Renewable Portfolio Standards, Vertical Structure, and Investment*

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Abstract

Policy effectiveness within industries depends on market structures. We provide evidence of this by examining how vertical structure influences renewable capacity investments under Renewable Portfolio Standards (RPS). RPS links the upstream and downstream electricity sectors by mandating downstream firms to procure a fraction of sales from renewables. Considering various channels through which downstream firms can source investment to comply, we show that RPS-driven investments vary across states with different degrees of vertical integration in their electricity sector. We find lower investments in more vertically separated states, suggesting a misalignment between market structure and policy.

JEL codes: L42, L94, Q42, Q48

Keywords: Renewable portfolio standards, renewable energy, electricity markets, vertical relations, market structure

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1 Introduction

> *One of the great mistakes is to judge policies and programs by their intentions rather than their results.* – Milton Friedman

A central question in economics is how to design effective policies based on an understanding of the incentives of the parties involved. This becomes particularly challenging when a policy targets markets and industries, as the efficacy of the policy may depend on whether the incentives it creates align with firms' incentives under the prevailing market structure. This paper highlights the importance of market structure as a determining factor in the outcomes of the policy, exploiting an empirical setting where one can observe the same policy in action under different market structures. We quantify the effects of a policy aimed at increasing certain type of investment in the electricity sector – the Renewable Portfolio Standards – and how this outcome depends on the extent to which the market is vertically integrated.

The Renewable Portfolio Standards (RPS) are a set of policies in the US that have for objective to increase the generation capacity from renewable sources. Specifically, the RPS require that a minimum percentage of electricity supply in a state be met by generation from renewable sources. The policy is enacted at the state level, and as of November 2022, 29 states and the District of Columbia had established an RPS.[1] The Energy Information Administration claims that half of the growth in renewable generation since 2000 is due to the RPS mandates alone.[2]

Although there is a rich set of studies evaluating the outcomes of the RPS policy – which we describe in the literature review section – there has not been an evaluation of the policy's impact on investment in renewable capacity that accounts for the underlying market structure. We argue that this interaction is important when considering how the policy creates incentives to invest, especially in the context of the electricity industry being a vertical supply chain. This emerging factor presents a nuanced interaction that may either reinforce or challenge the prevailing deregulation trend in the US, often characterized by the segmentation of traditionally vertically integrated electricity markets. Our research highlights a fundamental tension between the objectives of deregulation and the necessity of expanding renewable energy efforts.

We focus on the fact that the RPS place an obligation on the downstream sector – electric utilities or other retail electric providers, in general load-serving entities – to achieve the goal of an increased renewable share in the upstream generation sector. The policy, therefore, creates a linkage between the vertically related sectors in the electricity industry. Since downstream retail companies

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[1] In addition, seven other states have put in place "renewable energy goals", they do not have the same stringency level as the RPS and therefore, we only focus on the RPS states (`https://t.ly/e7RID`). As of date, there is no federal RPS or similar policy in place.

[2] "Roughly half of all growth in U.S. renewable electricity generation and capacity since 2000 is associated with state RPS requirements" (Barbose (2021) and `https://t.ly/PPXYK`).

are responsible for inducing new investment upstream, the policy's effectiveness in achieving the goal depends on the vertical relationship between the retail and wholesale sectors – specifically, to what extent the retail and wholesale sectors are integrated.

An interesting aspect of the US electricity industry is that the degree and prevalence of vertical ties between the retail and wholesale sectors vary significantly across states. Since the early 1990s, the deregulation and restructuring processes in the US electricity sector have given place to a patchwork of market structures across the country. Before deregulation, most US markets were dominated by vertically integrated companies owning assets in both retail and wholesale, but the restructuring process accompanying deregulation aimed at separating these vertical ties to create competitive markets, though this was not completely achieved and not uniformly across states.[3] Nowadays, after several waves of deregulation, we observe a mix of cases where a retail company also operates in the generation sector, referred to as the vertically integrated case, and cases where a retail company is completely separated from generation – the vertically separated case. These two types of vertical relationships coexist in most states, including those that underwent restructuring, creating varying degrees of vertical structure at the state level. We use this variation in the overall extent of vertical separation/integration across states in our analysis.

We explore two channels through which the policy can induce new investments. The first is the *contracting channel*, where a retailer complies with the RPS by contracting with an upstream firm that invests in new renewable capacity, using the generation from these investments for compliance in exchange for a contracted payment.[4] Being involved in the construction of a renewable generator through contracts allows the retailer to plan for policy compliance and reduce uncertainty in compliance costs, but requires contributing to the investment costs of building the asset. Note that direct investments made by a vertically integrated retail firm are included in the contracting channel because the contracting process is complete and fully internalized in this case. Another compliance channel is through the market, where retailers comply by purchasing Renewable Energy Credits (RECs) from renewable generators in the spot market, referred to as the *REC market channel*. Since upstream generating firms are not obligated to meet policy requirements, investments in renewable capacity through this channel respond to REC market conditions (e.g., high REC prices) and occur only if the market provides sufficient incentives.

While these two channels may coexist, the extent to which policy-driven investments at the state level differ by the vertical structure is determined by investments sourced through the contracting

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[3] For example, California suspended the restructuring process after experiencing an electricity crisis in 2001. This incident also influenced restructuring processes in other states.

[4] As explained later in the paper, the implementation of the RPS policy relies on the issuance of a Renewable Energy Credit (REC) for each unit of electricity produced from approved renewable sources. RECs can be traded under certain rules, and firms that need to comply with the policy must acquire RECs either via their own output or through the REC market.

channel. The stronger the vertical relationship between the downstream retailer and upstream generators, the more closely the retailer's compliance needs are aligned with upstream investment incentives. This alignment gives the retailer an advantage in establishing and enforcing investment contracts, ultimately resulting in more investment through the contracting channel.[5] On the other hand, investments made through the REC market channel respond only to the incentives created by the REC market, which are not necessarily affected by the vertical structure. Therefore, we expect sourcing investments for RPS compliance will be more effective in vertically integrated settings than in vertically separated environments.

To quantify this relationship, identifying the contractual links between invested renewable capacity and retail firms is important. While firm-level contract data are often confidential, we compiled unique data on contractual agreements (e.g, power purchase agreements) between retail firms and renewable generators from the Federal Energy Regulatory Commission (FERC Form 1). We identified renewable generators that established contracts with retail firms at the start of their operations as investments sourced through the contracting channel. The contract data were then merged with data from various sources, including generating sector information from the Energy Information Administration (EIA Form 860), retail electricity provider data (EIA Form 861), and state-specific electricity sector characteristics (EIA Electric Power Annual). The electricity sector data were then combined with the dataset on RPS compiled by the National Renewable Energy Laboratory (Barbose (2021)). For each state that has enacted an RPS and for each year, we observe the annual minimum percentage requirement (i.e., RPS target levels) for renewable energy sales, which are announced and publicly known several years in advance. The database also reports each state's compliance status, indicating whether the state fully complied with RPS requirements that year and, if not, the extent to which it did not meet the requirements.

Our empirical strategy explores the relationship between annual state-level renewable investments attached to the RPS policy and the state's vertical structure. Since RPS requirements are published in advance, retail firms can plan to ensure their invested capacities, and generation from those capacities, are ready by the compliance year. We aggregate the new wind and solar generation capacities contracted by retailers within each state that come online each year. By using this measure, our analysis focuses on the aggregate-level outcomes of individual-level decisions, rather than individual firms' decisions to invest. However, identifying whether the invested capacity is driven by the policy presents a challenge. To address this, we leverage the exogenous variation in RPS requirements over time along with the variation in annual compliance status. We focus on the investments that occur in the non-compliance years, exploiting the fact that if the state did not achieve compliance, all new renewable investment coming online were used to comply with the

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[5] Establishing and enforcing contracts for renewable energy projects is particularly challenging due to the variability in generation, which makes long-term commitments harder to secure (Ryan (2023)).

policy, i.e. the policy was binding. Therefore, we expect a stronger influence of the RPS policy on renewable investments during non-compliance years. By focusing on these binding years, we implicitly assume a causal relationship between the policy and investment.

We use three different measures to characterize a state's vertical market structure, capturing the rich heterogeneity in vertical linkages between firms in the upstream and downstream. A binary indicator assigned to restructured states was often used in the literature to indicate vertical separation, as the restructuring resulted in separating the generation sector from the retail sector. Additionally, we define two new continuous measures of vertical separation in the electricity sector, using firm-level vertical linkage data. The first measure takes the capacity share of upstream generators not owned by companies with a presence in the downstream level. The second measure, our preferred measure, computes the market share of retail companies that do not own generation assets in the upstream level. This aggregate measure effectively captures the varying degrees of existing firm-level vertical linkages across states.

Our main results are obtained from a regression of new annual investment on renewable capacity on the interaction of the measure of vertical integration with the variable that captures whether the RPS policy was binding or not in a given year. We add a rich set of controls and fixed effects as well. We argue that since the RPS schedules are announced in advance and do not change over time, whether the RPS is binding is not a function of current investment because the investment realized this year was decided to be built years in advance. In addition, we assume the market structure to be fixed at the level of the first year that the RPS was enacted, since new additions on renewable generation do not largely change the composition of the share of vertically integrated assets. With these considerations in mind, we find that states with a vertically separated structure invest less in renewable capacity than their vertically integrated counterparts by a factor between 1.2 and 1.5 times the overall average investment in renewables. The results suggest that states with stronger vertical linkages between upstream and downstream firms may be more effective in sourcing investments for compliance.

