECs and can therefore be a net seller of RECs rather than a net buyer. For example, when the tracking system NARR launched in 2009 a large number of non-RPS states came online as net sellers of RECs. This drove out-of-state REC demand below zero for several states.

renewable capacity is relatively new and has zero or low marginal costs of generation, we believe this to be a plausible assumption.

3.2 Empirical Framework

The time frame for our study is 2001-2013, allowing us to observe a total of 29 RPSs turning on and 13 states achieving an RPS above 10 percent. We perform both state level and plant level analyses of the generation responses to changes in out-of-state demand for RECs.[18] We begin with a fixed effects specification:

$$
\begin{aligned}
Y_{st} = \; & \textit{Out-of-State REC Demand}_{st}\, \beta_{out} \\
& + \textit{In-State REC Demand}_{st}\, \beta_{in} + \mathbf{X}_{st}\, \boldsymbol{\phi} + \boldsymbol{\alpha}_{s,p} + \boldsymbol{\delta}_t + \boldsymbol{\theta}_{N,t} + \varepsilon_{st}
\end{aligned} \tag{6}
$$

Our dependent variables are log generation from coal, natural gas, all fossil fuels, and wind; and the percentage of electricity that comes from fossil fuels (fossil-fuel ratio).[19] *Out-of-State REC Demand*$_{st}$ and *In-State REC Demand*$_{st}$ are the variables described in Section 3.1. $\mathbf{X}_{st}$ is a vector of state level covariates including median household income, and dummy variables for whether or not the state has a mandatory green power options, interconnection standards, and public benefits fund. $\mathbf{X}_{st}$ also includes dummy variables for whether or not the RPS policy in state s allows for RECs to be unbundled from the energy, if there's a multiplier if a REC was generated in the state, and if there is an alternative compliance payment for the state's RPS, which is effectively a price cap on RECs retired in that state. $\boldsymbol{\alpha}_{s,p}$ is a state fixed-effect for the state level analysis, and a plant fixed effect for the plant level analysis. $\boldsymbol{\delta}_t$ is a year fixed-effect and $\boldsymbol{\theta}_{N,t}$ is an region-specific time trend corresponding to the NERC regions. The year fixed effect will capture any annual federal shocks or policies such as the Renewable Electricity Production Tax Credit (PTC). We include $\boldsymbol{\theta}_{N,t}$ to capture regional trends, such as declining prices for installing renewable capacity. ε_{st} is a robust standard error clustered at the state level.

3.3 Identification

There are several potential threats to identification in our fixed effects models. One is if a state's nominal RPS was selected by legislators as a function of the expected changes in out-of-state fossil fuel generation, introducing reverse causality. Our identifying assumption is that causality only flows in one direction, however it is difficult to prove that legislators did not select their RPS based on out-of-state generation. Below we list a set of excerpts from statements by policymakers and the actual RPS legislative documents, which provide support for the assumption that RPSs are not selected as a function of out-of-state generation, but on in-state characteristics and trends.

When discussing the need for Ohio's RPS then Governor Ted Strickland (D) urged that Ohio "must implement an advanced energy portfolio standard in order to create thousands of new Ohio

[18]For our plant level analysis, we focus on plants where each fuel is the primary fuel. For example, when estimating the effect of out-of-state REC demand on coal, we include only plants where coal is deemed the primary fuel in the EIA data. This is to avoid any estimation issues that may come up from using another fuel solely during the process of spinning up the generator.

[19]Estimates of the effects on solar generation are highly unstable and are omitted from the main text. A potential reason for this is that smaller installations, such as rooftop solar, are not included in the EIA data.

jobs" (Strickland, 2007). Similarly Ohio House Speaker, Jon Husted (R), claimed that the law would "scrap last century's energy policies and create a new energy policy that embraces the environmental and economic needs of our future" and would "make Ohio a leader in renewable energy now and in the future" (Ohio House of Representatives, 2008).

In addition, in California's legislation, it is written that the law "is intended to provide unique benefits to California, including all of the following, each of which independently justifies the program: (1) Displacing fossil fuel consumption within the state, . . ., (3) Reducing air pollution in the state, [and] (4) Meeting the state's climate change goals by reducing emissions of greenhouse gases associated with electrical generation" (Public Service Commission of California, 2005).

In New York, a preliminary report by the Department of Public Service on their RPS stated "...[the RPS] can be implemented in a manner that is consistent with the wholesale and retail marketplace in New York and that an RPS has the potential to improve energy security and help diversify the state's electricity generation mix" (New York State Department of Public Service, 2002). Maryland's 2005 RPS report cites, "The benefits of electricity from renewable energy resources, including long-term decreased emissions, a healthier environment, increased energy security, and decreased reliance on and vulnerability from imported energy sources, accrue to the public at large..." (Public Service Commission of Maryland, 2005). Holt and Wiser (2007) document that other states have passed RPSs to address similar in-state concerns including energy self-sufficiency and security (New Mexico and Hawaii), enhancing the quality of the state environment (Texas), in-state job creation (Hawaii, Washington), and decreased reliance on imported energy sources (Washington D.C.). With this evidence we believe that it is unlikely policymakers are selecting RPSs as a function of out-of-state features or expectations about what may be occurring in other states in the future.

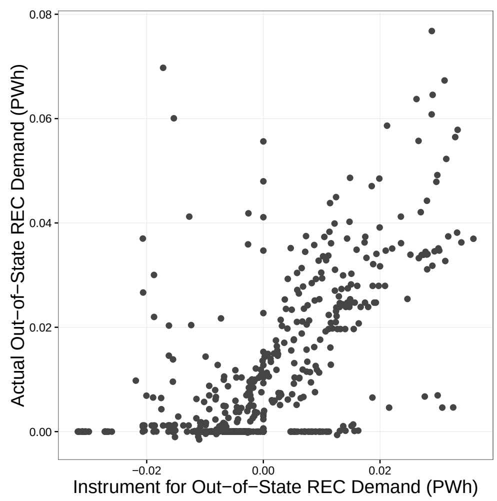
A second potential threat to identification is the possibility that policymakers could be endogenously determining from which outside states RECs can be accepted. For example, policymakers may be allowing for REC trade with renewable-abundant states so their electricity providers can more easily meet their RPS requirements.

A third threat to our identification is if states have endogenously modified their existing RPS in response to out-of-state generation or changes in out-of-state REC demand. One example of a state changing its RPS after it was enacted is California. The California RPS has been revised three times during our sample, in 2006, 2009, and 2011. Each time, the RPS schedule was made more stringent. These changes may be in response to other states' policies and out-of-state firm behavior, potentially biasing the fixed effects estimates.[20]

We address these potential threats to identification by instrumenting for *Out-of-State REC* $Demand_{st}$. Our instrument corrects for potentially endogenous REC trade eligibility between states, endogenous generation responses, and endogenous increases in RPS stringency. The instrument is a version of the out-of-state REC demand variable but with three changes. First, each state's RPS

[20]California is just one example of several states that have changed their RPS to become more stringent after it was originally passed.

Figure 5: Actual out-of-state REC demand compared to the instrumented value.



schedule is fixed at its initially passed levels to address potential endogenous changes to the RPS after it has been passed. Second, each state's electricity sales are held constant at the level in the year prior to RPS passage to ensure that all variation in our estimate is coming from out-of-state changes in RPS stringency rather than from changes in generation due to general equilibrium effects. Last, we assume that only those states within the same tracking system can trade RECs with one another to avoid endogenous selection of trading partners outside the tracking system. This set of trade partners largely lines up with ISOs and where RECs could be sold if they were unable to be unbundled from the electricity.[21]

Our identification strategy yields a local average treatment effect that is the most informative for those regions whose out-of-state REC demand is composed of a larger share of RECs demanded by states, which are within their own tracking system and which exhibit smaller deviations from originally passed RPS and baseline generation.[22] Figure 5 displays a scatter plot of observations of the potentially endogenous regressor against observations of our instrument. There is a clear and positive correlation between the two, suggesting that this is a strong instrument. Additional evidence of instrument strength is provided by the Kleibergen-Paap F-statistic from each of our first stage regressions in Tables A13 and A14 in the appendix. We dismiss concerns of a weak instrument as our first stage F-statistics are all over 21 and are larger than the relevant Stock and Yogo (2005) critical value for 10 percent maximal IV Size of 16.38.

[21]One potential example of endogenous trade partner selection is North Carolina. North Carolina developed its own state level tracking system, NC-RETS, in addition to the PJM tracking system it already belonged to. NC-RETS is compatible with NARR, WREGIS, M-RETS, and ERCOT. The selection of these trading partners is potentially a function of their generation profiles, leading our measure of out-of-state REC demand for these trading partners to be a function of their generation. This introduces reverse causality. In our instrument we do not include out-of-state REC demand that relies on these inter-tracking system linkages.

[22]Data for REC sales in 2014 suggests that most states procure RECs from within their own tracking system (Heeter et al., 2015).

3.4 Data

We construct a new dataset describing the evolution of REC trade networks over the years 2001-2013. We construct these trade relationships using data provided by Heeter et al. (2015), individual state RPS legislative documents, and a list of the potential REC trade partners for each state created by Holt (2014). We obtain data on the current sets of RPS policies from DSIRE, and we obtain data on the originally passed RPSs from state legislative and public utilities commission documents, and from historical versions of the DSIRE database. For each state, our RPS data contain information on: the level of the RPS in 2001-2013, whether generation from capacity that existed before the RPS passage can be used for RPS compliance, and the percentage of a state's total electricity load that is covered by each RPS type. Our data also detail whether a state has a REC multiplier policy which gives firms additional RECs for in-state renewable generation, and whether the state has an alternative compliance penalty, a penalty the firm must pay for each REC it is short of the RPS in a given year.[23] Unlike other states, Texas and Iowa have capacity standards which we translate into an intensity standard by using the average capacity factors for each type of renewable energy and generation data for each year. If the capacity factor is not available we use a default of 0.35 (Yin and Powers, 2010).

We use DSIRE to collect data on non-RPS renewable energy policies including mandatory green power options, public benefits funds, and interconnection standards. Mandatory green power options require electric providers to give end-use consumers the option to buy power from renewable sources, public benefits funds are pools of funding for research and implementation of energy efficiency and renewable energy projects, and interconnection standards set rules for connecting distributed generation facilities to the grid. Each of these policies has a direct impact on state level demand and costs of renewable energy.

We collect data on electricity sales, generation and CO_2 emissions from the EIA. Sales data are collected from EIA form 861. Generator-level generation data are obtained from EIA forms 906, 920 and 923. Generator-level capacities are collected from EIA form 860.[24] We aggregate the generator level data up to the state level for our main analysis. We collect capacity data since several states set a maximum threshold capacity on hydroelectric generators for generation to count as renewable, and a subset of these states also allow for existing capacity to count towards the RPS. Therefore when we build the REC demand variables, we must account for which hydroelectric generators satisfy the capacity threshold outlined in the RPS legislation.

The distribution of generation between fossil fuels and renewables within a state may be driven by preferences and beliefs of its constituents. To capture state level green preferences, we use the average score given to each state's senate and house members from the League of Conservation Voters (LCV). Jointly with environmental groups, the LCV develops a list of bills in congress that have crucial environmental implications and assigns a score to each member of congress based on

[23]The alternative compliance payment effectively sets a cap on the REC price firms face in a state.

[24]The previous literature has found that the percentage of electricity load served by different types of providers is stable over time and opted to construct the electricity coverage variable by imputing the current year's observation for all years (Yin and Powers, 2010). We follow the standard set in the RPS literature.

how often they vote in alignment with a pro-environmental stance. LCV scores range from 0-100 and higher scores indicate that the congressperson has taken a more pro-environmental stance with their voting. We obtain median household income from the Current Population Survey (CPS).

Table A1 displays both plant and state summary statistics. The average state generates 37 TWh of coal electricity annually. There is substantial variation across states and over time. Some states such as Rhode Island have no coal generation while other states such as Texas are generating over 100 TWh from coal per year. Over time most states display a decline in coal generation, spurred by advances in natural gas extraction and the proliferation of renewables, although there are several states that have brought new coal plants online during our sample. There is also substantial variation in out-of-state demand for RECs, ranging from -1.5 TWh to 77 TWh. A minority of RPS states have multiplier bonuses for RECs generated in state while a majority of RPS states have alternative compliance payments. Less than half the total number of states have the other included energy policies. League of Conservation Voters (LCV) scores span the entire range of possible scores.

3.5 Results

Section A.1 contains the tables of our main results at the state and plant levels. Each table presents three fixed effects regressions and our preferred instrumental variables specification for a series of dependent generation variables. Each specification controls for year effects and either state or plant fixed effects. The first specification begins with only out-of-state REC demand as a control variable, in the second specification we add in other controls, and in the third specification, which corresponds to Equation (6), we add a NERC region specific time trend. In the final specification we instrument for out-of-state REC demand to address endogenous policy adjustments, endogenous generation responses, and endogenous REC market formation. The Kleibergen-Paap F-statistic from our first-stage estimate is reported under the coefficient estimates.[25]

To facilitate interpretation of our results, plots of our main fixed effects and instrumental variables estimates are presented in Figures 6a and 6b. Each point corresponds to the estimated percentage change in generation due to a one standard deviation increase in out-of-state REC demand. A one standard deviation increase in out-of-state REC demand corresponds to a 0.014 petawatt-hour (PWh) increase in renewable generation requirements, or an increase of 14 million RECs demanded.[26] Figure 6a depicts the results for aggregate generation at the state level, and Figure 6b depicts the results for plant level generation by plant-type.[27] The estimates plotted by the orange triangles are derived from our fixed effects specification, Equation 6. The estimates plotted by blue circles come from our instrumental variables specification.

Figure 6a conveys several key findings. First, is that a one standard deviation increase in out-of-state REC demand results in a 14.7% reduction in coal generation at the state level, and a

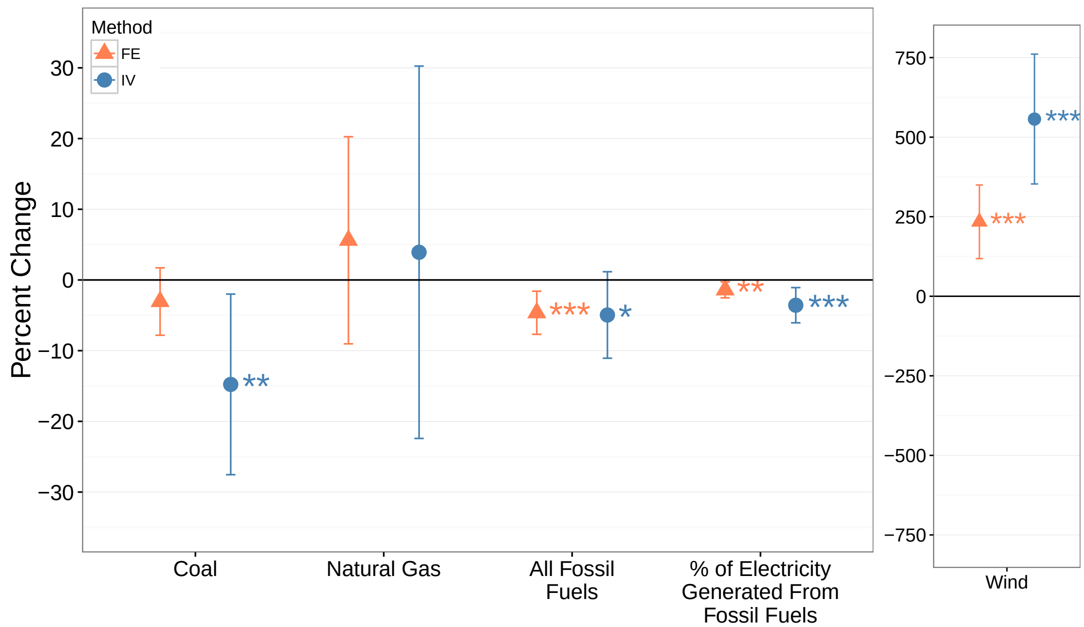
[25]The full first stage results for all IV specifications used in the paper are reported in Tables A13 and A14 of the Appendix.

[26]1 PWh is equivalent to 1 billion MWh.

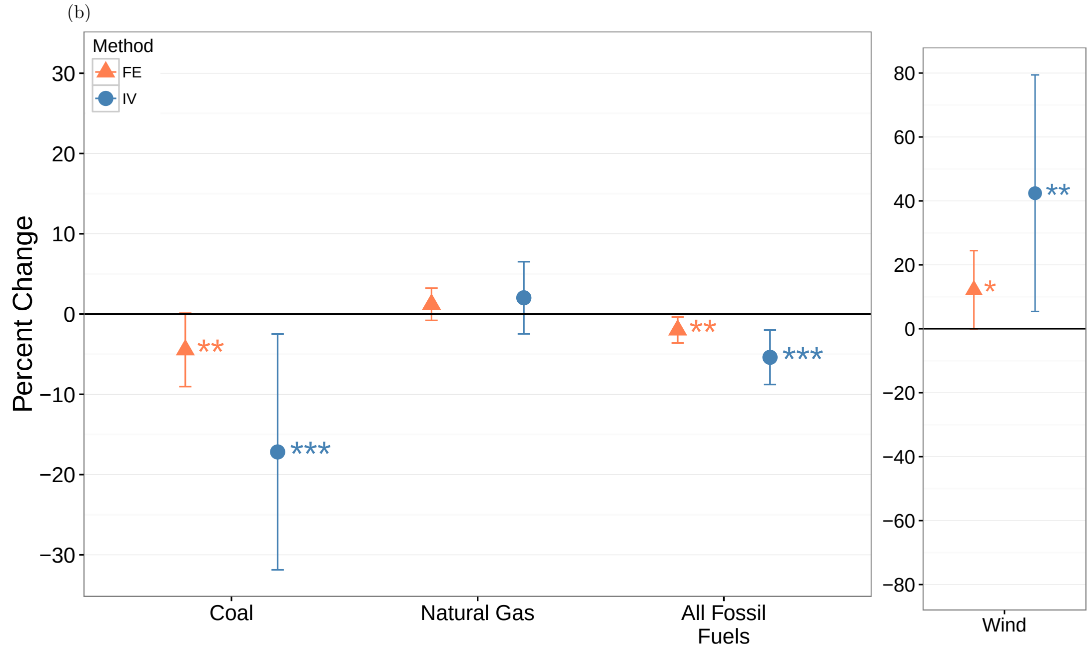
[27]We define a plant as a coal plant if its primary fuel source is coal. Other plants are defined similarly.

Figure 6: The percentage change in state level (a) and plant level (b) generation by type caused by a one standard deviation (.014) increase in out-of-state REC demand (PWh).

(a)



(b)



Note: * p < 0.1, ** p < 0.05, *** p < 0.01. Standard errors clustered at the state level. The bars represent 95% confidence intervals. % electricity generated is not included in the plant level panel as the majority of plants produce electricity from either completely renewable or completely fossil fuel sources. Each coefficient is from a separate specification. Tables reporting complete coefficients for each specification and the first-stage results for the IV specifications can be found in the Appendix.

17.1% reduction in coal generation at the plant level. This result is consistent with our theoretical prediction in Section 2 that an increase in the quantity of RECs demanded in outside REC trade-eligible states should decrease in-state fossil fuel generation. However, in both specifications at both the state and plant level, we do not obtain a precise estimate of the impact on natural gas generation. The estimated coefficients for the natural gas regression are positive but statistically insignificant. One potential reason that natural gas generation may not definitively decline in out-of-state REC demand is that natural gas plants have more flexible generation than coal plants which provides key complementaries with intermittent renewables. These complementaries may offset the effects of the implicit non-renewable tax imposed by RPSs.

Second, we find that increasing out-of-state REC demand by one standard deviation will decrease total fossil fuel generation by 4.9% at the state level and 5.4% at the plant level. This indicates that we are unlikely to be spuriously picking up on a switch from coal-fired generation to gas-fired generation driven by declines in gas prices over the latter half of our sample.[28] We estimate the state level model with the percent of a state's electricity generated from fossil fuel sources as a dependent variable. A one standard deviation increase in out-of-state demand decreases state level fossil fuel intensity by 3.6%, indicating that fossil fuel generation is decreasing in both levels and intensity.

Our last finding is that increases in out-of-state REC demand is driving a substitution from coal to wind. The right set of points in each figure shows that a one-standard deviation increase in out-of-state REC demand increases wind generation by 550% at the state level and 42% at the plant level. The discrepency in the size of the two estimates is driven by the non-dispatchability of wind. Increases in generation at the plant level can only be driven by expanding capacity or random annual fluctuations, while increases in generation at the state level can also be achieved by building entirely new wind farms. Hence, our larger state level estimates suggest new wind farms are being built in addition to expanding existing wind farms. These estimates also align with our theoretical predictions that increases in out-of-state demand for RECs induces firms to increase renewable generation via a larger implicit renewable subsidy.

A common theme in our empirical results is that our IV point estimates are all larger in magnitude than the fixed effects point estimates, and in some cases, they are many times larger. This raises a question as to what about the instrument is driving this shift in the estimate. Since our instrument differs from the endogenous out-of-state REC demand variable in three ways we pre-defined, we can identify which change is causing this impact by considering only one of the three changes at a time. When isolating each change, we find that the restriction to the originally passed RPS is what drives the IV's larger point estimates. Historically, RPS revisions have almost all been to increase its stringency. Therefore, using the original, and less stringent, RPS schedule reduces the calculated amount of out-of-state REC demand as can be seen in Figure 5. A best fit line through the scatter plot would lie above the 45° line, indicating that a one unit increase in

[28]Total electricity consumption is generally increasing or constant over our sample indicating that we are unlikely picking up on a trend of decreasing electricity consumption. Estimates of our state level model with the percent of fossil fuels in the electricity mix as the dependent variable also provide evidence that this is not the case.

actual out-of-state REC demand corresponds to a smaller increase in our instrument. To obtain the same change in generation, the coefficient estimate must be larger with the instrument. Indeed this is what we should expect. If an upward revision of an RPS is endogenous, and potentially because renewable generation outpaced the standard, then the fixed effects estimate is an understatement of the true effect. However using the initially passed RPS may overstate the true effect if the interim revisions to the RPS schedule actually caused additional add-ons of renewables and reductions in coal. The true effect will lie somewhere in between the two estimates.

3.6 Robustness Checks

Although we find evidence that RPSs can induce generation changes out-of-state, perhaps this effect limited to RPS states. To explore the potential for RPSs to affect generation in non-RPS states we estimate generation responses for solely non-RPS states. Tables A15 and A16 in the Appendix display state and plant level instrumental variables estimates for the coefficient on the out-of-state REC demand variable when states with RPSs are dropped from the sample, but are still included in construction of the REC demand variables. The main results hold for all dependent variables at the state level and all but wind at the plant level, which has a similar point estimate, but is not statistically significant due to a weak instrument. The estimates at both the state and plant levels are not statistically different from the estimates using the full sample.[29]

An alternative way to examine the effect of out-of-state REC demand on fossil fuel generation is to examine its effect on fossil fuel emissions. If increases in out-of-state REC demand are actually reducing coal use then we should also find decreases in coal-fired emissions. Since coal is a carbon dense fuel, the largest emissions effect should be on carbon dioxide (CO_2). Table A17 in the Appendix displays state level results with CO_2 emissions as the dependent variable.

The first set of results show that an increase of out-of-state demand by 1 MWh, a single REC, results in a statistically significant reduction of 129 kg of carbon dioxide emissions. In the second set of results, we include aggregate state level coal generation as a control variable. If the decreases in CO_2 are due to reductions in coal combustion induced by out-of-state REC demand then the inclusion of coal generation as a regressor should absorb all of the out-of-state REC effect. But, if the out-of-state REC coefficient remains significant after the inclusion of coal then the emissions reductions may be a spurious finding or they could be due to decreases in other fossil fuels. As expected, the inclusion of coal generation absorbs all of the explanatory power of out-of-state REC demand for emissions, providing further evidence that coal generation reductions are in fact caused by increased out-of-state REC demand.

As a final robustness check, we explore the effect of another large-scale energy policy: the regional greenhouse gas initiative (RGGI). RGGI has nine member states mostly located in the Northeastern US. It is a cap and trade program for carbon dioxide emissions, where allowances for CO_2 usage are auctioned on a quarterly basis. If prices in the RGGI permit market are varying

[29]Our results also hold when interacting out-of-state REC demand with a binary for whether a state has an RPS instead of doing a subsample analysis.

systematically with out-of-state REC demand than we may be finding an effect of RPSs when there is none.

We control for the effect of RGGI by adding a dummy variable that is equal to 1 if a state is in RGGI and is zero otherwise. We also include an interaction of RGGI membership with CO_2 allowance price to capture the shadow cost of the policy. Finally, we control for the industrial natural gas price as an additional check for robustness against the declining natural gas prices over the past several years. The results from this final check are displayed in Tables A19 and A20 in the Appendix. Our results show that RGGI leads to decreases in coal generation, but the out-of-state REC demand effect is still negative and statistically significant. Findings for total fossil fuel generation, percent of electricity from fossil fuels, and wind generation are also robust to the inclusion of RGGI controls.

4 External Benefits from Out-of-State Coal Generation Reductions

Riders, rate hikes to retail electricity consumers, are the most common method used to fund RPSs. The size of a rider is typically set to offset the increased costs of forcing electricity providers to procure a larger portion of their electricity mix from renewable sources. These rate hikes are borne only by the retail customers in the state mandating the RPS. While most of the costs are internalized within the regulated state, our empirical evidence shows that generators in external states are responding to the RPS so these states may also be reaping some of the RPS benefits.[30] This section provides ballpark estimates of both the spatial distribution and the magnitude of external benefits from avoided local pollution.[31] The spatial distribution is important because the costs of the policy are primarily located in the state which passed the RPS. Additionally, the distribution of the benefits is not obvious because only some states have passed RPSs, these states have passed RPSs with different stringencies, there is heterogeneity in the emissions rates of plants, emitted local pollutants are dispersed non-uniformly over space, and there is spatial heterogeneity in damages due to spatial differences in population, farmland, and other dimensions.