In the main analysis, we assume that differences in investment outcomes across vertical structures are mainly driven by the contracting channel. However, investments through the REC market channel could affect these differential impacts if the REC market channel serves as an alternative to the contracting channel for investors. Although this indirect effect via the REC market could be controlled for by including REC spot market variables in our main regression, we are unable to do so because REC market data are not available for the entire set of states. Therefore, we explore the potential bias from omitting the REC market channel in our analysis, considering the incentives of retailers and wholesalers. We find that the direction of this bias depends on whether wholesalers perceive the REC market as a reliable source for making investment decisions. We then empirically verify the direction of the bias using a subsample of states within the PJM interconnection, where REC market data are publicly available, confirming that the REC market channel may be less reliable and thus less explored by investors compared to the contracting channel.[6] This subsample analysis also indicates that there may be a positive bias in our main results due to the inability to control for the REC market channel, but that the magnitude of this bias is small and therefore not a major concern.

Overall, what we find is that the investment due to the RPS policy through the contracting channel is much smaller in more vertically separated states than in those more integrated. Our results underscore the importance of the role played by the market structure in the evaluation of policy outcomes. In the case of the electricity sector, our results indicate that there may be a misalignment in objectives between different waves of policies over time. On one hand, deregulation was supposed to increase market efficiency and provide the correct incentives for new investment but not necessarily in clean energy. On the other hand, more recent policies with specific investment objectives –targeting renewables– have more difficulty to find their way through when the upstream and downstream sectors are owned by different entities. Altogether, our study quantifies the conflicting incentives that deregulation and the push for clean energy may have in the electricity sector, emphasizing the role of market structure when designing new or reforming current policies. Further research should explore strategies to address this misalignment and optimize policy effectiveness in diverse market structures.

Related literature. There are several strands of the literature related to this paper. The first strand of literature studies the effects of Renewable Portfolio Standards (RPS) on emissions, market outcomes, and other aspects such as design and implementation of the policy. Greenstone and Nath (2021) find that RPS enactment reduces emissions but leads to increased electricity prices. Similarly, Feldman and Levinson (2023) find that RPS decreased emissions and natural gas generation, albeit the impacts are small. Wolverton et al. (2022) focuses on the manufacturing sector and finds that electricity prices are slightly higher in RPS states than in non-RPS states. Fullerton and Ta (2022) use a general equilibrium model around the RPS policy in addition to the reduced-form evidence of the effect of RPS on market outcomes including the retail price. Hollingsworth and Rudik (2019) examine the spillover effect of RPS policy and measure the reduction of emissions associated with it. Abito et al. (2022) examines the cost-effective REC market trading mechanism.

There is a relatively small set of studies that explicitly examine the interplay between RPS and renewable capacity investment. Yin and Powers (2010) study the relationship between the renewable capacity and RPS stringency, finding a positive effect, though without accounting for

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[6] PJM, a regional transmission organization coordinating wholesale electricity supply and demand in 13 states and D.C. publishes monthly statistics for solar REC (SREC) prices. More details provided in Section 4.5.

market structure. More recently, Deschenes et al. (2023) address a similar question using staggered differences-in-differences methods, finding a causal effect of RPS on wind investments, but they also do not consider market structure or vertical relationships. Our paper is the first to explore the role of vertical relationships in conjunction with RPS-driven investment, suggesting that its effects may not be entirely technology-specific but may also depend on market structure.

Second, our paper relates to the literature exploring vertical integration and investment. Transaction cost theory suggests that the difficulty of specifying and enforcing a contract is an important factor determining the extent to which the firms are vertically integrated (Joskow (2003), Lafontaine and Slade (2007)). Our paper is broadly related to this theory as we draw on this literature to argue that a stronger vertical relationship leads to a more effective contract specification as well as enforcement. There is also a stream of the literature that focuses on the fact that investments in power plants are relationship-specific, thus prone to hold-up problems. Joskow (1987) studies the relation between coal power plants investments and the extent of the vertical relationship between input coal suppliers and coal plants. More recently, Ryan (2023) shows that the hold-up problem arising from counter-party risk of investing in solar capacity can be significant, especially for renewable assets, and can result in inefficient levels of investment (procurement). Although not directly related to this literature, Brown and Sappington (2022) is close to our paper from a conceptual point of view as they provide theoretical predictions that vertical integration would increase the capacity investment in electricity markets.

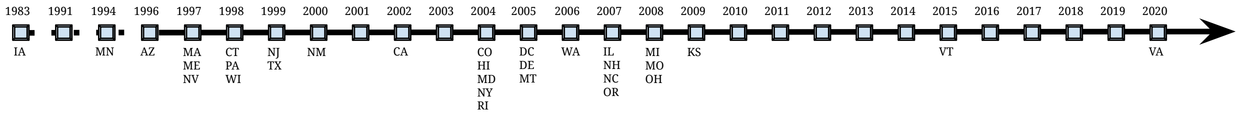
Lastly, our paper is also broadly related to the empirical studies exploring the market effects of vertical integration, deregulation, and restructuring in electricity markets. Deregulation has been associated with significant reductions in maintenance costs (Davis and Wolfram (2012)), and labor and fuel costs (Fabrizio et al. (2007), Cicala (2015)), which implies a reduction in electricity prices. Mansur (2007) finds that market power is exercised to a lesser extent in vertically integrated markets than in restructured markets. MacKay and Mercadal (2022) find that in some cases, deregulation has resulted in higher prices than in regulated markets.

2 Institutional Background and the Importance of Market Structure

2.1 The Renewable Portfolio Standards

The RPS is a state-level policy that sets a minimum requirement for the share of the in-state electricity supply coming from designated renewable energy sources by a certain date or year (EIA (2022)). Specifically, the policy obligates the *retail* electricity providers (electric utilities) to source a certain percentage of their electricity sales (load supplied to the households) to come from re-

Figure 1: RPS Enactment by State



Notes: Year in which the state implemented an RPS policy for the first time. Data from Barbose (2021).

newable sources. These resources include wind, solar, geothermal, biomass, and some types of hydroelectricity and in some cases, include landfill gas, municipal solid waste, and ocean energy. Which energy source is considered renewable differs by state, but wind and solar are the dominating sources among the diverse set of renewables. Some states impose a minimum requirement separately for solar and the rest of the renewables.[7]

The RPS policy exists in 30 states and the District of Columbia as of 2021, which implies that the policy applies to 58% of total U.S. retail electricity sales (Barbose (2021)). The adoption times vary across states. Early adopters include Iowa, Montana, and Arizona, whereas Vermont and Virginia are the most recent adopters in 2015 and 2020, respectively. Figure 1 shows a timeline of these adoption events.

When the state decides to adopt an RPS policy, the annual minimum percentage requirements (i.e., targets) and how they will increase gradually over time are set and announced several years in advance. Although the state may revise the target levels occasionally, it is usually the case that retail electricity companies know the target levels of subsequent years at the time of the state's RPS policy adoption. The magnitude and the growth rate of the annual target levels differ by state. In addition, the levels and growth rates of targets are determined based on specific characteristics of each state. Therefore, the annual RPS target levels are fairly exogenous.[8]

Figure 2 shows the annual RPS mandate as a percentage of total sales for four states: Arizona, DC, California, and New York. Each state enacted its RPS policy at different points in time and with different speeds in the changes in their target levels. Arizona was an early adopter with a very gradual increase in the size of the target and with a maximum target level under 20% to be reached in 2026. A much more aggressive set of schedules can be found in DC, where the RPS was enacted in 2008 initially at a target under 10% but with a very steep curve to get to a target of 100% by 2033. New York and California exhibit a behavior in between the two first examples but once again

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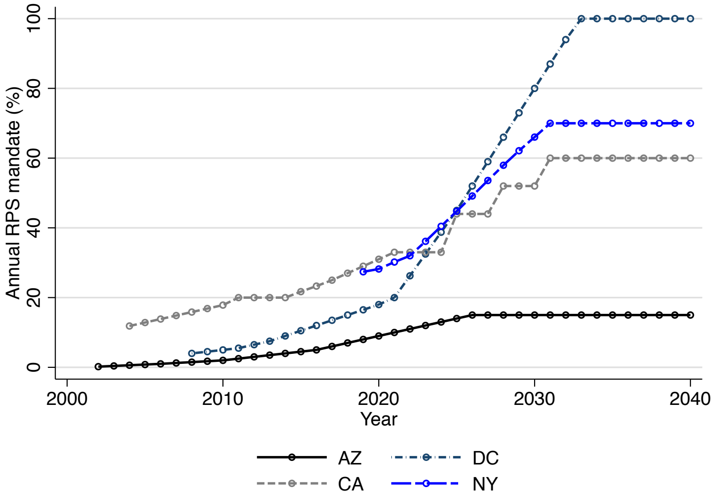
[7] RPS solar carve-outs are state-specific minimum requirements that must be fulfilled with solar generation. In those states, the Renewable Energy Credits (RECs) generated this way are known as SREC (solar RECs), see Barbose (2021).

[8] For example, the Arizona legislature passed the full schedule of RPS targets, one for each year for the period 2006 - 2024 on 14 November 2006 as it can be verified in this document of the state legislature `https://t.ly/QtkUw` (p. 85-86).

Figure 2: RPS Targets Per Year (Selected States)



Notes: The annual RPS mandate is a minimum requirement of electricity sales that must be generated using renewable sources. The requirements are expressed as percentages of annual sales. Different states have enacted the RPS policy at different points in time and with different levels of stringency. Data from Barbose (2021).

with different enactment years. These schedules are public information and announced before the enactment of the policy in the state.

2.2 RPS compliance and Renewable Energy Certificates (RECs)

At the end of a compliance year, the state calculates each retail electricity provider's required amount of Renewable Energy Certificates (RECs), or Renewable Energy Credits, based on the share of the state's total electricity consumption sold by the provider. If the retail provider fails to meet the requirement for that year, the provider must pay a penalty in the form of Alternative Compliance Payments (ACP), which allows it to make a payment at a pre-established price for the amount of the unfulfilled requirements. Table A.5 in the Appendix summarizes the ACP values reported in 2014 for each state. The penalty value is about 50 \$/MWh, with some variation across states. Such value is in the middle of the range of average spot prices in the US for that year, which implies that the penalty was a true financial burden to be avoided.[9]

There are several ways in which retail electricity providers can comply with the RPS policy. First, the retail electricity provider can generate the required amount either from their own renewable generators or by establishing a long-term contract (Power Purchase Agreement, PPA) with

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[9] According to the EIA, the average spot wholesale electricity price in 2014 was above 50 \$/MWh in the northeast US markets and California. Other markets had averages slightly below that threshold but above 38 \$/MWh. See `https://t.ly/2Uu1J`

renewable generators upstream. For each MWh of electricity generated from their own or contracted renewable generation, the provider receives a credit – referred to as a bundled REC, as the credit is bundled with the actual generated electricity. Since the total maximum amount of electricity generated by existing generators cannot increase beyond their capacities, new renewable generators must be built to keep up with the increasing RPS target levels. This gives retail providers an incentive to invest in renewable generation capacities, either by constructing the plants themselves or by setting up a long-term PPA contract with a new renewable generator in the planning stage.

Second, the retail electricity providers can purchase credits in the spot market for renewable energy credits (i.e., REC market). The credits supplied in the spot market are referred to as unbundled credits, as it does not require the retailer to purchase the electricity that produced the credit. Any renewable generator, regardless of whether it is owned by Independent Power Producers (IPPs) or retail providers, can sell its generation in the spot market if the state has a deregulated generation sector.[10]. Similar to other spot markets, transactions of RECs occur through the brokers, and the market exists at the state level. The increasing RPS target levels would increase the demand for credits in the REC market, which could induce new investments that would increase the supply of credits in the market.

Many states require RECs produced within the state to meet their RPS goals, aiming to increase in-state renewable generation. However, some states allow credits from other states to be used for compliance, potentially leading to spillover effects across state lines (Hollingsworth and Rudik (2019)). Even then, these states typically limit eligible credits to those produced within the same interconnection as the state (Abito et al. (2022)).

A state implementing an RPS policy does not always comply with its target levels, and as a result the compliance status can vary over time. If a certain year is designated as a 'non-compliance' year, it indicates that the total RECs procured by the state's retail providers – whether bundled, unbundled or purchased from other states – fell short of the state's minimum RPS requirement.

2.3 Deregulation vs Vertical Integration

The electricity sector is composed by three main segments: generation, transmission, and retail (distribution).[11] A common market structure prevailing until before the 1990s consisted of one

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[10] In some states, renewable generators are allowed to retain and bank the credits for use at a later point in time but must be used within a certain time period (Greenstone and Nath (2021)).

[11] There is a distinction between retail and distribution services, where in some markets retail has been open to competition and in others it is vertically integrated with distribution. However, the distribution services are still mostly legacy local monopolies managed by electric utilities. When there is a retail choice program, final consumers are typically billed by their local electric utility or by a company focused exclusively in the retail sector, in either case we will refer to them as retailers. Since retail is the sector directly affected by the RPS, we refer to the retail sector throughout the paper with the understanding that in some cases it is vertically integrated with some distribution company.

single company owning the assets across the three main segments. Such configuration corresponds with what we know as a vertically integrated market.

However, several states went through *deregulation* processes of their electricity sector starting in the late 1990s. We can distinguish two main cases. First, the deregulation of wholesale generation sector refers to the opening of the generation sector to competition by allowing different companies (e.g. unregulated electricity plants (IPPs)), to participate in generation. The deregulation of the wholesale sector is accompanied by implementing a spot wholesale market for electricity, operated by "independent system operators" and "regional transmission organizations", to allow for trade of electricity not settled in bilateral contracts. The generating companies in a restructured market can sell electricity in the spot market or through bilateral long-term contracts.

Second, the deregulation and restructuring of the retail electricity sector refers to opening the retail service market to different retailers that can compete for customers within the same geographical market. Such restructuring of the retail sector is often accompanied by 'Retail Electricity Choice' programs that enable end-use customers (including residential, industrial, and commercial customers) to choose their electricity provider from either the legacy electric utilities or from competitive retail suppliers, such as retail marketers.[12] Electric utilities serve as local monopolists in their geographical markets when retail choice is not allowed, essentially meaning that in those cases there is no 'retail market'.

As our focus is on the extent to which a retail firm interacts with the wholesale generation sector – with vertical integration being the strongest form – the restructuring and deregulation of the wholesale generation sector is more relevant to our analysis. While deregulation aims to break vertical ties between retail and wholesale sectors, the nature of vertical integration in the electricity market has not been entirely eliminated after the deregulation process. Even in states with restructured wholesale sectors, vertical ties between retail and wholesale sectors persist. For example, legacy retail firms may still own generation assets in the wholesale market despite the state's wholesale generation market being officially restructured (e.g., *PG&E* in California and *Reliant* in Texas). Therefore, vertical integration is not always a binary characteristic of an electricity market, as some markets still have assets in the upstream wholesale sector owned by firms operating in the downstream retail sector.

We define vertical integration as a retail firm's capability to source electricity from its own generation assets in the wholesale market. Hence, we need to explore the firm-level linkages between

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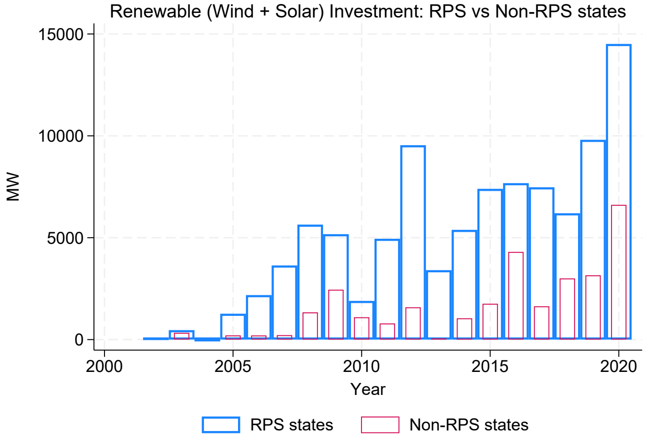
[12] Source: `https://www.nrel.gov/docs/fy18osti/68993.pdf`. However, the specifics of these retail choice programs differ across states. As of 2018, 13 states and the District of Columbia have active, statewide *residential* retail choice programs. In Texas, for example, a retail choice program is mandatory under state law and more than 87% of residential customers choose their retail suppliers. On the other hand, retail choice programs are available only to the non-residential customers in some states (Michigan, Oregon, Nevada, Georgia, and Virginia) according to the EIA, Today in Energy, Nov 2018, `https://www.eia.gov/todayinenergy/detail.php?id=37452)`.

Figure 3: Renewable Investment: RPS states vs. Non-RPS states



Notes: Renewable resource includes wind and solar generation capacities. The bar graphs shows the addition of new investment each year, separately for states that have eventually enacted RPS policy and those have not.

the wholesale and retail sectors to derive a measure of vertical integration that accurately reflects the market structure. Once firm-level integration status is considered, the degree of vertical integration at the state level can vary across states, even among states with the same binary indicator for a restructured market.

2.4 Vertical Structure and Renewable Investment

In this section, we discuss how the difference in vertical structure affects the state's compliance through investments. The RPS policy is imposed on the downstream retail electricity providers. Since the RPS target level (requirement) ramps up across years, the retail electricity provider cannot comply with the policy unless new investments in renewable generation in the upstream generation sector occur over time. Especially given the small share of renewable generation capacity by the time of enactment, along with their small capacity factor, inducing new investments in renewable generation is the critical and ultimate goal of the RPS policy.[13] Figure 3 shows a steady growth in invested renewable capacities over time, with significantly larger capacity additions in the states that adopted RPS compared to those that did not.

Because the policy is designed in such a way that downstream retail companies are in charge of inducing the investment upstream, how effectively the investment can happen depends on the vertical relationship between the downstream and upstream firms. Due to different deregula-

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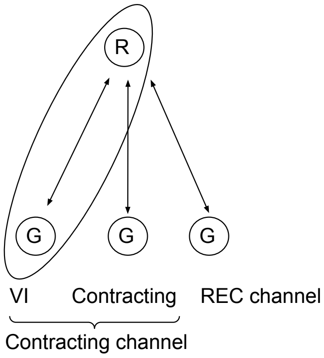
[13] Moreover, one of the main reasons that the state legislation cited for passing the RPS policy was the expected in-state employment gains from strengthening the green power industry (Hollingsworth and Rudik (2019)), which cannot be achieved without continuously large investments in renewable generation within the state.

tion/restructuring status, states have very different vertical structures, as discussed in Section 2.3. That is, in some states, a substantial portion of wholesale generation is still owned by retail firms, while in others, the sectors are either fully separated or integrated. Despite this, the design and structure of RPS policies, though state-level, exhibit a high degree of similarity across states.

2.4.1 Two channels of RPS compliance.

As discussed in Section 2.2, the aggregate level of a state's renewable investments compliant with the RPS policy – our main dependent variable in the empirical analysis – can be driven by two channels: the contracting channel and the REC market channel. Figure 4 illustrates these two channels through which a retailer can comply with the RPS policy.

Figure 4: Two channels to comply with the RPS policy



Notes: Two channels through which a retailer can meet the RPS regulation. The contracting channel implies building new capacity to meet the requirement. In the REC channel the retailer waits for the market forces to "induce" new investment from a generator that is not vertically integrated with this retailer and purchase REC credits from it.