In Section 4.1, we describe how we combine our plant level estimate of the coal generation response to out-of-state REC demand with plant-specific emissions rates to obtain plant-specific emissions responses to out-of-state REC demand. In Section 4.2, we outline how we combine these plant-specific emissions responses with the APEEP model. The APEEP model allows us to determine to which counties the avoided coal-fired emissions would have been transported, how the reductions in transported emissions reduce ambient atmospheric concentrations of the pollutants in these counties, and what is the value of the reduced pollution because of avoided deaths, agricultural damage, and other impacts. Additional details on the APEEP model can be found in Muller and

[30]The air quality benefits will never be fully internalized within a state, but having emissions reductions occur in-state would generally provide larger reductions of in-state pollution concentrations. Also if RECs are being imported from out-of-state then the RPS passing state is also not obtaining the maximum potential increase in green jobs if that happened to be a goal of the RPS.

[31]Others such as Cullen (2013), Kaffine et al. (2013), and Novan (2015) have estimated the emissions impact of renewable energy using high frequency fluctuations in wind or solar generation instead of directly using policy.

Mendelsohn (2012).

The end result of this welfare analysis is an estimate of the avoided pollution benefits summed up over the entire contiguous United States from a 1 percentage point increase of a state's RPS, but solely through the REC market channel estimated in Section 3. An important point to note is that some of the pollutants in the welfare analysis, namely SO_2 and NO_x, are regulated under cap-and-trade systems so that RPSs would not affect aggregate emissions, but only shift emissions across space. However, in 2011 and 2012, SO_2 and NO_x permit prices were at historic lows and very close to \$0. In 2011 the market clearing price for an SO_2 permit was \$2.00 and the in 2012 the market clearing price was \$0.56, down from over \$35 in the previous two years and from historic highs of over \$800 in 2006 (EPA, 2016).[32] Over 2007-2011, NO_x prices followed a similar trajectory and plummeted by approximately 98% (EPA, 2012).[33] We perform our welfare analysis using RPS increases between 2011 and 2012 assuming that these near-zero permit prices are a good approximation to SO_2 and NO_x markets being completely slack. Under this assumption, RPSs can induce aggregate emissions reductions.

4.1 Plant Specific Emissions Factors

We calculate an annual average plant-specific emissions factor for a given pollutant as the number of pounds of that pollutant emitted per MWh of electricity generation. Creating a plant-specific emissions factor is necessary to determine emissions since plants use different types of coal and plants also employ different abatement technologies. We link emissions data from the 2011 National Emissions Inventory (NEI) to plant level generation data from the EIA to calculate a plant-specific emissions factor. We restrict our analysis to coal plants whose primary census designation is the sale of electricity. The NEI reports total emissions in 2011 from each power plant in the United States for SO_2, NO_x, particulate matter (PM 2.5 and PM 10), volatile organic compounds (VOCs), and ammonia (NH_3). The NEI data come primarily from the continuous emissions monitoring sources data. We generate a plant-specific emission factor for each pollutant by dividing the total pounds emitted of each pollutant by the total MWh of electricity generation for every plant. Others have noted that introducing more intermittent renewable generation on the electricity grid can endogenously alter a plant's emissions rate if it's a marginal producer (Cullen, 2013; Novan, 2015), however given the annual nature of our estimates we do not account for this.

Table A1 displays summary statistics for the plant specific emissions factors by pollutant. There is substantial variation in emissions rates across plants, indicating that generation reductions will not have the same emissions impact across coal plants. Indeed, some plants have emissions factors of 50 or even 100 times greater than the mean.

[32]These are the spot auction prices, 7 year advance auction prices are typically even lower.

[33]Two major factors in the price collapse are the Clean Air Interstate Rule being struck down in 2008 and the shale revolution during this time frame.

4.2 Modeling Emissions Transport and Heterogeneous Damages

The benefits from avoided emissions at any given plant are not homogeneous across space. Indeed, fossil fuel emissions like SO_2, NO_x, particulate matter (PM), volatile organic compounds (VOCs), and ammonia (NH_3) can be transported substantial distances from their point source by wind, but tend to concentrate more heavily near their source. In addition, differences in county characteristics and demographics drive heterogeneity in the benefits from avoided damages. For example, a county with a higher population would, in aggregate, benefit more from a reduction in pollution concentrations than a county with a smaller population. To capture these two sources of spatial damage variation we use the APEEP integrated assessment model developed by Muller and Mendelsohn (2012). This model allows us to simulate both emissions transport and the welfare impacts of changes in pollution concentrations driven by out-of-state REC demand.[34] For each county, the APEEP model calculates how an additional unit of SO_2, NO_x, PM, VOCs, and NH_3 is transported to other counties in the United States, how the change in emissions affects ambient concentrations, and then translates changes of ambient concentration into costs in dollar terms.

4.3 Analysis of Avoided Pollution Benefits

First, we evaluate the avoided pollution benefits of a 1 percentage point RPS increase, while holding other state's RPSs constant.[35] We define a 1 percentage point increase to be a 1 percentage point increase in all RPS types (primary, secondary, tertiary) over each state's 2011 levels. For each state, we first determine the additional number of RECs that were required for RPS compliance because of the change in the RPS between 2011 and 2012.[36] Using our empirical estimates, we then determine how the increase in the number of RECs required for RPS compliance impacted coal generation in power plants located in states that are potential trading partners with the RPS increasing state. We next insert these plant level responses into the APEEP model to determine both the transport and marginal benefit of any avoided emissions. Finally, we total the benefits from the out-of-state plant responses to obtain a dollar value estimate of the benefit from a marginal increase in the state's RPS. We perform this process separately for each state that increased their RPS between 2011 and 2012.

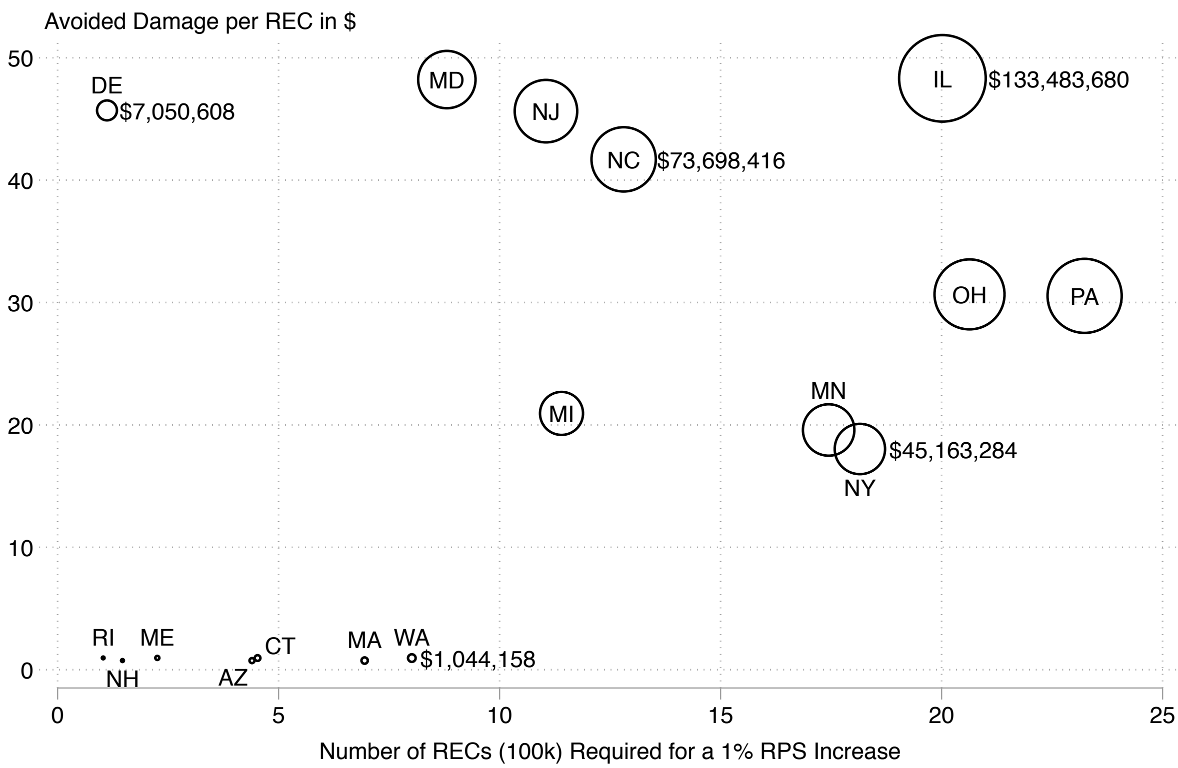
The avoided pollution benefits, summed over the entire contiguous United States, of a 1 percentage point RPS increase is displayed in Figure 7 as the size of the point corresponding to that state, with some states having the number explicitly on the plot. Again recall that these benefits are only calculated via the out-of-state REC market channel and do not capture the avoided pollution benefits of any in-state coal reductions in response to an RPS. Benefits range from just above $100,000

[34]See Muller and Mendelsohn (2007, 2009); Muller et al. (2011); Holland et al. (2015) for other work using the APEEP and AP2 models.

[35]We consider only a 1 percentage point RPS increase rather than large increases to ensure that our counterfactual remains grounded within the observed RPS levels in our full sample. It is unlikely that our estimates would be able to reliably inform us about out-of-state coal responses to RPS levels above what we observe in our data.

[36]Thus we do not have welfare estimates for those states, such as California, that did not increase their RPS from 2011 to 2012.

Figure 7: The aggregate avoided pollution benefit of a marginal REC (vertical axis), the number of RECs required to satisfy a 1 percentage point increase in the RPS (horizontal axis) and the total avoided pollution benefits from a 1 percentage point RPS increase (point size).

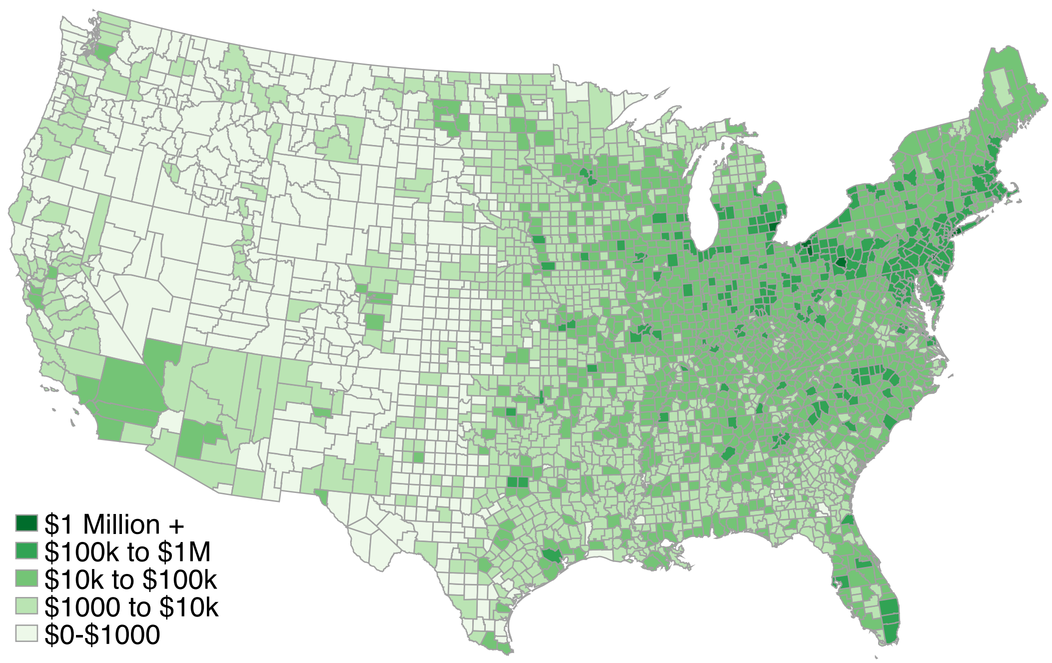


Note: Size of circle displays aggregate U.S. benefit from the out-of-state emissions reduction induced by the reported state raising its RPS by 1%. These benefits displayed in this graph are solely from changes in out-of-state REC demand. They do not include the emissions benefits from changing generation within the state increasing the RPS. The estimate for each state assumes that all other states' RPS levels are held constant.

for RPS increases in small states such as Rhode Island, to tens of millions for North Carolina and New York, to over $100 million for Illinois. Heterogeneity in the avoided pollution benefits from a marginal RPS increase is driven by two main effects. First, some RPS states' REC trade partners have larger populations or dirtier power plants, increasing the benefits of coal generation reductions in these areas. Second, some RPS states have greater electricity consumption and larger levels of electricity sales, so that a marginal increase in the RPS leads to a bigger jump in the additional RECs required for compliance compared to states with lower electricity consumption.