The *contracting* channel involves retail firms investing in new renewable generation capacity through contracts with upstream firms planning to build such facilities. This channel also includes cases of vertical integration, where a retail firm invests directly through its own affiliate in the upstream sector. While vertical contracting and vertical integration are not the same concepts, vertical integration can be viewed as an extreme form of contracting. Moreover, contracting can achieve outcomes similar to vertical integration, provided that the issues related to incomplete contracts are not severe (Lafontaine and Slade (2007); Joskow (2003)).

Therefore, the contracting channel here encompasses both vertical contracting and vertical integration. The contract usually takes the form of a long-term purchasing power agreement (PPA) at a specified price per MWh generated by the renewable facility, allowing the developer to recover the investment cost. The documentary evidence on the relationship between the policy implementation and the decision to build new capacity supports our claim that for a retailer entering into a contract with renewable generators can be interpreted as that specific generator's investment decision to be strongly influenced by the needs of the retailer.[14] In the case of vertical integration, the retail company builds its own renewable generation assets by incurring the investment cost. In both cases, the retailer acquires the bundled credits (RECs) for each unit of renewable electricity generated by the new facilities.

The *REC market* channel involves a retail firm complying by purchasing credits (RECs) in the spot market, positioning the firm as the demand side of this market. In this case, the retail firm must rely on the credit market to incentivize upstream renewable investments, so that new credits can be supplied. Retail firms have no control over the wholesale firm's decision to invest in new renewable generation capacity. If the upstream firm finds the revenue from selling credits in the REC market is sufficient enough to cover the investment costs, it will proceed with the investment.

To an upstream firm considering the investment and operation of renewable generation capacity, these are two channels through which they can cover the upfront costs of capacity investment.[15] These two channels coexist in the current electricity market.

2.4.2 The effect of vertical structure on investment

The stronger the vertical relationship between a retailer and upstream wholesale generators, the more closely the retailer's need to comply with the RPS policy aligns with upstream investment incentives. Such a close vertical relationship makes it easier for retail firms to induce new investments in renewable capacity, particularly through the contracting channel. For instance, a vertically integrated retailer can directly build new renewable generation to meet RPS requirements. Even when not directly investing but instead contracting with an upstream firm, having an integrated upstream affiliate offers an advantage in negotiating contracts with wholesalers developing renewable generation. This advantage arises from the upstream firms' awareness that retailers with direct investment options and a good understanding of wholesale operations can more effectively draft and enforce long-term contracts, which often involve complex terms related to quantity, pricing, and duration.

On the contrary, greater separation between retail and wholesale sectors makes it harder to establish contracts that align their investment incentives. When vertically separated, retail firms without a wholesale market presence cannot directly invest in capacity and must rely more on upstream firms, particularly under binding RPS policies. This reliance weakens their bargaining

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[14] A PWC report on PPAs and RPS notes that "[A]s utilities get closer to meeting their RPS requirements, their need to enter into PPAs for new renewable energy projects diminishes." (`https://t.ly/v6hzu`). In the specific context of California, there is an annual report that documents how the procurement expenses through PPAs on renewable generation due to the RPS have changed over time (`https://t.ly/-zyoe`).

[15] These channels serve as additional revenue sources, alongside tax credits or other national support available to renewable capacity developers.

position during contract negotiations. Combined with their lack of experience in the wholesale sector, these challenges can lead to incomplete contracts, which, in turn, may incentivize upstream firms to hold up investment, and ultimately resulting in suboptimal levels of contracting and investment.

Note that investments tied to the REC channel –selling or buying unbundled credits in the REC spot market– are unlikely to be affected by vertical structure since any firm, whether upstream or downstream and regardless of their vertical relationship, can trade in the REC market.[16] This implies that any differences in overall investments across distinct vertical structures, which are used towards compliance, are primarily due to differences in investments through the *contracting channel*. Therefore, separating out investments specifically sourced through the contracting channel would be ideal for the analysis. However, this is challenging in general due to the difficulty of observing contract data. We address this challenge by using a unique dataset that provides information about the contractual relationships between retail firms and renewable generators. Nevertheless, even in the absence of these data, the fact that only investments in the contracting channel are influenced by the vertical structure suggests that the effect can still be identified from aggregate investment, provided there is sufficient variation in the degree of vertical structure.

Due to the policy's complexity and the multiple interaction channels between sectors, the existing literature on modeling these interactions is limited and not fully aligned with our context. However, it still informs our understanding of vertical relations. Therefore, building on the existing literature, we present a simple model of investment and vertical relationships between a retailer and a generation plant in Online Appendix E.1. Under certain assumptions, we find that renewable investment is higher when both downstream and upstream parts of the industry are integrated within the same firm, compared to a vertically separated structure. However, given the intricacies of real-world vertical structures, we rely on an empirical analysis to assess the impact of RPS on investment through market structure and RPS stringency interactions.

3 Data

Renewable Generation Capacity and Investment Data: EIA Form 860. Generator-level capacity investment data can be obtained from EIA form 860. This data includes the generator's nameplate capacity, location (state), status (i.e., operating, proposed, retired, etc.), type of owner, and energy source. Although the dataset is available at the monthly level, we aggregated the data to the annual level to match the time frame of the RPS policy.

We identify new investments in renewable generation using the 'status' indicator of each generator, categorizing those that changed their status from 'proposed' to 'in operation' as new in-

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[16] We will discuss the REC market channel investment further in Section 4.5.

vestments.[17] We sum the nameplate capacities of these new investments at the state(s)-year(t) level. Note that t refers to the year the generator completed construction and began operation, which is more relevant than the proposal year, as industry reports suggest that the involved parties typically determine the operational year of a new plant when negotiating contracts or at the start of construction.[18] Furthermore, annual RPS targets (requirements) are published well in advance (e.g., 10 years), allowing retail and wholesale firms to plan investments ahead of the target year t based on projected shortfalls in renewable energy acquisition. For these reasons, we believe that new investments strategically planned for RPS compliance and that come online in year t are relevant to the RPS requirement for that year.

Our renewable energy categorization focused on wind and solar, which are consistently recognized as renewable across all states. The RPS policy primarily targets these sources, as other sources like hydroelectric power have reached full capacity and can only be expanded in limited areas. Indeed, as shown in Figure E.3 in Online Appendix, capacities of other renewables, such as biomass and hydro, have not increased over time, and their investment levels are significantly smaller compared to wind and solar generation.

Vertical Relationship and Contract Data: FERC Form 1 The EIA Form 860 provides information about power plant ownership, including whether the owner is an Independent Power Producer (IPP) or an Electric Utility. This information allows us to identify power plants that are directly owned and invested in by electric utilities operating in the retail sector, which fit into the vertical integration case. We aggregate the capacities of these vertically integrated generators at the state-year level.

However, retail companies can also establish long-term purchasing contracts with renewable generators owned by IPPs. These IPP-owned generators, though contractually linked to retail firms, are listed as IPP-owned in the EIA Form 860, making it difficult to identify these relationships using EIA data alone.

To address this, we use the FERC Financial Report Form No.1 (Annual Report of Major Electric Utilities) Yearly Purchased Power and Exchanges data to identify contract links between major retail companies and renewable generators invested in by IPPs.[19] While contract information is

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[17] New generators that appear in the data without a ‘proposed’ status were also included as newly invested capacities.

[18] For example, the construction duration, determined from the EIA Form 860 by calculating the years between the generator’s initial proposal and the start of operations, varies significantly (with an average of approximately 2 to 3 years) across projects. Industry reports indicate that project commissioners and developers initially agree on the project completion year and subsequently adjust the construction pace to meet that deadline. Online reports detailing the development of renewable projects are available at (`power-technology.com`).

[19] FERC Form No. 1 is an annual regulatory requirement for major electric utilities, designed to collect financial and operational information.

typically difficult to obtain, this dataset allows us to identify which renewable generators have long-term purchasing contracts with major retail companies. If a retailer establishes a power purchasing contract with a renewable generator and continuously purchases power from it, we categorize that generator as being contracted with the retailer. Since it is common practice to set up purchasing contracts during the planning stage of a renewable project as part of its financing, we can assume that such capacity is invested via the contracting channel.

The FERC data lists the names of generators (on the seller side) and the retail firms with which they have set up purchasing agreements, but it does not include details such as nameplate capacity or energy source. To obtain this information, we matched the generators in the FERC data with those in the EIA 860 dataset using their names. A more detailed discussion about the FERC data and the data matching process can be found in Online Appendix E.2.

Note that the FERC data is incomplete, as it does not cover all retail firms and states.[20] To address this limitation, we use two types of capacity investment variables in our analysis. The first is the total state-level capacity of new renewable generators sourced through the contracting channel by retail firms in each state. This variable combines: (i) new generators owned by IPPs but contracted with retail firms (identified from the FERC data) and (ii) new generators vertically integrated with retail firms (identified from the EIA 860).[21] The second variable is the total state-level capacity of new renewable generation, without separating the capacities by their sourcing channels. While the first variable is our primary focus, we use the second variable for states with missing FERC data.

Another advantage of using the contract data is its ability to capture spillovers in RPS policy-driven investments. Spillovers occur when an RPS policy in one state increases renewable generation in neighboring states, as shown by Hollingsworth and Rudik (2019). The contract data allows us to identify the location of generators contracted by retailers, distinguishing between in-state and out-of-state sources. Our measure of state-level contracted capacity aggregates the capacities of all generators contracted to retail firms within a state, regardless of whether generators are in-state or out-of-state.[22] This approach ensures that our investment variable reflects spillover capacity investments. We also include a measure of net electricity flows between states in our analysis to account for generation spillovers, similar to the approach in Hollingsworth and Rudik (2019). The

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[20] For example, since Texas is not regulated by FERC, none of the electric utilities in Texas appear in this FERC form. Additionally, some utilities list only major IPPs and companies specializing in renewable generation, rather than individual generators. Consequently, for these states, we cannot match contracting at the generation asset level and assume that state-level aggregate investment is linked to the contracting channel.

[21] Note that we cannot further separate out the capacities possibly invested with the motive to supply unbundled Renewable Energy Credits (RECs) from their generation, which is a limitation we elaborate on in Section 4.5.

[22] For example, retail firms in Arizona may source capacities from IPPs within Arizona or from New Mexico and California. Since out-of-state capacities are still driven by Arizona's RPS, they are included in Arizona's contracted capacities.

identified spillover patterns and their sizes are presented in Online Appendix E.3.1.

RPS Policy Data. Data on timing and target levels of the RPS are publicly available. We use a dataset constructed by Barbose (2021), which reports the states that have enacted an RPS, the year when the RPS started in each state, the RPS target levels (in %) along with the RPS requirements in MWh for each state over time. The RPS target is reported in percentage and the RPS requirement levels are simply total annual electricity sales within a state (MWh) multiplied by the target level (%).

We also use the annual percentage of RPS compliance data compiled by Barbose (2021). These data report the actual percentage of compliance, which is the percentage of total sales (MWh) that was used for complying out of total sales, for states that enacted an RPS policy. For example, suppose that the total annual sales in Arizona in year 2005 was X MWh and the RPS target was 1%. This means that $RPS_{2005,AZ} = X \times 0.01$ MWh amount of electricity must be sourced from renewables in that year. If the compliance percentage in AZ that year was 25%, it means that retailers in AZ were able to meet only 25% of the RPS requirements by acquiring credits (either bundled or unbundled).

The RPS policy is imposed at the individual retail electricity providers and the compliance is verified at the firm level. However, Barbose (2021) only reports the compliance at the state level, thus unless the percentage of the state's compliance is 100%, we cannot identify the compliance/non-compliance status at the firm level. That means, we cannot identify which of the retail firms in the state failed to meet the requirement. However, this is not a significant data limitation as we carry the analysis at the state level. Online Appendix E.3 expands on other relevant factors affecting compliance with the RPS.

State-level control variables. We specify state-level market variables to control for any differences across states that may affect the investment decision. We have compiled datasets from the EIA Electric Power Annual, including total annual net summer capacity and net generation to account for the electricity generation scale differences across states.[23]

We also control for the general profitability of renewable generation in each state. States have different weather conditions that result in different operation hours of renewable generation. For example, a solar panel may operate longer hours in Arizona than in Minnesota and a wind plant may generate longer hours, and more continuously, in Idaho than in Arizona. Operating longer hours means higher profits from the regular spot market and bilateral market. To capture this difference resulting from weather, we compute annual generation per MW of the existing renewable

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[23] `https://www.eia.gov/electricity/annual/`

generation capacity at the state level, which represents the average capacity factor of renewable generation in each state.[24]

Lastly, we obtain data on the annual net interchange (net flows) between the states within the same interconnection from the EIA Electric Power Annual to account for any physical trades of renewable generation across states that could have been caused by the RPS. While it makes more sense to check net flows at the daily or hourly level, we had to resort to the annual data to match the frequency of the main dataset. Since the investment of renewable generation affects the import/export volumes of a given year, we take a lag of this variable and include it in the regression. The net interchange data capture some of the spillovers of the RPS policy in generation in addition to the spillovers in capacity that our contract-level data already account for.

Firm Data. We obtain firm-level data from the EIA Form 860 (wholesale firms) and the EIA Form 861 (retail firms). The EIA Form 860 provides information about generating firms, including Independent Power Producers (IPPs) and Investor-Owned Utilities (IOUs), that own generators. From this dataset, we can compute firm-level variables, such as the firm's total capacity and generation composition. The EIA Form 861 provides information about retail electricity providers (retail firms) that serve customers within each state. This dataset reports the company name, total sales (in MWh), and the number of customers. We use these datasets to explore the state-level measure of vertical structure, which we discuss in Section 4.2.

4 Empirical Analysis

To meet the increasing RPS requirements, states must make ongoing investments in renewable generation capacities. Our goal is to explore how the patterns of new investments in renewable generation, specifically aimed at meeting RPS compliance requirements, differ across states with varying degrees of integration between retail firms and wholesale generators. We begin by explaining the key variables in our main specification and then elaborate on the empirical strategy.

4.1 Binding Years: Variation in the compliance status

4.1.1 Importance of RPS targets and regulatory compliance motives

Several studies examining the RPS policy employ a (staggered) differences-in-differences (DiD) analysis, with RPS adoption as the treatment, leveraging the staggered nature of state-level adoption. While we have implemented a staggered DiD regression similarly to the literature, with results presented in Table A.4 in the Appendix, we find this method less suitable for our analysis for the

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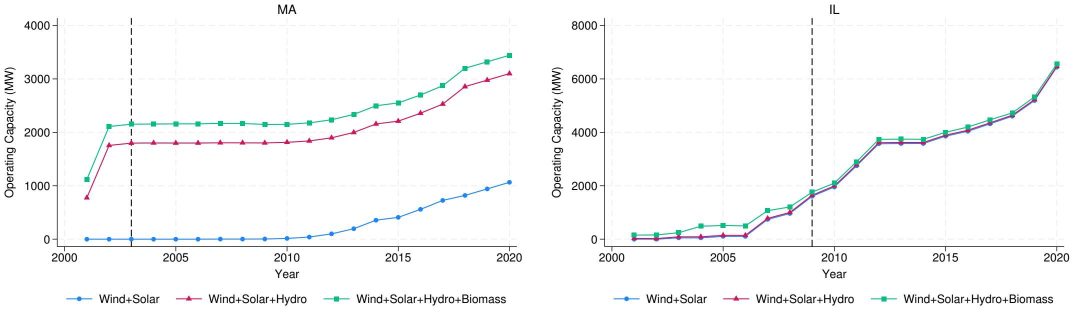
[24] To avoid incorporating contemporaneous year capacity additions, we use the operating hours per MW of renewable capacity with a one year lag.

Figure 5: Operating Capacities: Eligible Renewables in Three Categories



Notes: Figures show the existing capacities in MA and IL, summarized by different fuel categories. "Wind+Solar" shows the existing wind and solar generation capacities, with hydro ("Wind+Solar+Hydro") and biomass ("Wind+Solar+Hydro+Biomass") added subsequently. RPS adoption dates indicated with vertical dashed lines.

following reasons. First, our focus is on the impact of vertical structure on renewable investments induced by RPS, which requires a triple difference-in-differences design that is generally not supported by the staggered DiD framework. Second, wind and solar capacity investments were nearly non-existent in most states before the RPS, resulting in limited pre-treatment variation. Additionally, the small number of treated states within the same cohort (calendar year) poses challenges for implementing staggered DiD estimation.[25]

Moreover, there is considerable heterogeneity in states' investment responses to the RPS policy, even in the post-RPS years, due to differences in initial stocks of renewable generation eligible for compliance and RPS target levels.[26] Figure 5, which plots cumulative capacities by renewable energy sources, illustrates how investment patterns differ between Massachusetts (MA) and Illinois (IL), which have different levels of initial renewable stock and target levels. In MA (left panel), wind and solar capacities remain stagnant for several years after RPS adoption (indicated by the vertical dashed line) because the state's cumulative renewable capacity, including hydro and biomass, was sufficient to meet the low initial RPS requirements. However, as the requirements steadily increase, investment begins to rise accordingly. On the other hand, IL (right panel) had a relatively small initial stock of renewable capacity, with minimal wind and solar capacities. Moreover, the RPS target in IL in the first year of adoption was more than twice as large as in MA.[27] Thus, new wind and solar investments began shortly after RPS adoption in IL.

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[25] The lack of pre-treatment variation weakens the power to test parallel trends, which is crucial for establishing causality. Moreover, a small treated sample within each calendar year (cohort) creates the sparse dummy problem (Hansen (2022)), leading to imprecise parameter estimates.

[26] The importance of accounting for preexisting renewable capacity in the analysis has been noted in other studies (Greenstone and Nath (2021), Deschenes et al. (2023)).

[27] Although the pre-existing capacity in the RPS start year appears similar in both states, MA had an RPS requirement of 498,344 MWh in while IL had a requirement of 1,210,441 MWh in 2009.

We observe similar heterogeneous investment responses across states, indicating that investments occur when the existing renewable capacity, combined with projected RPS targets (requirements), becomes binding for the state. Thus, pre- and post-RPS adoption variation alone cannot explain this rich heterogeneous pattern of investments. This is another reason why difference-in-differences is not suitable for our analysis, as these RPS-related variables are not defined for the states that do not have the policy in place.[28] Therefore, we leverage the variation in RPS targets and retailers' compliance needs in our analysis.

4.1.2 Binding Years: Compliance Status

We introduce a binary measure of compliance status, termed 'Binding', constructed from state-level annual compliance data. This variable indicates the years when a state fails to fully comply with the RPS, capturing year-to-year compliance variation in the post-RPS period for states that have adopted the policy. A state is designated as non-compliant if total renewable generation within the state – whether from existing or new capacity, contracted capacities, or REC market purchases, in-state or out-of-state – falls short of the requirement level.[29]

As explained in Section 4.1.1, retailers would have incentives to source investments when they project that renewable generation within the state will fall short of meeting the state's requirement. In this respect, a state's compliance status is useful, as non-compliance ex-post suggests that retailers likely anticipated the shortfall ex-ante and made investments accordingly. This is supported by the positive coefficient of the Binding variable in our main regression, indicating that new investments are larger in binding years than in non-binding years, which we discuss in Section 4.4.