Figure 7 also decomposes the aggregate U.S. benefit into these two channels. The vertical axis displays the avoided pollution benefits, again summed over the entire contiguous United States, of a state requiring one additional REC to maintain RPS compliance. The horizontal axis displays the additional number of RECs required for compliance when the RPS is increased by 1 percentage point, given that electricity sales are held fixed between the two years. The size of the the points

Figure 8: The avoided pollution benefit in each county due to a 1% increase in Illinois' RPS in 2011.



Note: The benefits displayed in this graph are solely from out-of-state REC demand. They do not include the in-state emissions benefits from changing generation within a state due to its own RPS.

on the graph correspond to the product of these two channels, scaled by a factor of 100,000. States further to the right in Figure 7 tend to be more populous states with higher levels of electricity sales, while states higher on the plot tend to have REC trade partners where coal emissions are particularly damaging.

States like Delaware, towards the top left region, have the highest marginal benefits for each REC required by its electricity providers. Delaware's REC trade partners have an abundance of coal generation and large, dense populations located near coal plants. Yet, Delaware is a small state so a marginal increase in its RPS only requires a small number of additional RECs to maintain compliance. Conversely, a state like New York has a high amount of electricity sales, so despite the fact that New York's avoided damages per REC are approximately average for states plotted in Figure 7, there is a large net impact of an RPS increase.

States in the upper right of the graph, such as Illinois, Pennsylvania, North Carolina, and Ohio have larger levels of electricity sales and also have REC trade partners with high levels of marginal damages. Correspondingly, these are the states with the largest aggregate external benefits induced by a marginal increase in their RPS stringency.

In general, RPS increases in eastern states have larger benefits due to a greater and denser population in REC trade partners, which results in larger human health benefits from avoided pollution exposure. In addition the response is magnified in the east because of its larger concentration of coal power plants, and also its larger level of overall coal generation.

To better understand where these benefits are occurring, Figure 8 displays the aggregate avoided pollution benefits in each county induced by a 1 percentage point increase in only Illinois' RPS. Darker colors indicate counties that obtained larger benefits with the darkest colors indicating counties that received over \$1 million in avoided pollution benefits. The aggregate benefit in the United States is over \$100 million.[37] Benefits range from near zero in some counties in the west, to millions of dollars for some counties in Michigan, Ohio, Pennsylvania, and New York. The counties that benefit the most are primarily large population centers that are located near coal plants, such as Cleveland, Pittsburgh, Philadelphia, and New York. Importantly, 96.5% of the benefit is occurring outside of Illinois and all of the top 20 counties in terms of benefits are outside the state of Illinois, despite the fact that the costs of the policy are borne by Illinois electricity consumers.

Although not included in this paper, in-state coal generation reductions due to RPSs should result in a greater fraction of the avoided pollution benefits occurring in-state, but by how much is unknown. Since local pollutants can be transported far from the point of emission, decreases of in-state coal generation reduce both in-state pollution concentrations and out-of-state pollution concentrations. The relative weight between the two depends on the in-state generation response to RPS, as well as plant heterogeneity in emissions factors and marginal damages across states.

5 Conclusions

Second and third-best regional policies have been implemented across the globe and are likely to see continued success. Since they represent the near-term future of environmental policy, a better understanding of their performance is necessary (Burke et al., 2016).

RPSs in the United States provide a current and economically important setting for analysis and can also provide insights for other linked sets of intensity standards such as in the European Union or the Clean Power Plan.[38] REC markets link RPS policies across states and allow for an RPS to "spillover" into other states, changing the implicit taxes and subsidies faced by firms located in outside states with any inter-state trade of the actual energy. We verify this effect empirically and find that coal generation at the state and plant levels declines as REC demand outside of that state increases. We also demonstrate how out-of-state REC demand has driven down the fraction of fossil fuels in the electricity mix and provide evidence fossil fuels are being substituted with wind energy. Moreover, these generation responses persist even in states without an RPS.

Redistributing reductions in fossil fuel generation spatially redistributes the corresponding benefits from improved air quality. We find large and heterogeneous benefits from avoided pollution through our estimated REC market channel. Given policy and energy market conditions in 2011, some states are reaping hundreds of millions of dollars worth of benefits of improved air quality, while others are benefiting less than a million dollars. Facing the loss of millions of dollars of bene-

[37]This external benefit is calculated using coefficients derived from our preferred instrumental variables specification. If instead we use the more conservative coefficient from the fixed effects specification, the aggregate external benefit in 2011 is estimated to be \$32 million. Both of the coefficients can be found in Table A3.

[38]In the European Union, there is flexibility at the country-level to adjust RPSs, and each country has a unique RPS target.

fits into other states, regulators may consider increasing restrictions on REC trade to recover some of these benefits in-state. However, we caution against suggesting that this would actually improve welfare since in-state REC and electricity prices may rise and reduce overall welfare. Regulators more focused on using RPSs for greenhouse gas reductions may also prefer more open REC trade since greenhouse gas mitigation has global benefits and more open REC trade can allocate mitigation to lower cost areas. Future work should determine how best to design an RPS, and how to best link together RPSs. It is not obvious if the current atmosphere of decentralized policies linked via renewable credit markets is even a second-best method for addressing the many externalities of fossil fuel generation from the perspective of a national policymaker.

References

Burke, M., M. Craxton, C. Kolstad, C. Onda, H. Allcott, E. Baker, L. Barrage, R. Carson, K. Gillingham, J. Graff-Zivin, et al. (2016). Opportunities for Advances in Climate Change Economics. *Science 352*(6283), 292–293.

Bushnell, J., Y. Chen, and M. Zaragoza-Watkins (2014). Downstream Regulation of CO2 Emissions in California's Electricity Sector. *Energy Policy 64*, 313–323.

Bushnell, J., C. Peterman, and C. Wolfram (2008). Local Solutions to Global Problems: Climate Change Policies and Regulatory Jurisdiction. *Review of Environmental Economics and Policy 2*(2), 175–193.

Carley, S. (2009). State Renewable Energy Electricity Policies: An Empirical Evaluation of Effectiveness. *Energy Policy 37*(8), 3071–3081.

Cullen, J. (2013). Measuring the environmental benefits of wind-generated electricity. *American Economic Journal: Economic Policy 5*(4), 107–133.

Driscoll, C. T., J. J. Buonocore, J. I. Levy, K. F. Lambert, D. Burtraw, S. B. Reid, H. Fakhraei, and J. Schwartz (2015). US Power Plant Carbon Standards and Clean Air and Health Co-Benefits. *Nature Climate Change 5*(6), 535–540.

EPA (2012). Emissions Allowance Prices for SO2 and NOx Remained Low in 2011.

EPA (2015). Why We Need a Cleaner More Efficient Power Sector.

EPA (2016). SO2 Allowance Auctions.

Fell, H. and P. Maniloff (2015). Beneficial Leakage: The Effect of the Regional Greenhouse Gas Initiative on Aggregate Emissions.

Fischer, C. (2010). Renewable portfolio standards: when do they lower energy prices? *The Energy Journal*, 101–119.

Fowlie, M. L. (2009). Incomplete Environmental Regulation, Imperfect Competition, and Emissions Leakage. *American Economic Journal: Economic Policy 1*(2), 72–112.

Fremeth, A. R. and J. M. Shaver (2014). Strategic Rationale for Responding to Extra-Jurisdictional Regulation: Evidence from Firm Adoption of Renewable Power in the US. *Strategic Management Journal 35*, 629–651.

Heeter, J., G. Barbose, L. Bird, S. Weaver, F. Flores-Espino, K. Kuskova-Burns, and R. Wiser (2014). A Survey of State-Level Cost and Benefit Estimates of Renewable Portfolio Standards. (May 2014), 1–109.

Heeter, J., P. Beiter, Francisco, Flores-Espino, D. Hurlbut, and C. Liu (2015). Quantifying the Level of Cross-State Renewable Energy Transactions. http://www.nrel.gov/docs/fy15osti/63458.pdf.

Heeter, J. and L. Bird (2011). Status and Trends in U.S. Compliance and Voluntary Renewable Energy Certificate Markets. *NREL Technical Report*.

Helfand, G. (1991). Standards Versus Standards: The Effects of Different Pollution Restrictions. *The American Economic Review 81*(3), 622–634.

Holland, S., J. Hughes, and C. Knittel (2009). Greenhouse Gas Reductions under Low Carbon Fuel Standards? *American Economic Journal: Economic Policy 1*(1), 106–146.

Holland, S. P., E. T. Mansur, A. J. Yates, and N. Z. Muller (2015). Measuring the Spatial Heterogeneity in Environmental Externalities from Driving: A Comparison of Gasoline and Electric Vehicles.

Holt, E. (2014). Potential RPS Markets for Renewable Energy Generators. *CESA Report*.

Holt, E. and L. Bird (2005). Emerging Markets for Renewable Energy Certificates: Opportunities and Challenges. (January), 76.

Holt, E., J. Sumner, and L. Bird (2011). The Role of Renewable Energy Certificates in Developing New Renewable Energy Projects. *NREL Technical Report*.

Holt, E. A. and R. H. Wiser (2007). The Treatment of Renewable Energy Certificates, Emissions Allowances, and Green Power Programs in State Renewables Portfolio Standards. *LBNL Report*.

Johnson, E. P. (2014). The cost of carbon dioxide abatement from state renewable portfolio standards. *Resource and Energy Economics 36*(2), 332–350.

Kaffine, D. T., J. Lieskovsky, and B. J. McBee (2013). Emissions savings from wind power generation in texas. *The Energy Journal 34*(1).

Lemoine, D. (2016, feb). Escape from Third-Best: Rating Emissions for Intensity Standards. *Environmental and Resource Economics*.

Lyon, T. P. and H. Yin (2010). Why Do States Adopt Renewable Portfolio Standards? An Empirical Investigation. *The Energy Journal 31*(3), 131–156.

McKitrick, R. (2005). Decentralizing a Regulatory Standard Expressed in Ratio or Intensity Form. *Energy Journal*.

Menz, F. C. and S. Vachon (2006). The Effectiveness of Different Policy Regimes for Promoting Wind Power: Experiences from the States. *Energy Policy 34*, 1786–1796.

Moss, D. and J. Cisternino (2009). *New Perspectives on Regulation.* The Tobin Project.

Muller, N. Z. and R. Mendelsohn (2007). Measuring the Damages of Air Pollution in the United States. *Journal of Environmental Economics and Management 54*(1), 1–14.

Muller, N. Z. and R. Mendelsohn (2009). Efficient Pollution Regulation: Getting the Prices Right. *American Economic Review 99*(5), 1714–1739.

Muller, N. Z. and R. Mendelsohn (2012). *Using Marginal Damages in Environmental Policy: A Study of Air Pollution in the United States* (1 ed.). Washington, D.C.: AEI Press.

Muller, N. Z., R. Mendelsohn, and W. Nordhaus (2011). Environmental Accounting for Pollution in the United States Economy. *American Economic Review 101*(5), 1649–1675.

New York State Department of Public Service (2002). 03-E-0188: Renewable Portfolio Standard.

Novan, K. (2015). Valuing the wind: renewable energy policies and air pollution avoided. *American Economic Journal: Economic Policy 7*(3), 291–326.

Ohio House of Representatives (2008). House Speaker Unveils Alternative Energy Package.

Public Service Commission of California (2005). Public Utilities Code Section 399.11-399.32.

Public Service Commission of Maryland (2005). Renewable Energy Portfolio Standard Report of 2005.

Rudik, I. (2016). Tradable Credit Markets for Intensity Standards.

Schmalensee, R. (2011). Evaluating Policies to Increase the Generation of Electricity from Renewable Energy. *CEEPR Working Paper 2011-008*.

Shrimali, G., S. Jenner, F. Groba, G. Chan, and J. Indvik (2012). Have State Renewable Portfolio Standards Really Worked? Synthesizing Past Policy Assessments to Build an Integrated Econometric Analysis of RPS effectiveness in the U.S.

Shrimali, G. and J. Kniefel (2011). Are Government Policies Effective in Promoting Deployment of Renewable Electricity Resources? *Energy Policy 39*(9), 4726–4741.

Stock, J. and M. Yogo (2005). *Testing for Weak Instruments in Linear IV Regression*, pp. 80–108. New York: Cambridge University Press.

Strickland, T. (2007). Energy, Jobs and Progress for Ohio. http://www.ohioairquality.org/energy/speech_8-29-07.asp.

Yin, H. and N. Powers (2010). Do State Renewable Portfolio Standards Promote In-State Renewable Generation. *Energy Policy 38*(2), 1140–1149.