Moreover, the compliance status strengthens the analysis by clearly linking the observed investments to the policy. If full compliance is not reached in a given year, all new renewable capacities available during that binding year, regardless of the sourcing channel, are expected to be used by retail firms for compliance purposes, yet the state still fails to meet the requirement. For a retailer facing non-compliance penalties, it would be inefficient not to use available renewable energy from new capacities in this binding year. Therefore, the RPS policy's influence on renewable investments is expected to be stronger in binding years than in non-binding years, allowing us to establish a stronger causal link between the observed investments and the policy. This serves as a complement

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[28] Despite the limitation, we implemented a simple triple difference-in-differences estimation using pre- and post-enactment, where we interacted the treatment with the vertical structure variable. Table E.3 in the Online Appendix shows the results, which are qualitatively similar to our main analysis, finding that vertical separation is associated with lower renewable capacity investment.

[29] Some states allow renewable energy (RECs) generated out-of-state to count toward compliance, leading retail companies to contract with out-of-state capacities or purchase out-of-state credits. For a detailed discussion of RPS spillover effects across states or REC trading scheme, see Hollingsworth and Rudik (2019) and Abito et al. (2022). We also summarize documented spillovers in capacity contracting in Tables E.1 and E.2, with further discussion in Online Appendix E.3.1.

Figure 6: RPS Requirement, RPS Goal, and Binding: Connecticut

Notes: The graph shows the annual minimum requirement set by the RPS policy in Connecticut (CT). The RPS requirement is a minimum percentage target requirement set by RPS multiplied by the annual generation within CT, which is equivalent to the total sales of retail providers in CT. RPS goal is the amount of annual generation unfulfilled by the state for that fiscal year, and the values are plotted only for the Binding variable, which is a variable that indicates the years when the state was in full compliance with the RPS policy.

to our analysis, where econometric methods face challenges in estimating a clear causal relationship between the policy and investment.

To account for the degree of incomplete compliance, we introduce the *RPS Goal* variable, which measures the shortfall from the target in a given year. For example, if the compliance percentage is 80% with a total target of X MWh, the RPS goal is 20% of X MWh. This variable complements our Binding indicator, which is binary and does not capture the extent of non-compliance. Figure 6 provides an example of the Binding and RPS Goal variables for Connecticut. The solid line represents the annual RPS requirement, calculated as RPS target (%) multiplied by total electricity sales (MWh), with Binding and RPS Goal variables plotted together.

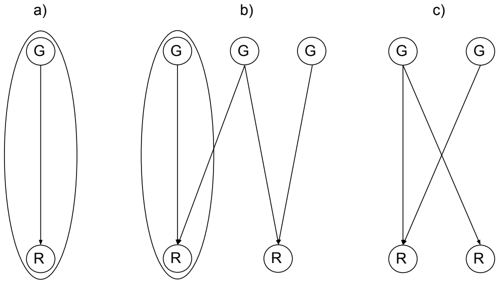
4.2 Different Measures of Vertical Structure

We construct a variable, termed as VS (Vertical Separation), to measure the degree of vertical separation between the generation and retail sectors at the state level. While vertical structure at the firm level is binary, representing vertical integration or separation at the state level requires more than a simple binary indicator. We introduce three versions of this variable, including the binary indicator, a generation sector-, and a retail-based measure.

4.2.1 Binary indicator for vertical separation.

The first measure is a binary variable assigned to the restructuring status of each state. Restructuring can happen at either wholesale or retail markets, or both, as discussed in Section 2.3. We assigned $VS_{\text{binary}} = 1$ to states that have restructured both wholesale and retail sectors. This

Figure 7: Different market structures and their vertical separation nature



Notes: Arrows represent sales of power from generation entities to retailers. Ovals represent joint ownership. a) Fully vertically integrated: A classic electricity utility company where both generation and retail are owned by the same company. b) Partial vertical separation: A wholesale generator that sells also to an independent retailer. c) Fully vertically separated structure.

categorization closely resembles the list of restructured states used in the literature as well as policy reports (Fabrizio et al. (2007), Borenstein and Bushnell (2015), Barbose (2021), MacKay and Mercadal (2022), and the EPA[30]). Restructuring of the wholesale sector is associated with increased separation between generation and retail as retail firms are required to purchase electricity from the market instead of generating it by themselves. Retail market restructuring enables entry of retail firms that often specialize only in retail services, which further increases separation between wholesale and retail at the state level.

4.2.2 Continuous measures using firm-level information

While a binary indicator for state-level restructuring is common in many studies, it has limitations due to the lack of a unified definition, with restructuring and deregulation often used interchangeably and not clearly distinguishing between wholesale and retail sectors (Borenstein and Bushnell (2015)). In practice, restructuring did not always lead to complete separation between generation and retail, as utilities in restructured states often continue to own and operate generation assets (see Section 2.4).

To illustrate the need for a continuous measure of vertical separation, Figure 7 depicts three possible configurations in the electricity sector, all of which can coexist within the same state. The simplest configuration is full vertical integration, where all generators and retail assets belong to the same company. Another case is partial vertical integration, where a retail firm owns and generates using its own generation assets but also purchases electricity from an independent upstream firm. Finally, there is full vertical separation, where the generation and retail sectors share no common ownership.

Given the varying degrees of vertical ties across states, we develop continuous measures of

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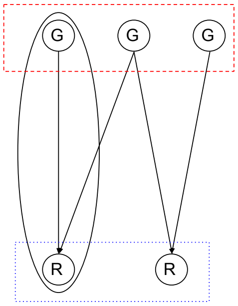
[30] `https://www.epa.gov/greenpower/understanding-electricity-market-frameworks-policies`

Figure 8: Construction of continuous VS measures



Notes: Arrows represent sales of power from generation entities to retailers. Ovals represent joint ownership. When constructing the VS measure using the generation capacity data (red dashed rectangle), we obtain VS = 0.66 (assuming equal generation capacities). However, when using the retail sales data (blue rectangle at bottom), then VS = 0.5 (assuming equal sizes of retail sales).

vertical separation using firm-level data on these relationships, which are then aggregated at the state level for our analysis.

Vertical separation measure using generation capacity data. The first continuous vertical separation variable, VS_{gen}, measures the extent to which generation capacities in the wholesale market are not owned by retail firms. Using EIA 860 data, we calculate the share of generation capacity within a state that is not vertically integrated – not directly owned by firms operating in the retail sector.[31] To address potential endogeneity in shares as new investments occur, we fix the variable at its 2002 value, before most states adopted RPS, for all subsequent years.

Vertical separation measure using the retail provider and generator. The previous measure, VS_{gen}, focused on the wholesale sector and did not incorporate retail market information. Since the RPS primarily affects retail electricity providers, we develop a continuous measure of vertical separation, VS_{retail}, which accounts for retail market conditions. This measure captures the presence of retail firms that do not have direct vertical linkages with the wholesale sector. Using data from EIA Form 861, which includes information on retail firms – such as total sales and revenues – in each state, we identified retail firms without generation assets and computed their share of retail sales (total annual electricity sales in MWh) within the state.[32] To address potential endogeneity from changes in market shares due to retailer compliance strategy and new investments, we fix the variable at its 2002 value, before most states adopted RPS.

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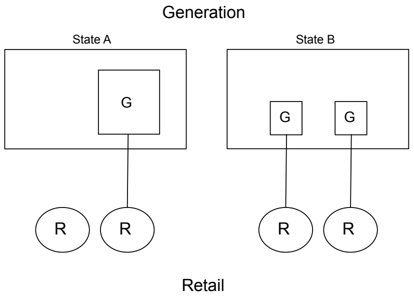
[31] This share is based on total available capacity, not the utilized capacity (i.e., share or sales), and includes all fuel types.

[32] We include only retail firms with at least 5% of the market share in terms of total annual sales.

Figure 9: Comparison of VS measures



Notes: The figure describes the status of vertical relationship between the generators and retailers, which differ across two states A and B. Lines between retail (R) and generation (G) indicate that a vertical relationship (integration) exists between these sectors.

4.2.3 Relationships between the three measures of vertical separation.

We explain how the continuous measures are constructed using Figure 8. In the generation sector, shown in the upper red dashed box, one of the three generators (G) is owned by a downstream retailer (R), shown in the lower blue dotted box. To calculate VS_{gen}, we compute the share of generation capacities that are not owned by a retail firm. Assuming equal capacities for all three generators, VS_{gen} is $\frac{2}{3}$. On the other hand, in the retail sector (blue box), one of the two retail firms owns a generator. The share of retail sales of the firm that does not own generation assets represents VS_{retail}. Assuming equal market shares, VS_{retail} is $\frac{1}{2}$. This example demonstrates that the two continuous measures of vertical separation, VS_{gen} and VS_{retail}, do not necessarily coincide.

The key difference between VS_{gen} and VS_{retail} lies in the sector where the shares of vertically linked firms are calculated. We believe VS_{retail} more accurately reflects the vertical linkages relevant to our research question. This is demonstrated in Figure 9, which depicts two states with the same number of retail firms but differing vertical ownership statuses. In state A, half of the retail sector is vertically integrated with upstream generators, though the integrated generator's capacity is large. In state B, all retail firms are integrated with generators, but integrated generators are smaller in capacities. Since all retail firms in state B have vertical ties with the upstream, our notion of vertical integration suggests that it is more pervasive in state B, making state A more vertically separated than state B. VS_{retail} captures this by assigning a higher value to state A, while VS_{gen} assigns a lower value to state A due to the large size of the vertically integrated generator.

Table 1 presents summary statistics for the three measures of vertical separation. While these measures differ from one another, they are somewhat correlated. Figure E.2 in the Online Appendix depicts the pairwise correlations, showing the highest correlation of 0.8 between the two continuous VS measures. However, when comparing these measures at the state level, significant differences

Table 1: Summary statistics of measures of vertical separation (VS)

	Mean	Min	Max	S.D.
Binary (VS_{binary})	0.48	0	1	0.50
Generation capacity (VS_{gen})	0.50	0.04	1	0.37
Retail sales (VS_{retail})	0.28	0	1	0.39

Notes: $N = 31$. See main text for a description of the three different ways to measure vertical separation. The three measures take on values in the unit interval.

emerge for some states. This is shown in Figure 10, where each dot represents the combination of VS_{gen} and VS_{retail} for each state.[33]

4.3 Main specification

Taking into account all of the previous considerations, we estimate the following regression model:

$$\begin{aligned}\text{Renewable Investment}_{s,t} \quad &= \alpha_0 + \alpha_1 \text{ RPS Goal}_{s,t} \ + \alpha_2 \text{ Binding}_{s,t} \\ &+\beta \text{ VS}_s \times \text{Binding}_{s,t} + \textstyle\sum_{l=-2}^{l=+2} \lambda_l D_{s,t^*+l} \\ &+ \textstyle\sum_{l=-2}^{l=+2} \gamma_l D_{s,t^*+l} \times \text{VS}_s + \boldsymbol{\gamma}'\mathbf{X}_{s,t} + \varepsilon_{s,t}. \end{aligned} \qquad (1)$$

To that end, we use only states that have adopted RPS. Thus, our empirical analysis differs from a standard difference-in-difference estimation, where RPS-adopting states are considered treated and non-adopting states serve as the control group. As discussed in Section 4.1, we adopt this modified approach because increasing policy target levels and retailers' regulatory compliance motives, which are present only in states that have adopted an RPS, better explain changes in state investments than the RPS adoption event alone.[34]

The dependent variable Renewable $\text{Investment}_{s,t}$ represents the aggregate level of new investments in wind and solar generation capacities in state s in year t, as explained in Section 3. Note that our focus is not on analyzing individual firms' decisions to invest in renewable generation, which would require using firm-plant level data as the primary variable. Instead, we examine the outcomes of individual-level decisions in an aggregate sense. We use the year t when new capacity starts operations and match that year with the RPS variables of that same year. Since the schedule of annual RPS targets is set up several years in advance, the typical process of contracting for in-

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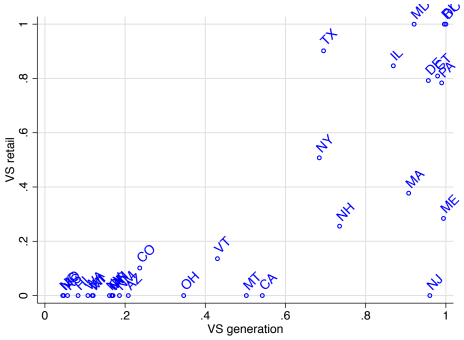
[33] For example, in California, VS_{gen} is slightly above 0.5, while the VS_{retail} is close to 0, indicating that California's retail sector has a strong vertical ties with the generation sector. In California, although a large portion of generators are not tied to retailers, all retailers operating within the state own generation capacity in the wholesale sector.

[34] We implemented a staggered difference-in-differences analysis using the Callaway and Sant'Anna (2021) estimator to investigate the causal relationship between RPS adoption and renewable investment, as presented in Table A.4 in the Appendix. The results are consistent with those of Deschenes et al. (2023), showing that a state's adoption of an RPS policy increases renewable investments.

Figure 10: Vertical separation measures by state: retail sales and generation capacity



Notes: For most states, the Vertical Separation measure using retail sales data is similar to that obtained using generation capacity shares.

vestment is that the plant construction is planned and decided years in advance so that the invested plant can go online at the time needed to comply with the RPS.

The main variable of interest is the interaction of the state's market structure (VS) and Binding. Therefore, the coefficient β captures to what extent the investment increases influenced by the policy differ across different vertical structures conditional on non-compliance. We also control for RPS Goal, which captures how far the state is from complying with the policy.[35] $\mathbf{X}_{s,t}$ includes state-level controls, such as total capacity and total net generation, net import flows into the state from neighboring states, average profitability of a MW renewable capacity, as well as year fixed effects and market (Regional Transmission Organization) fixed effects.[36] Note that we included state fixed effects to control for any policy changes that occurred within the state that could potentially affect the investment. In all the specifications, standard errors are clustered at the state level. In addition and in order to capture time trends that are common to all states but that only occur around the point in time where the RPS policy is binding in certain states, we added time dummies D_{s,t^*+l} associated with each year l before and after the event –the year t^* in which the RPS regulation is binding in a given state– in a separate set of robustness specifications as well as the interaction of these dummies and the vertical separation measure.[37]

The data span from 2002 to 2020, including the states that have eventually adopted RPS by 2020.[38] We use only the years after the state enacted the RPS policy because the compliance

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[35] We do not include VS as a separate regressor since we include state fixed effects.

[36] Total net summer capacity and net generation capture the size differences in electricity sector across states. Capacity and generation values associated with the contemporaneous year's capacity investment are excluded from these control variables.

[37] We used a window of two years before and after the event. These dummy variables are different from the year fixed effects. This is inspired by some of the specifications in Greenstone and Nath (2021) and from the use of similar dynamic effects specifications in a different context in Vannutelli (2022).

[38] We do not to use investment data prior to 2002 because the restructuring process was completed in most of the

variable cannot be defined for years before the RPS policy started. Because each state enacted RPS in different years, we have an unbalanced panel data set. Note that most states, a total of 18 states, adopted an RPS policy between 2002-2008, and the data are not significantly unbalanced.[39]

Identification Our estimate of the interaction term in specification shown in Equation (1) has a causal interpretation, provided the following assumptions hold: the residuals are uncorrelated with the state's market structure (VS) and uncorrelated with whether or not the RPS is binding. For the former, vertical market structure in each state evolved primarily due to the deregulation movement that preceded the relatively recent RPS policy. We also keep the level of VS fixed over time, using the value from the year prior to the policy enactment in each state.

The exogeneity of the Binding variable follows from the discussion below. Note that our Binding variable is described as below:

$$\text{Binding}_{s,t} = \mathbf{1}(G_{s,t} < \tau_{s,t} R_{s,t}),$$

where $\tau_{s,t}$ indicates the RPS target percentage and $R_{s,t}$ indicates total retail electricity sales, both of which are exogenous variables determined outside the wholesale sector. $G_{s,t}$ represents the total annual generation from renewable sources, including the generation from newly installed capacity that comes online in year t, denoted as Renewable $\text{Investment}_{s,t}$, which we will refer to as the dependent variable $Y_{s,t}$ henceforth. Since the generation from this year's new capacity $Y_{s,t}$ is included in G_{it}, one might think that the Binding variable could be endogenous. However, note that the Binding variable is an indicator function, and the inequality $G_{s,t} < \tau_{s,t} R_{s,t}$, which defines this function, holds even when excluding the generation from the new capacity $Y_{s,t}$. In other words, if $G_{s,t}$ (including the generation from $Y_{s,t}$) falls below the target requirement ($\tau_{s,t} R_{s,t}$), the inequality will also hold when the generation from $Y_{s,t}$ is excluded. This means that the Binding variable, as an indicator function, is not determined by $Y_{s,t}$ thus exogenous with respect to $Y_{s,t}$. More details can be found in Appendix B.

4.4 Results

The results from regression (1) using the three different measures of vertical separation (binary, generation capacity, and retail sales) are shown in Table 2 and in detailed form in Appendix Tables A.1, A.2, and A.3. In the three cases and in all the specifications, our variable of interest ($VS\times$ Binding) has a negative and statistically significant coefficient except for a couple of specifications

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states by 2002 and that investment data prior to 2002 are contaminated with the investment boom that resulted from restructuring.

[39] Although our sample spans over the period 2002 to 2020, the RPS compliance data does not exist for latter years of the sample in some states.

Table 2: Renewable investment and compliance using different measures of vertical separation

	(1) Binary VS	(2) Generation VS	(3) Retail VS
	Renewable Investment		
VS x Binding	-248.8***	-224.3**	-276.3**
	(86.64)	(103.2)	(109.8)
Binding	151.2**	186.2**	152.5**
	(60.48)	(89.35)	(62.97)
RPS goal (GWh)	0.000486	-0.0000904	-0.00117
	(0.0214)	(0.0194)	(0.0212)
Net summer capacity (MW)	0.0926***	0.0935***	0.0912***
	(0295)	(0.0322)	(0.0283)
Net generation (GWh)	-0.00703	-0.00640	-0.00666
	(0.00730)	(0.00765)	(0.00725)
Renewable per cap. lag (GWh per MW)	-0.000324	-0.00664	-0.0100
	(0.0160)	(0.0175)	(0.0188)
Net flow lag (GWh)	1.300	2.480	1.185
	(3.693)	(3.819)	(3.835)
Constant	-3932.6***	-4143.1***	-3882.5***
	(407.8)	(484.1)	(412.5)
N	388	388	388
Adj. R^2	0.62	0.62	0.62
Dep. var. mean	183.27	183.27	183.27
Market FE	✓	✓	✓
State FE	✓	✓	✓
Year FE	✓	✓	✓

Standard errors in parentheses

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

Notes: Dependent variable: New renewable capacity (MW). Each column corresponds to the results obtained using each of the three different measures of vertical separation: binary, continuous-generation, and continuous-retail. The data combine EIA and FERC information, see main text for further details. For each state, only years when RPS policy had been put in place. Standard errors clustered at the state level.

with the generation capacity vertical separation measure. In other words, our coefficient of interest reveals that renewable investment is lower when the RPS policy is binding and the retail sector is more separated from the generation sector relative to states that are more integrated. The positive coefficient for the Binding variable confirms that investments sizes are larger in binding years, which corresponds to retail firms planning more investment for years in which generation will fall short of RPS requirement.