A Appendix

A.1 Complete Specification Tables

Table A1: Summary Statistics

	Mean	S.D.	Min.	Max.	N
State Level Variables					
Coal Net Generation, TWh	36.89	36.10	0.00	157.89	650
Natural Gas Net Generation, TWh	15.70	29.10	–0.00	176.94	650
Petroleum Net Generation, TWh	1.32	4.06	–0.18	40.28	650
Fossil Fuel Net Generation, TWh	53.91	53.20	0.00	323.37	650
Solar Net Generation, TWh	0.03	0.16	–0.00	2.49	650
Wind Net Generation, TWh	1.17	3.24	0.00	35.27	650
% Electricity Generated from Fossil Fuels	0.69	0.24	0.00	1.00	650
Out-of-State REC Demand, TWh	9.25	14.47	–1.51	76.79	650
In-State REC Demand, TWh	1.22	3.77	–1.52	29.30	650
REC Multiplier Binary	0.04	0.19	0.00	1.00	650
Alternative Compliance Payment Binary	0.11	0.32	0.00	1.00	650
Mandatory Green Power Option Binary	0.10	0.30	0.00	1.00	650
Unbundled RECs Binary	0.28	0.45	0.00	1.00	650
Public Benefits Fund Binary	0.35	0.48	0.00	1.00	650
Interconnection Standards Binary	0.58	0.49	0.00	1.00	650
LCV State Senate Score	50.07	35.04	0.00	100.00	650
LCV State House Score	46.61	28.00	0.00	100.00	650
Median Income, $100k	0.54	0.08	0.37	0.79	650
Year	2007	4	2001	2013	650
Plant Level Variables					
Coal Net Generation, TWh	3.83	4.42	0.00	25.04	6264
Natural Gas Net Generation, TWh	0.58	1.32	0.00	24.33	17725
Petroleum Net Generation, TWh	0.05	0.31	0.00	6.66	16796
Fossil Fuel Net Generation, TWh	1.25	2.78	0.00	25.05	28005
Solar Net Generation, TWh	0.02	0.05	0.00	0.68	829
Wind Net Generation, TWh	0.16	0.21	0.00	2.04	4769
Coal Plant Emission Factors, 2011					
NH_3 lbs. emitted per MWh	0.02	0.08	0.00	1.08	476
NO_x lbs. emitted per MWh	4.33	12.31	0.00	201.90	476
PM 2.5 lbs. emitted per MWh	0.45	1.30	0.00	21.46	476
PM 10 lbs. emitted per MWh	0.67	2.38	0.00	46.33	476
SO_2 lbs. emitted per MWh	11.00	31.31	0.00	617.20	476
VOC lbs. emitted per MWh	0.08	0.48	0.00	9.56	476

Table A2: Effect of Out-of-State REC Demand (PWh) on Aggregate State Level Coal Generation

	(1)	(2)	(3)	(4)
Out-of-State REC Demand (PWh)	–4.75*	–4.27*	–2.14	–11.05**
	(2.57)	(2.28)	(1.66)	(4.36)
In-State REC Demand (PWh)		–26.14**	–20.65**	–21.70**
		(12.35)	(9.57)	(9.70)
REC Multiplier Binary		0.07	0.01	–0.00
		(0.11)	(0.11)	(0.14)
Alternative Compliance Payment Binary		0.10	0.03	–0.01
		(0.11)	(0.13)	(0.15)
Unbundled RECs Binary		0.04	0.10	0.16
		(0.09)	(0.11)	(0.11)
LCV State Senate Score		0.00	0.00	0.00
		(0.00)	(0.00)	(0.00)
LCV State House Score		–0.00*	–0.00	–0.00
		(0.00)	(0.00)	(0.00)
Median Income $100k		0.92	0.94	1.13*
		(0.62)	(0.59)	(0.60)
Mandatory Green Power Option Binary		0.02	0.03	–0.05
		(0.08)	(0.06)	(0.07)
Public Benefits Fund Binary		–0.39	–0.27	–0.34
		(0.33)	(0.24)	(0.23)
Interconnection Standards Binary		0.11*	0.06	0.08
		(0.06)	(0.05)	(0.05)
State Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Kleibergen-Paap F-Stat	.	.	.	45.83
Observations	650	650	650	650

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state level in parentheses.

Table A3: Effect of Out-of-State REC Demand (PWh) on Plant Level Coal Generation at Coal Plants

	(1)	(2)	(3)	(4)
Out-of-State REC Demand (PWh)	–3.73	–3.91*	–3.16**	–13.03***
	(2.30)	(2.23)	(1.59)	(5.00)
In-State REC Demand (PWh)		–4.27	0.97	–0.13
		(8.77)	(5.62)	(6.54)
REC Multiplier Binary		–0.01	0.06	0.08
		(0.11)	(0.07)	(0.11)
Alternative Compliance Payment Binary		0.06	–0.05	–0.17
		(0.08)	(0.07)	(0.13)
Unbundled RECs Binary		0.05	0.07	0.17**
		(0.07)	(0.07)	(0.08)
LCV State Senate Score		–0.00	–0.00	–0.00
		(0.00)	(0.00)	(0.00)
LCV State House Score		–0.00	0.00	–0.00
		(0.00)	(0.00)	(0.00)
Median Income $100k		0.63	0.37	0.35
		(0.55)	(0.40)	(0.42)
Mandatory Green Power Option Binary		–0.06	–0.05	–0.16
		(0.13)	(0.08)	(0.10)
Public Benefits Fund Binary		–0.09	–0.02	–0.11
		(0.20)	(0.11)	(0.10)
Interconnection Standards Binary		0.05	0.03	0.05
		(0.04)	(0.03)	(0.04)
Plant Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
Controls	No	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Kleibergen-Paap F-Stat	.	.	.	27.14
Observations	6260	6260	6260	6260

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state levels in parentheses.

Table A4: Effect of Out-of-State REC Demand (PWh) on Aggregate State Level Natural Gas Generation

	(1)	(2)	(3)	(4)
Out-of-State REC Demand (PWh)	2.66	3.11	3.77	2.66
	(5.39)	(4.73)	(4.98)	(8.71)
In-State REC Demand (PWh)		–8.63	3.33	3.20
		(17.74)	(12.29)	(12.02)
REC Multiplier Binary		0.18	–0.10	–0.10
		(0.31)	(0.22)	(0.23)
Alternative Compliance Payment Binary		–0.27	–0.12	–0.13
		(0.18)	(0.17)	(0.16)
Unbundled RECs Binary		0.18	0.35**	0.35**
		(0.16)	(0.13)	(0.16)
LCV State Senate Score		0.00	0.00**	0.00**
		(0.00)	(0.00)	(0.00)
LCV State House Score		–0.00	0.00	0.00
		(0.00)	(0.00)	(0.00)
Median Income $100k		–4.37***	–2.56**	–2.54*
		(1.59)	(1.29)	(1.29)
Mandatory Green Power Option Binary		0.08	–0.08	–0.09
		(0.20)	(0.18)	(0.18)
Public Benefits Fund Binary		0.02	0.04	0.03
		(0.13)	(0.13)	(0.14)
Interconnection Standards Binary		–0.06	0.02	0.03
		(0.16)	(0.14)	(0.15)
State Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Kleibergen-Paap F-Stat	.	.	.	45.83
Observations	650	650	650	650

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state level in parentheses.

Table A5: Effect of Out-of-State REC Demand (PWh) on Plant Level Natural Gas Generation at Natural Gas Plants

	(1)	(2)	(3)	(4)
Out-of-State REC Demand (PWh)	1.09	1.32	0.83	1.39
	(1.15)	(1.02)	(0.71)	(1.57)
In-State REC Demand (PWh)		–5.06**	0.83	0.95
		(2.56)	(1.81)	(1.91)
REC Multiplier Binary		0.07	–0.01	–0.01
		(0.05)	(0.04)	(0.04)
Alternative Compliance Payment Binary		–0.02	0.02	0.02
		(0.04)	(0.03)	(0.03)
Unbundled RECs Binary		–0.03	0.01	0.01
		(0.03)	(0.02)	(0.02)
LCV State Senate Score		–0.00	0.00	0.00
		(0.00)	(0.00)	(0.00)
LCV State House Score		–0.00	0.00	0.00
		(0.00)	(0.00)	(0.00)
Median Income $100k		–0.22	0.01	0.01
		(0.18)	(0.12)	(0.12)
Mandatory Green Power Option Binary		0.05	0.01	0.01
		(0.03)	(0.02)	(0.02)
Public Benefits Fund Binary		–0.02	–0.02	–0.02
		(0.02)	(0.02)	(0.02)
Interconnection Standards Binary		0.01	0.01	0.01
		(0.02)	(0.01)	(0.01)
Plant Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
Controls	No	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Kleibergen-Paap F-Stat	.	.	.	32.71
Observations	17616	17616	17616	17616

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state levels in parentheses.

Table A6: Effect of Out-of-State REC Demand (PWh) on Aggregate State Level Total Fossil Fuel Generation

	(1)	(2)	(3)	(4)
Out-of-State REC Demand (PWh)	–3.48***	–4.01***	–3.29***	–3.51*
	(1.25)	(1.37)	(1.07)	(2.12)
In-State REC Demand (PWh)		2.05	4.66	4.64
		(4.50)	(4.92)	(4.96)
REC Multiplier Binary		–0.10	–0.09	–0.09
		(0.08)	(0.09)	(0.09)
Alternative Compliance Payment Binary		0.01	–0.05	–0.05
		(0.07)	(0.08)	(0.08)
Unbundled RECs Binary		0.05	0.10	0.10
		(0.05)	(0.07)	(0.07)
LCV State Senate Score		–0.00	–0.00	–0.00
		(0.00)	(0.00)	(0.00)
LCV State House Score		0.00	0.00	0.00
		(0.00)	(0.00)	(0.00)
Median Income $100k		–0.31	–0.24	–0.24
		(0.27)	(0.23)	(0.23)
Mandatory Green Power Option Binary		–0.00	0.00	–0.00
		(0.06)	(0.05)	(0.06)
Public Benefits Fund Binary		–0.03	0.03	0.03
		(0.09)	(0.12)	(0.12)
Interconnection Standards Binary		0.05	0.03	0.03
		(0.05)	(0.04)	(0.03)
State Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Kleibergen-Paap F-Stat	.	.	.	45.83
Observations	650	650	650	650

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state level in parentheses.

Table A7: Effect of Out-of-State REC Demand (PWh) on Plant Level Total Fossil Fuel Generation at All Fossil Fuel Plants

	(1)	(2)	(3)	(4)
Out-of-State REC Demand (PWh)	–1.51*	–1.25*	–1.39**	–3.83***
	(0.80)	(0.65)	(0.57)	(1.19)
In-State REC Demand (PWh)		–4.64***	–0.62	–0.87
		(1.62)	(1.52)	(1.57)
REC Multiplier Binary		0.02	–0.04	–0.03
		(0.02)	(0.03)	(0.04)
Alternative Compliance Payment Binary		0.01	–0.00	–0.02
		(0.03)	(0.03)	(0.04)
Unbundled RECs Binary		–0.03	0.01	0.04**
		(0.02)	(0.02)	(0.02)
LCV State Senate Score		0.00	0.00	0.00
		(0.00)	(0.00)	(0.00)
LCV State House Score		–0.00	0.00	0.00
		(0.00)	(0.00)	(0.00)
Median Income $100k		–0.21	–0.04	–0.04
		(0.14)	(0.13)	(0.14)
Mandatory Green Power Option Binary		0.02	–0.00	–0.02
		(0.02)	(0.02)	(0.02)
Public Benefits Fund Binary		–0.05	–0.05*	–0.07**
		(0.05)	(0.03)	(0.03)
Interconnection Standards Binary		0.01	0.02**	0.03***
		(0.02)	(0.01)	(0.01)
Plant Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
Controls	No	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Kleibergen-Paap F-Stat	.	.	.	43.83
Observations	27877	27877	27877	27877

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state levels in parentheses.

Table A8: Effect of Out-of-State REC Demand (PWh) on Aggregate State Level Solar Generation

	(1)	(2)	(3)	(4)
Out-of-State REC Demand (PWh)	8.15	–15.66	3.21	103.71***
	(23.72)	(23.73)	(23.74)	(38.90)
In-State REC Demand (PWh)		190.11*	183.21*	195.11**
		(109.78)	(108.76)	(84.21)
REC Multiplier Binary		–2.23	–2.23	–2.06
		(1.85)	(1.76)	(2.12)
Alternative Compliance Payment Binary		0.13	0.58	0.98
		(1.61)	(1.65)	(2.15)
Unbundled RECs Binary		1.51**	0.92	0.18
		(0.74)	(0.67)	(0.68)
LCV State Senate Score		0.01	0.01	0.01
		(0.01)	(0.01)	(0.01)
LCV State House Score		0.02**	0.02**	0.02***
		(0.01)	(0.01)	(0.01)
Median Income $100k		–5.57	–6.36	–8.54**
		(4.17)	(4.07)	(4.08)
Mandatory Green Power Option Binary		–1.02*	–0.36	0.57
		(0.51)	(0.38)	(0.39)
Public Benefits Fund Binary		–1.18	–0.52	0.18
		(1.12)	(0.86)	(0.86)
Interconnection Standards Binary		0.60	0.38	0.15
		(0.43)	(0.34)	(0.36)
State Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Kleibergen-Paap F-Stat	.	.	.	45.83
Observations	650	650	650	650

Note: These results are not included in our paper due to the small sample size, the lack of power in the IV at the plant level, and the inconsistency of the results across specifications.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state level in parentheses.

Table A9: Effect of Out-of-State REC Demand (PWh) on Plant Level Solar Generation at Solar Plants

	(1)	(2)	(3)	(4)
Out-of-State REC Demand (PWh)	15.12	25.16*	–59.67***	–442.28
	(17.59)	(13.66)	(18.80)	(734.28)
In-State REC Demand (PWh)		10.47	–44.82**	–244.38
		(25.60)	(19.64)	(360.67)
REC Multiplier Binary		0.64	0.45	–1.84
		(0.59)	(0.34)	(5.79)
Alternative Compliance Payment Binary		–0.39	0.11	3.53
		(0.46)	(0.31)	(7.72)
LCV State Senate Score		0.00	0.00	–0.01
		(0.00)	(0.01)	(0.03)
LCV State House Score		–0.01	0.01	0.03
		(0.01)	(0.01)	(0.03)
Median Income $100k		–4.93	–5.33*	–4.18
		(3.94)	(3.01)	(6.77)
Interconnection Standards Binary		–0.07	0.42	2.44
		(0.42)	(0.26)	(3.39)
Plant Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
Controls	No	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Kleibergen-Paap F-Stat	.	.	.	0.27
Observations	684	684	684	684

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state levels in parentheses.

Note: These results are not included in our paper due to the small sample size, the lack of power in the IV at the plant level, and the inconsistency of the results across specifications..

Table A10: Effect of Out-of-State REC Demand (PWh) on Aggregate State Level Wind Generation

	(1)	(2)	(3)	(4)
Out-of-State REC Demand (PWh)	80.97***	89.87***	83.35***	130.10***
	(29.38)	(28.17)	(32.07)	(49.31)
In-State REC Demand (PWh)		–46.43	–80.57	–75.04
		(77.20)	(88.32)	(85.95)
REC Multiplier Binary		–1.18	–0.14	–0.06
		(1.77)	(1.79)	(1.77)
Alternative Compliance Payment Binary		2.14*	1.42	1.60
		(1.08)	(1.14)	(0.99)
Unbundled RECs Binary		–0.70	–1.00	–1.34
		(0.92)	(0.94)	(1.00)
LCV State Senate Score		0.00	–0.00	–0.00
		(0.01)	(0.01)	(0.01)
LCV State House Score		0.00	–0.00	–0.00
		(0.01)	(0.01)	(0.01)
Median Income $100k		11.96*	6.94	5.93
		(6.67)	(5.95)	(5.72)
Mandatory Green Power Option Binary		2.14	2.47	2.90*
		(1.96)	(1.79)	(1.76)
Public Benefits Fund Binary		1.67	1.56	1.89
		(1.91)	(2.12)	(2.15)
Interconnection Standards Binary		1.39*	1.21*	1.10
		(0.77)	(0.70)	(0.71)
State Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Kleibergen-Paap F-Stat	.	.	.	45.83
Observations	650	650	650	650

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state level in parentheses.

Table A11: Effect of Out-of-State REC Demand (PWh) on Plant Level Wind Generation on Wind Farms

	(1)	(2)	(3)	(4)
Out-of-State REC Demand (PWh)	5.21*	5.50**	7.96*	24.44**
	(3.13)	(2.73)	(4.18)	(11.95)
In-State REC Demand (PWh)		3.55	9.11	13.97
		(2.94)	(5.96)	(9.29)
REC Multiplier Binary		–0.16	–0.23	–0.41
		(0.25)	(0.26)	(0.27)
Alternative Compliance Payment Binary		0.05	0.09	0.30
		(0.25)	(0.28)	(0.30)
Unbundled RECs Binary		–0.05	–0.06	–0.13
		(0.12)	(0.15)	(0.18)
LCV State Senate Score		–0.00	–0.00	–0.00
		(0.00)	(0.00)	(0.00)
LCV State House Score		–0.00	0.00	0.00
		(0.00)	(0.00)	(0.00)
Median Income $100k		0.66	0.44	–0.60
		(1.36)	(1.44)	(1.89)
Mandatory Green Power Option Binary		0.69***	0.65***	0.75***
		(0.08)	(0.10)	(0.12)
Public Benefits Fund Binary		–0.19*	–0.19	–0.02
		(0.11)	(0.15)	(0.21)
Interconnection Standards Binary		0.05	0.08	0.01
		(0.09)	(0.10)	(0.13)
Plant Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
Controls	No	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Kleibergen-Paap F-Stat	.	.	.	21.76
Observations	4721	4721	4721	4721

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state levels in parentheses.

Table A12: Effect of Out-of-State REC Demand (PWh) on State Level Percentage of Electricity Sourced from Fossil Fuels

	(1)	(2)	(3)	(4)
Out-of-State REC Demand (PWh)	–0.73*	–0.71*	–0.98**	–2.51***
	(0.36)	(0.36)	(0.40)	(0.87)
In-State REC Demand (PWh)		1.44	0.94	0.75
		(1.13)	(0.96)	(0.92)
REC Multiplier Binary		–0.00	0.01	0.01
		(0.03)	(0.03)	(0.03)
Alternative Compliance Payment Binary		–0.01	–0.02	–0.02
		(0.02)	(0.02)	(0.03)
Unbundled RECs Binary		–0.00	–0.00	0.01
		(0.01)	(0.01)	(0.01)
LCV State Senate Score		–0.00	–0.00	–0.00
		(0.00)	(0.00)	(0.00)
LCV State House Score		0.00	0.00	0.00
		(0.00)	(0.00)	(0.00)
Median Income $100k		–0.22**	–0.20**	–0.17*
		(0.10)	(0.09)	(0.09)
Mandatory Green Power Option Binary		0.00	0.00	–0.01
		(0.01)	(0.01)	(0.01)
Public Benefits Fund Binary		0.01	0.01	–0.00
		(0.02)	(0.02)	(0.02)
Interconnection Standards Binary		0.00	0.00	0.00
		(0.01)	(0.01)	(0.01)
State Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Kleibergen-Paap F-Stat	.	.	.	45.83
Observations	650	650	650	650

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state level in parentheses.

A.2 First Stage Tables

Table A13: First Stage of State Level IV Regressions

	(1) Out-of-State REC Demand (PWh)
Instrument for Out-of-State REC Demand (PWh)	0.40***
	(0.06)
In-State REC Demand (PWh)	0.20
	(0.22)
REC Multiplier Binary	–0.00
	(0.01)
Alternative Compliance Payment Binary	–0.00
	(0.01)
Unbundled RECs Binary	0.00**
	(0.00)
LCV State Senate Score	–0.00
	(0.00)
LCV State House Score	–0.00
	(0.00)
Median Income $100k	0.01
	(0.01)
Mandatory Green Power Option Binary	–0.01***
	(0.00)
Public Benefits Fund Binary	–0.01***
	(0.00)
Interconnection Standards Binary	0.00**
	(0.00)
State Fixed-Effects	Yes
Year Fixed-Effects	Yes
Controls	Yes
NERC-Specific Time Trends	Yes
IV	Yes
Kleibergen-Paap F-Stat	45.83
Observations	650

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state level in parentheses.

Table A14: First Stage of Plant Level IV Regressions

	(1) Coal Net Gen, Log TWh	(2) NG Net Gen, Log TWh	(3) Pet Net Gen, Log TWh	(4) All Fossil Fuel Net Gen, Log TWh	(5) Solar Net Gen, Log TWh	(6) Wind Net Gen, Log TWh
Instrument for Out-of-State REC Demand (PWh)	0.40***	0.46***	0.46***	0.45***	–0.11	0.46***
	(0.08)	(0.08)	(0.06)	(0.07)	(0.21)	(0.10)
In-State REC Demand (PWh)	0.05	0.25	0.25*	0.21	–0.65*	0.25
	(0.20)	(0.18)	(0.14)	(0.13)	(0.36)	(0.21)
REC Multiplier Binary	0.00	0.01	0.00	0.00	–0.01***	0.01**
	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Alternative Compliance Payment Binary	–0.01	–0.01**	–0.01*	–0.01**	0.01***	–0.01**
	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Unbundled RECs Binary	0.01***	0.01**	0.00*	0.01**		0.00*
	(0.00)	(0.00)	(0.00)	(0.00)		(0.00)
LCV State Senate Score	–0.00*	–0.00	–0.00	–0.00	–0.00	0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
LCV State House Score	0.00	0.00	0.00	0.00	0.00	–0.00**
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Median Income $100k	–0.01	–0.01	–0.01	–0.01	0.00	0.05***
	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)	(0.01)
Mandatory Green Power Option Binary	–0.01***	–0.01**	–0.01***	–0.01***		–0.00
	(0.00)	(0.00)	(0.00)	(0.00)		(0.00)
Public Benefits Fund Binary	–0.01***	–0.01***	–0.01***	–0.01***		–0.01**
	(0.00)	(0.00)	(0.00)	(0.00)		(0.00)
Interconnection Standards Binary	0.00**	0.00***	0.00**	0.00***	0.01**	0.00***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Plant Fixed-Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
NERC-Specific Time Trends	Yes	Yes	Yes	Yes	Yes	Yes
IV	Yes	Yes	Yes	Yes	Yes	Yes
Kleibergen-Paap F-Stat	27.14	32.71	50.05	43.83	0.27	21.76
Observations	6260	17616	16677	27877	684	4721

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state levels in parentheses.

Note: The results for solar are not included in our paper due to the small sample size, the lack of power in the IV at the plant level, and the inconsistency of the results across specifications. The lack of power in the plant level IV is evidenced in this table by an F-Stat of .27. This is likely due to a small sample size due to the small number of electricity plants that use solar electricity in the United States. See Tables A8 and A9 in the Appendix for tables presenting the full specifications for solar.

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A.3 Robustness Check: Drop RPS States

Table A15: Robustness Check: Effect of Out-of-State REC Demand (PWh) on Aggregate State Level Generation by Source only in States without an RPS

	(1)
Coal Generation (Log MWh)	
Out-of-State REC Demand (PWh)	–7.29*
	(3.75)
Natural Gas Generation (Log MWh)	
Out-of-State REC Demand (PWh)	–2.82
	(15.23)
Total Fossil Fuel Generation (Log MWh)	
Out-of-State REC Demand (PWh)	–5.99**
	(3.02)
Wind Generation (Log MWh)	
Out-of-State REC Demand (PWh)	110.72**
	(54.76)
% Electricity Generated from Fossil Fuels	
Out-of-State REC Demand (PWh)	–3.50***
	(1.26)
State Fixed Effects	Yes
Year Fixed Effects	Yes
Controls	Yes
NERC Specific Time Trends	Yes
IV	Yes
Kleibergen-Paap F-Stat	27.03
Observations	452

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state level in parentheses.

Table A16: Robustness Check: Effect of Out-of-State REC Demand (PWh) on Plant Level Generation by Plant Type only in States without an RPS

	(1)
Coal Generation (Log MWh)	
Out-of-State REC Demand (PWh)	–16.85**
	(7.12)
Kleibergen-Paap F-Stat	27.49
Observations	4443
Natural Gas Generation (Log MWh)	
Out-of-State REC Demand (PWh)	–0.93
	(1.93)
Kleibergen-Paap F-Stat	17.32
Observations	10288
Total Fossil Fuel Generation (Log MWh)	
Out-of-State REC Demand (PWh)	–5.93***
	(1.38)
Kleibergen-Paap F-Stat	30.56
Observations	17149
Wind Generation (Log MWh)	
Out-of-State REC Demand (PWh)	86.54
	(77.45)
Kleibergen-Paap F-Stat	1.47
Observations	1817
Plant Fixed Effects	Yes
Year Fixed Effects	Yes
Controls	Yes
NERC Specific Time Trends	Yes
IV	Yes

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state levels in parentheses.

A.4 Robustness Check: State Level Emissions Check

Table A17: Robustness Check: Effect of Out-of-State REC Demand (PWh) on State Level Emissions

	(1)	(2)	(3)	(4)
CO_2 from Electric Power Industry, Million Metric Tons				
Out-of-State REC Demand (PWh)	–118.00**	–113.12**	–150.72***	–128.51**
	(57.23)	(50.70)	(46.74)	(64.42)
In-State REC Demand (PWh)		–267.81*	–358.21***	–355.58***
		(150.71)	(127.43)	(128.44)
Kleibergen-Paap F-Stat	.	.	.	45.83
CO_2 from Electric Power Industry, Million Metric Tons				
Out-of-State REC Demand (PWh)	–17.99	–16.81	–17.19	20.01
	(23.52)	(20.25)	(15.31)	(35.07)
In-State REC Demand (PWh)		–156.57	–88.76	–78.55
		(145.40)	(117.73)	(118.20)
Coal Generation, TWh	0.71***	0.71***	0.77***	0.79***
	(0.04)	(0.04)	(0.03)	(0.03)
Kleibergen-Paap F-Stat	.	.	.	32.99
State Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
Controls	No	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Observations	650	650	650	650

* p < 0.1, ** p < 0.05, *** p < 0.01. Robust standard errors clustered at the state level in parentheses.

Table A18: Robustness Check: Effect of Out-of-State REC Demand (PWh) on State Level Emissions

	(1)	(2)	(3)	(4)
CO_2 from Electric Power Industry, Million Metric Tons				
Out-of-State REC Demand (PWh)	–133.06***	–132.29***	–150.63***	–128.70**
	(48.67)	(42.56)	(46.98)	(64.58)
In-State REC Demand (PWh)		–182.92	–363.49***	–361.38***
		(140.52)	(125.47)	(124.37)
Natural Gas Generation, TWh	–0.18***	–0.17***	0.01	0.01
	(0.06)	(0.06)	(0.09)	(0.09)
Kleibergen-Paap F-Stat	.	.	.	46.61
CO_2 from Electric Power Industry, Million Metric Tons				
Out-of-State REC Demand (PWh)	7.60	16.81	10.79	37.70*
	(24.65)	(19.84)	(12.54)	(20.87)
In-State REC Demand (PWh)		–222.68*	–277.15***	–273.39***
		(129.63)	(68.23)	(65.39)
Natural Gas Generation, TWh	0.14*	0.16*	0.34***	0.34***
	(0.09)	(0.10)	(0.04)	(0.04)
Coal Generation, TWh	0.81***	0.81***	0.91***	0.92***
	(0.04)	(0.04)	(0.02)	(0.02)
Kleibergen-Paap F-Stat	.	.	.	36.19
State Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
Controls	No	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Observations	650	650	650	650

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state level in parentheses.

A.5 Robustness Check: Add Additional Control Variables

Table A19: Robustness Check: Effect of Out-of-State REC Demand (PWh) on Aggregate State Level Generation by Source adding Additional Variables

	(1)	(2)	(3)	(4)
Coal Generation (Log MWh)				
Out-of-State REC Demand (PWh)	–4.75*	–2.48	–1.89	–9.29**
	(2.57)	(1.80)	(1.60)	(3.97)
In-State REC Demand (PWh)		–20.64**	–19.77**	–20.66**
		(9.59)	(9.40)	(9.50)
RGGI Membership Dummy		–1.07***	–0.74**	–0.70**
		(0.40)	(0.30)	(0.29)
RGGI Membership x RGGI CO2 Allowance Price		0.28**	0.24**	0.21**
		(0.11)	(0.09)	(0.09)
Industrial Natural Gas Price		–0.00	–0.00	–0.00
		(0.01)	(0.01)	(0.01)
Natural Gas Generation (Log MWh)				
Out-of-State REC Demand (PWh)	2.66	3.52	3.70	3.56
	(5.39)	(4.65)	(5.03)	(8.80)
In-State REC Demand (PWh)		–9.30	4.01	4.00
		(19.64)	(12.17)	(11.84)
RGGI Membership Dummy		–0.15	–0.22	–0.22
		(0.40)	(0.43)	(0.44)
RGGI Membership x RGGI CO2 Allowance Price		0.01	0.04	0.04
		(0.13)	(0.12)	(0.12)
Industrial Natural Gas Price		–0.04	0.01	0.01
		(0.02)	(0.03)	(0.03)
Total Fossil Fuel Generation (Log MWh)				
Out-of-State REC Demand (PWh)	–3.48***	–3.38***	–3.56***	–3.36*
	(1.25)	(1.10)	(1.08)	(1.95)
In-State REC Demand (PWh)		3.97	4.29	4.32
		(4.15)	(4.69)	(4.70)
RGGI Membership Dummy		0.01	0.21	0.21
		(0.12)	(0.15)	(0.15)
RGGI Membership x RGGI CO2 Allowance Price		–0.09***	–0.12***	–0.12***
		(0.03)	(0.04)	(0.04)
Industrial Natural Gas Price		–0.01	–0.00	–0.00
		(0.01)	(0.01)	(0.01)
Wind Generation (Log MWh)				
Out-of-State REC Demand (PWh)	80.97***	81.59***	83.88***	104.11**
	(29.38)	(29.97)	(31.71)	(44.85)
In-State REC Demand (PWh)		–73.32	–93.06	–90.60
		(70.19)	(84.57)	(82.91)
RGGI Membership Dummy		4.89**	7.34***	7.24***
		(2.34)	(2.17)	(2.18)
RGGI Membership x RGGI CO2 Allowance Price		–1.25	–1.61**	–1.56*
		(0.80)	(0.81)	(0.82)
Industrial Natural Gas Price		–0.00	–0.10	–0.11
		(0.12)	(0.17)	(0.17)
% Electricity Generated from Fossil Fuels				
Out-of-State REC Demand (PWh)	–0.73*	–0.69*	–1.04***	–2.39***
	(0.36)	(0.35)	(0.40)	(0.84)
In-State REC Demand (PWh)		1.54	0.95	0.78
		(1.10)	(0.90)	(0.86)
RGGI Membership Dummy		0.04	0.02	0.02
		(0.03)	(0.02)	(0.02)
RGGI Membership x RGGI CO2 Allowance Price		–0.02***	–0.02***	–0.02***
		(0.01)	(0.01)	(0.01)
Industrial Natural Gas Price		0.00	0.00	0.00
		(0.00)	(0.00)	(0.00)
State Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
Controls	No	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes
Kleibergen-Paap F-Stat	.	.	.	48.19
Observations	650	650	650	650

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state level in parentheses.

Table A20: Robustness Check: Effect of Out-of-State REC Demand (PWh) on Plant Level Generation by Plant Type adding Additional Control Variables

	(1)	(2)	(3)	(4)
Coal Generation (Log MWh)				
Out-of-State REC Demand (PWh)	–3.73	–3.10	–3.10*	–13.48***
	(2.30)	(2.12)	(1.60)	(4.91)
In-State REC Demand (PWh)		0.49	0.54	–0.92
		(6.94)	(5.42)	(6.61)
RGGI Membership Dummy		–1.13***	–0.61***	–0.49**
		(0.22)	(0.19)	(0.22)
RGGI Membership x RGGI CO2 Allowance Price		0.27***	0.18***	0.13*
		(0.07)	(0.07)	(0.08)
Industrial Natural Gas Price		0.02**	0.02**	0.02***
		(0.01)	(0.01)	(0.01)
Kleibergen-Paap F-Stat	.	.	.	25.68
Observations	6260	6260	6260	6260
Natural Gas Generation (Log MWh)				
Out-of-State REC Demand (PWh)	1.09	1.46	0.78	1.61
	(1.15)	(1.06)	(0.69)	(1.55)
In-State REC Demand (PWh)		–4.90*	0.64	0.83
		(2.83)	(1.87)	(1.98)
RGGI Membership Dummy		0.03	0.01	0.00
		(0.08)	(0.07)	(0.07)
RGGI Membership x RGGI CO2 Allowance Price		–0.02	–0.02	–0.01
		(0.03)	(0.02)	(0.02)
Industrial Natural Gas Price		–0.01	–0.00	–0.00
		(0.01)	(0.00)	(0.00)
Kleibergen-Paap F-Stat	.	.	.	33.06
Observations	17616	17616	17616	17616
Total Fossil Fuel Generation (Log MWh)				
Out-of-State REC Demand (PWh)	–1.51*	–0.82	–1.52***	–3.73***
	(0.80)	(0.62)	(0.56)	(1.20)
In-State REC Demand (PWh)		–3.72**	–0.83	–1.11
		(1.72)	(1.59)	(1.65)
RGGI Membership Dummy		–0.07	0.05	0.07
		(0.05)	(0.05)	(0.05)
RGGI Membership x RGGI CO2 Allowance Price		–0.01	–0.04***	–0.05***
		(0.02)	(0.01)	(0.02)
Industrial Natural Gas Price		–0.00	–0.00	–0.00
		(0.00)	(0.00)	(0.00)
Kleibergen-Paap F-Stat	.	.	.	43.78
Observations	27877	27877	27877	27877
Wind Generation (Log MWh)				
Out-of-State REC Demand (PWh)	5.21*	5.52**	7.81*	24.43**
	(3.13)	(2.75)	(4.24)	(11.61)
In-State REC Demand (PWh)		3.63	8.76	13.75
		(2.97)	(5.96)	(9.36)
RGGI Membership Dummy		0.05	0.46	0.45
		(0.33)	(0.58)	(0.55)
RGGI Membership x RGGI CO2 Allowance Price		–0.06	–0.09	–0.06
		(0.11)	(0.13)	(0.11)
Industrial Natural Gas Price		–0.03	–0.04	–0.04
		(0.02)	(0.03)	(0.03)
Kleibergen-Paap F-Stat	.	.	.	21.51
Observations	4721	4721	4721	4721
Plant Fixed-Effects	Yes	Yes	Yes	Yes
Year Fixed-Effects	Yes	Yes	Yes	Yes
Controls	No	Yes	Yes	Yes
NERC-Specific Time Trends	No	No	Yes	Yes
IV	No	No	No	Yes

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors clustered at the state levels in parentheses.

A.6 Theory Proofs

A.6.1 Proof of Proposition 1

In equilibrium, the first order conditions defined in equations (4) and (5) are satisfied for each firm i, along with the market clearing condition in equation (3) and each firm's electricity demand constraint. Taking the Jacobian of this system of equations, we can form the bordered Hessian for the system of firm profit maximization problems with variable vector $\{q_1^r, q_1^n, ..., q_N^r, q_N^n, \lambda_1, ..., \lambda_N, \xi\}$:

(7)

$$H_{sys} = \begin{bmatrix} 0 & 0 & ... & 0 & 1-\alpha_1 & -\alpha_1 & ... & 1-\alpha_{N-1} & -\alpha_{N-1} & 1-\alpha_N & -\alpha_N \\ 0 & 0 & ... & 0 & 1 & 1 & ... & 0 & 0 & 0 & 0 \\ ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... \\ 0 & 0 & ... & 0 & 0 & 0 & ... & 0 & 0 & 1 & 1 \\ 1-\alpha_1 & 1 & ... & 0 & -\frac{\partial^2 C_1^r(q_1^r)}{\partial {q_1^r}^2} & 0 & ... & 0 & 0 & 0 & 0 \\ -\alpha_1 & 1 & ... & 0 & 0 & -\frac{\partial^2 C_1^n(q_1^n)}{\partial {q_1^n}^2} & ... & 0 & 0 & 0 & 0 \\ ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... \\ 1-\alpha_{N-1} & 0 & ... & 0 & 0 & 0 & ... & -\frac{\partial^2 C_{N-1}^r(q_{N-1}^r)}{\partial {q_{N-1}^r}^2} & 0 & 0 & 0 \\ -\alpha_{N-1} & 0 & ... & 0 & 0 & 0 & ... & 0 & -\frac{\partial^2 C_{N-1}^n(q_{N-1}^n)}{\partial {q_{N-1}^n}^2} & 0 & 0 \\ 1-\alpha_N & 0 & ... & 1 & 0 & 0 & ... & 0 & 0 & -\frac{\partial^2 C_N^r(q_N^r)}{\partial {q_N^r}^2} & 0 \\ -\alpha_N & 0 & ... & 1 & 0 & 0 & ... & 0 & 0 & 0 & -\frac{\partial^2 C_N^n(q_N^n)}{\partial {q_N^n}^2} \end{bmatrix}$$

The bordered Hessian of the system of firm profit maximization problems is a (3N+1)x(3N+1) matrix in a bordered block diagonal form. The first comparative static of interest is given by

$$\frac{\partial q_i^r}{\partial \alpha_j} = -\frac{det(H_{N+2i})}{det(H_{sys})}.$$

Where $N + 2i$ indicates that column $N + 2i$ has been replaced by a vector of partial derivatives of the equilibrium conditions with respect to α_j. This vector is equal to $-\xi$ in rows $N + 2j$ and $N + 2j + 1$ and $-(q_j^r + q_j^n)$ in the first row. Next we re-arrange H_{N+2i} into block form in order to take the determinant. We will be making an even number of column and row operations so the determinant of the transformed matrix will be equivalent to the determinant of H_{N+2i}. First interchange column $N + 2i$ with all columns to its right so it is now the right-most column. Next, do the same with the column that has $-\alpha_i$ as its top row, which has index $N+2i$ after the previous set of column operations. Next interchange the rows beginning with $1 - \alpha_i$ and $-\alpha_i$ with all rows below them as we did with the columns. Last, interchange column $i + 1$ with all columns to the right, and row $i + 1$ with all rows below. This results in a block matrix with form,

(8)
$$H_{N+2i} = \begin{bmatrix} A & B \\ C & D \end{bmatrix},$$

where A is the upper left justified 3N-2x3N-2 matrix which is just the bordered Hessian of the global maximization problem without state i. B is the 3N-2x3 matrix to the right of A composed of zeros except for α_i in the first row of the second column, $-(q_j^r + q_j^n)$ in the first row of the first column, and $[-\xi \quad -\xi]^T$ in the first column in row location described above, unless $i < j$, then this vector is in rows $N+2j-2$ and $N+2j-1$. C is the 3x3N-2 matrix with $1-\alpha_i$ in index (1,1) and $-\alpha_i$ in index (2,1). D is the bottom right most 3x3 matrix given by,

$$D = \begin{bmatrix} 0 & 0 & 1 \\ 0 & -\frac{\partial^2 C_i^n(q_n)}{\partial q_i^{n\,2}} & 1 \\ 0 & 1 & 0 \end{bmatrix} \tag{9}$$

The determinant of the transformed block matrix is given by,

$$det(H_{N+2i}) = det(A)det(D - CA^{-1}B).$$

Notice that C is zero everywhere besides its first column, therefore we only need to obtain the top row of A^{-1}. Since A is also a bordered Hessian, we can use block matrix rules to invert it. First, let

$$\Delta \equiv - \left[\sum_{k \neq i} \left(\frac{1}{\frac{\partial^2 C_k^r(q_k^r)}{\partial q_k^{r\,2}} + \frac{\partial^2 C_k^n(q_k^n)}{\partial q_k^{n\,2}}} \right) \right]^{-1}.$$

Index the first element of a row or column by 1. The first N columns of the top row of A^{-1} are,

$$A^{-1}(1, 1:N) = \begin{bmatrix} -\Delta & \Delta \frac{(1-\alpha_i)\frac{\partial^2 C_1^n(q_1^n)}{\partial q_1^{n\,2}} - \alpha_1 \frac{\partial^2 C_1^r(q_1^r)}{\partial q_1^{r\,2}}}{\frac{\partial^2 C_1^r(q_1^r)}{\partial q_1^{r\,2}} + \frac{\partial^2 C_1^n(q_1^n)}{\partial q_1^{n\,2}}} & \dots & \Delta \frac{(1-\alpha_N)\frac{\partial^2 C_N^n(q_N^n)}{\partial q_N^{n\,2}} - \alpha_N \frac{\partial^2 C_N^r(q_N^r)}{\partial q_N^{r\,2}}}{\frac{\partial^2 C_N^r(q_N^r)}{\partial q_N^{r\,2}} + \frac{\partial^2 C_N^n(q_N^n)}{\partial q_N^{n\,2}}} \end{bmatrix}. \tag{10}$$

The next 2(N-1) columns are,

(11)

$$A^{-1}(1, N+1:3N-2) = \begin{bmatrix} \frac{-\Delta}{\frac{\partial^2 C_1^r(q_1^r)}{\partial q_1^{r\,2}} + \frac{\partial^2 C_1^n(q_1^n)}{\partial q_1^{n\,2}}} & \frac{\Delta}{\frac{\partial^2 C_1^r(q_1^r)}{\partial q_1^{r\,2}} + \frac{\partial^2 C_1^n(q_1^n)}{\partial q_1^{n\,2}}} & \cdots & \frac{-\Delta}{\frac{\partial^2 C_N^r(q_N^r)}{\partial q_N^{r\,2}} + \frac{\partial^2 C_N^n(q_N^n)}{\partial q_N^{n\,2}}} & \frac{\Delta}{\frac{\partial^2 C_N^r(q_N^r)}{\partial q_N^{r\,2}} + \frac{\partial^2 C_N^n(q_N^n)}{\partial q_N^{n\,2}}} \end{bmatrix}.$$

with the ith iteration of each term omitted. Using this we can obtain that,

$$det(D - CA^{-1}B) = \Delta(q_j^r + q_j^n) \leq 0.$$

Last we must sign the determinant of A and of H_{sys}. Consider the bordered Hessian for a two firm maximization problem. There are 4 first order conditions and 3 constraints therefore for a global maximum the bordered Hessian (the leading principal minor) must have sign $(-1)^{3+(1)} > 0$. Also notice that for a three firm maximization problem that there are 6 first order conditions and 4 constraints. The smallest principal minor must have sign $(-1)^{4+1}$ and the next principal minor, the entire bordered Hessian, must have sign $(-1)^{4+(1+1)} > 0$. Its easy to see that for an N firm maximization problem, the bordered Hessian must have sign $(-1)^{(N+1)+(N-1)} > 0 \; \forall N$. Therefore

$det(A)$ and $det(H_{sys})$ are both positive and we have that,

$$\frac{\partial q_i^r}{\partial \alpha_j} \propto -\Delta(q_j^r + q_j^n) \geq 0.$$

For the non-renewable comparative static we substitute the same column vector into H_{sys} and form a new matrix H_{N+2i+1}. Re-arranging the columns and rows in the same manner we can obtain a matrix in block matrix form where A and C are the same as before. D is identical except the element in index (2,2) is replaced by 0, the element in index (2,1) is replaced by $-\frac{\partial^2 C_i^n(q_n)}{\partial q_i^{n\,2}}$, the element in index (3,1) is now 1 and the element in index (3,2) is now 0. Finally in block B, the element in index (1,1) is now $(1-\alpha_i)$, element in index (1,2) is now $(q_j^r + q_j^n)$ and the subvector $[-\xi \quad -\xi]^T$ that was in the first column is now moved to the second but in the same rows within block B. Following the same steps, we can obtain that,

$$det(D - CA^{-1}B) = -\Delta(q_j^r + q_j^n) \geq 0,$$

which implies that

$$\frac{\partial q_i^n}{\partial \alpha_j} \propto \Delta(q_j^r + q_j^n) \leq 0.$$

A.6.2 Proof of Proposition 2

Define the total quantity of RECs demanded in state j as $D_j = \alpha_j \times Q_j$. Since Q_j is assumed to be fixed, an increase in RECs demanded in state j occurs strictly through increases in α_j.

$$\frac{\partial q_i^n}{\partial D_j} \leq 0 \qquad \text{and} \qquad \frac{\partial q_i^r}{\partial D_j} \geq 0 \quad \forall i \neq j$$

follows trivially from Proposition 1.

A.7 Proof of Corollary 3

Re-arrange H_{sys} so that the borders now lie below and to the right of the Hessian of the unconstrained system. The REC price comparative static is given by

$$\frac{\partial q_i^r}{\partial \alpha_j} = -\frac{det(H_{3N+1})}{det(H_{sys})},$$

where the last column of the bordered Hessian is replaced by the vector of partial derivatives of the equilibrium conditions with respect to α_j. This matrix is already in block form,

$$H_{3N+1} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}, \tag{12}$$

where A is the 2Nx2N Hessian of the unconstrained problem, B is the 2NxN+1 matrix composed of the set of N column vectors determining the demand constraint and the vector of partial derivatives in the final column. C is the N+1x2N matrix composed of the N+1 row vectors determining the demand and REC market clearing constraints. D is a N+1xN+1 matrix of zeros except in element (N+1,N+1) which is equal to $-(q_j^r + q_j^n)$.

The determinant of this matrix is given by

$$det(H_{3N+1}) = det(A)det(D - CA^{-1}B),$$

where the determinant of A is just the product of its elements since it is a diagonal matrix. $D - CA^{-1}B$ is an N+1xN+1 matrix with

$$\left[\frac{\partial^2 C_i^r(q_i^r)}{\partial q_i^{r2}}\right]^{-1} + \left[\frac{\partial^2 C_i^n(q_i^n)}{\partial q_i^{n2}}\right]^{-1}$$

in the diagonal elements for each row i, but descending in reverse order so jurisdiction N is in the first row and jurisdiction 1 is in the N^{th} row. The final diagonal element is

$$-(q_j^r + q_j^n) - \xi(1-\alpha_j)\left[\frac{\partial^2 C_j^r(q_j^r)}{\partial q_j^{r2}}\right]^{-1} + \xi\alpha_j\left[\frac{\partial^2 C_j^n(q_j^n)}{\partial q_j^{n2}}\right]^{-1}.$$

The rightmost column of the matrix has the above expression in the N^{th} row, and

$$-\xi\left[\frac{\partial^2 C_j^r(q_j^r)}{\partial q_j^{r2}}\right]^{-1} - \xi\left[\frac{\partial^2 C_j^n(q_j^n)}{\partial q_j^{n2}}\right]^{-1}$$

in the j^{th} row and zeros otherwise. The first N columns of the bottom row of the matrix contain elements of the form,

$$(1-\alpha_i)\left[\frac{\partial^2 C_i^r(q_i^r)}{\partial q_i^{r2}}\right]^{-1} - \alpha_i\left[\frac{\partial^2 C_i^n(q_i^n)}{\partial q_i^{n2}}\right]^{-1}$$

, beginning with jurisdiction N in the first column and descending to jurisdiction 1 in the N^{th} column. Jurisdiction j is skipped over. The rest of the elements of the matrix are zero. Define this matrix as

$$D - CA^{-1}B = \begin{bmatrix} E & F \\ G & H \end{bmatrix}, \tag{13}$$

where E is NxN, F is Nx1, G is 1xN and H is 1x1. The determinant is then, $(H-1)det(E) + det(E - FG)$. The determinant of E is

$$\prod_{i=1}^{N}\left(\left[\frac{\partial^2 C_i^r(q_i^r)}{\partial q_i^{r2}}\right]^{-1} + \left[\frac{\partial^2 C_i^n(q_i^n)}{\partial q_i^{n2}}\right]^{-1}\right).$$

$E - FG$ is an NxN matrix where the diagonal elements are

$$\left[\frac{\partial^2 C_i^r(q_i^r)}{\partial q_i^{r2}}\right]^{-1} + \left[\frac{\partial^2 C_i^n(q_i^n)}{\partial q_i^{n2}}\right]^{-1},$$

in all but row i and descending order from jurisdiction N in row 1 to jurisdiction 1 in row N. The i^{th} diagonal is,

$$\left(1 + \xi\left((1-\alpha_i)\left[\frac{\partial^2 C_i^r(q_i^r)}{\partial q_i^{r2}}\right]^{-1} - \alpha_i\left[\frac{\partial^2 C_i^n(q_i^n)}{\partial q_i^{n2}}\right]^{-1}\right)\right)\left(\left[\frac{\partial^2 C_i^r(q_i^r)}{\partial q_i^{r2}}\right]^{-1} + \left[\frac{\partial^2 C_i^n(q_i^n)}{\partial q_i^{n2}}\right]^{-1}\right).$$

All other elements off of row j are zero. The elements of row j that do not fall on the diagonal of the matrix contain elements,

$$\xi\left((1-\alpha_i)\left[\frac{\partial^2 C_i^r(q_i^r)}{\partial q_i^{r2}}\right]^{-1} - \alpha_i\left[\frac{\partial^2 C_i^n(q_i^n)}{\partial q_i^{n2}}\right]^{-1}\right)$$

beginning with jurisdiction N in the first column and descending to jurisdiction 1 in the final column. Jurisdiction j is skipped over. To take the determinant of this matrix, we put it in block form by performing an even number of row and column operations by first moving the j^{th} row to the bottom, and then the j^{th} column all the way to the right,

$$E - FG = \begin{bmatrix} J & K \\ L & M \end{bmatrix}, \tag{14}$$

where J is N-1xN-1, K is N-1x1, L is 1xN-1 and M is 1x1. K is a vector of zeros so the determinant of this matrix is simply

$$det(J)det(M) = \left[\prod_{i=1}^{N}\left(\left[\frac{\partial^2 C_i^r(q_i^r)}{\partial q_i^{r2}}\right]^{-1} + \left[\frac{\partial^2 C_i^n(q_i^n)}{\partial q_i^{n2}}\right]^{-1}\right)\right]\left[1 + \xi\left((1-\alpha_i)\left[\frac{\partial^2 C_i^r(q_i^r)}{\partial q_i^{r2}}\right]^{-1} - \alpha_i\left[\frac{\partial^2 C_i^n(q_i^n)}{\partial q_i^{n2}}\right]^{-1}\right)\right]$$

Combining this with $det(E)$ and $(H-1)$ we have that,

$$det(D - CA^{-1}B) = \left[\prod_{i=1}^{N}\left(\left[\frac{\partial^2 C_i^r(q_i^r)}{\partial q_i^{r2}}\right]^{-1} + \left[\frac{\partial^2 C_i^n(q_i^n)}{\partial q_i^{n2}}\right]^{-1}\right)\right]\left[-\left(q_j^r + q_j^n\right)\right] \leq 0.$$

$det(A)$ is simply the product of the diagonal elements of A which is clearly positive. Recall that the bordered Hessian has a positive determinant which results in,

$$\frac{\partial \xi}{\partial \alpha_j} \propto \left[\prod_{i=1}^{N}\frac{\partial^2 C_i^r(q_i^r)}{\partial q_i^{r2}}\frac{\partial^2 C_i^n(q_i^n)}{\partial q_i^{n2}}\right]\left[\prod_{i=1}^{N}\left(\left[\frac{\partial^2 C_i^r(q_i^r)}{\partial q_i^{r2}}\right]^{-1} + \left[\frac{\partial^2 C_i^n(q_i^n)}{\partial q_i^{n2}}\right]^{-1}\right)\right]\left[\left(q_j^r + q_j^n\right)\right] \geq 0.$$