The more detailed analysis shown in Appendix A starts with simple regressions to analyze the importance of controlling for different factors, that only include the interaction term, whether the policy is binding, the gap to achieve the RPS goal, and market and state fixed effects, for each of the three measures of vertical separation. In all those cases, except in Table A.2 when using the vertical measure based on generation capacity and almost no controls, the coefficient of interest is already negative and statistically significant in all those simple specifications.

While our preferred measure of vertical separation is given by the retail sales, shown in column (3), estimates for VS × Binding in all three columns in Table 2 are qualitatively similar, ranging between -276.3 and -224.3. On average, conditional on having a binding RPS policy, states with a more vertically separated structure invest less in renewable capacities than their more vertically integrated counterparts by a factor between 1.2 and 1.5 times the overall average investment in renewables. Our findings correspond to the differential impacts by vertical structure in contracting channel investment as discussed in Section 2.4.

As previously mentioned, we estimated specifications where we also included time dummies corresponding to each year before and after a year in which the RPS is binding. These results can be found in Appendix A. Across all the different measures of vertical separation, this type of specification gives estimates that are also consistent with our main results. In addition, we report in Tables E.5 - E.7 in the Online Appendix the same regressions as in this section but without using contract-linked data but only data from the EIA. The results are largely similar but slightly larger standard errors.

Placebo Test Natural gas-fired generators dominated the new fossil fuel capacity investment in the past few decades. As a placebo test, we run the same regressions using the state-level investment in natural gas-fired generation only as a dependent variable. Natural gas investment is not affected by the RPS regulation; thus, these additional regressions serve as a natural placebo test for vertical structure's effects on the RPS-induced renewable investment.

Tables E.8, E.9, and E.10 in Online Appendix show the result of regression specification in Equation (1) with the dependent variable replaced with the aggregate state-level investment in fossil fuel generation. We combine the investments in natural gas, coal and oil generation to construct this variable. In all of the twelve specifications (three measures of vertical separation and 4 specifications each) we find a positive coefficient, with only two of them statistically significant. In other words, there is not a relationship between the RPS policy and investments in non-renewable capacity conditional on the market structure. However, the coefficient on Binding has a negative and statistically significant sign in Column (4) of the three tables, indicating that when the RPS policy is binding, there is less investment on non-renewable capacity due to a substitution effect towards investment in renewables.

Wind and solar investments One potential concern is that our results may be driven by a specific type of technology. To address this question, Tables E.11 and E.12 in Online Appendix show the results from the same model from this section but with a dependent variable that measures the investment on wind capacity and on solar capacity, respectively. This specification isolates the effect that the RPS policy has on each of the two most commonly adopted renewable technologies in the US conditional on market structure. In this case, we use VS_{retail}. Similarly to the results when aggregating both types of investment, the estimate for the $VS\times$ Binding is negative and significant in our preferred specifications, with a combined effect that roughly corresponds to the effect using total renewable capacity.

4.5 The Effect of the Renewable Energy Credits (RECs) Market on Investment

Section 2.4 discussed the two main channels through which investments can occur: the contracting channel and the Renewable Energy Credit (REC) market channel. We assumed that the differential effect of vertical structure on investment is primarily driven by the contracting channel and that investments through the REC market channel do not significantly differ by vertical structure. While the best way to empirically verify this is to include REC spot market variables in our main regression to control for investment variation explained by REC market conditions, we cannot include these variables due to data limitations. REC market data, especially spot prices of credits, are not publicly available, and only a few states report monthly statistics for solar REC (SREC) prices.[40]

Omitting REC market variables could bias our estimate if investments through the REC market channel do occur and affect the differences in investment patterns attributable to the vertical market structure, which is captured by our main coefficient of interest (for the variable $VS\times$ Binding). In this subsection, we discuss whether attractive REC market conditions – characterized by high REC price levels – could either crowd out or enhance investments occurring through the contracting

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[40] For example, the PJM Interconnection provides summary statistics for REC prices for states within the market through the PJM-GATS (Generation Attribute Tracking System) platform, which includes weighted average prices from both long- or mid-term contracts and spot prices for solar capacity (See `https://www.pjm-eis.com/`).

channel and examine the direction of bias associated with each case when not accounting for the REC market related variables in the analysis. We then empirically confirm the direction of the bias from an analysis using a subsample for which REC market data are available.

The effect of the REC market channel on the Contracting channel investment. We first consider how a more attractive REC market might affect a wholesale generating firm's incentives to invest through the contracting channel. If the REC market provides a reliable source of revenues and serves as an alternative option for wholesale firms considering capacity investments, the REC market investment channel can affect the contracting channel investment. That is, if contracting is costly and parties fail to agree on terms, a renewable project developer may turn to the REC market to finance the investment. This implies that attractive REC market conditions could crowd out contracting channel investments, more so in vertically separated environments where contracting is more challenging and commitment to contracts is weaker than in the integrated case.

On the retailer's side, an attractive REC market condition for wholesalers – high REC price – is unattractive to retailers since they are buyers of the credits. Regardless of the vertical structure, retailers would prefer to comply through the contracting channel rather than the REC market if REC spot prices are higher than long-term contract payments, making them more likely to opt for the contracting channel.

The final equilibrium effect of the REC market investment channel on our main estimate depends on how a reliable source the REC market channel is to wholesale firms considering investing. If wholesalers view the REC market as a reliable channel, they are more likely to shift away from the contracting channel, more so in vertically separated markets. Conversely, retailers, regardless of their vertical structure, are more inclined to opt for the contracting channel when REC market conditions favor wholesalers, revealing a misalignment in upstream and downstream incentives. This misalignment becomes more problematic as the degree of vertical separation increases, further reducing contracting channel investment compared to a scenario without the REC market option.

On the other hand, if the REC market channel is not well established, meaning wholesalers do not view it as a reliable source comparable to the contracting option, they would not opt out of the contracting channel even if the REC market conditions are attractive. Since retailers would pursue the contracting channel more, the overall contracting investment could even increase in this case, or at least not be crowded out by the REC market channel. Misalignment in upstream and downstream incentives is not further intensified in the vertically separated case due to the presence of the REC market channel.

Note that in vertically integrated markets, the incentives of upstream and downstream are aligned, thus wholesale firms maintain investments at the level required by the retailer, regardless of the REC market conditions. Therefore, contracting channel investments in vertically integrated environment are less affected by REC market conditions.

In summary, if the REC market channel is a reliable source of investments for wholesalers, the presence of an attractive REC market is expected to further intensify the difference in the RPS-driven investment patterns between vertically integrated and separated structures. On the other hand, if the REC market channel is not well established, an attractive REC market would not intensify the difference, but instead reduce the difference in RPS-driven investment between the two vertical structures.

REC market variable as an omitted variable and the direction of bias. Based on the previous discussion, we know that while the REC market channel (Z) itself does not affect the contracting channel investment (Y) directly, it could change the differential effects across vertical structures, our main coefficient for $VS\times$ Binding (X). We can formalize this problem as

$$Y = \beta_0 + (\beta_1 + \beta_2 Z)\, X + \varepsilon,$$

where the effect of X could be affected by Z. If Z is present, the effect of X on Y is more intensified if β_1 and β_2 have the same sign, and more subdued if β_1 and β_2 have different signs. Since we do not include Z in the analysis, we can assess the direction of the bias for β_1 in this case. In Appendix C we obtain that the expression for this bias is $\beta_2 E[Z]$.[41]

The sign of β_2 depends on whether the REC market channel works or not, as discussed earlier. Thus, we can test whether this channel amplifies the difference between vertical structures (for crowding out the contracting channel) or reduces the gap between vertical structures. If it amplifies the difference, this implies that the signs of β_1 and β_2 are the same, while in the case where the difference is reduced, β_1 and β_2 must have opposite signs. Since $\beta_1 < 0$, this indicates that the bias will be negative if the REC market is working well, and the bias is positive if not. In other words, in the former case, our main regression without the REC market channel variable (Z) would estimate a b_1 that is larger in magnitude than when including Z. If the bias is positive, the estimate would be smaller in magnitude than when including Z.

Subsample regression including REC market variables. We empirically verify the direction of bias using a small sample of states within the PJM interconnection, where REC market data are available. PJM publishes summary statistics of solar renewable credits traded within the region, but only for the solar renewable credits (SRECs). Thus, we restrict our analysis to investments in *solar* generation capacity within these states. We use the state-level (weighted-average) prices of

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[41] The sign of $E[Z]$ is positive since we use REC prices as our variable for Z.

Table 3: With REC price as a control: Solar investment in PJM (using VS_{retail})

	(1)	(2)	(3)
	Solar Cap Investment		
VS x Binding	-60.96*	-69.26*	-80.83**
	(31.56)	(36.88)	(30.98)
Binding	35.56	38.31	34.39
	(26.41)	(27.87)	(28.70)
RPS goal (GWh)	0.00120	0.00149	0.00239
	(0.00352)	(0.00364)	(0.00343)
Net generation (GWh) -0.00000101	0.00307*	0.00328*	0.00335*
	(0.00154)	(0.00172)	(0.00177)
Net summer capacity (MW)	0.0160	0.0157	0.0169
	(0.00953)	(0.00969)	(0.0101)
REC price(t) x VS x Binding		0.00481	
		(0.1000)	
REC price($t-1$) x VS x Binding			0.0587
			(0.0884)
Constant	9.858	13.39	10.13
	(10.89)	(9.629)	(11.51)
N	93	88	86
R^2	0.64	0.64	0.64
Dep. var. mean	32.35	34.17	34.97

Standard errors in parentheses

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

Notes: Dependent variable is the new solar capacity (MW) that enters each state every year. This analysis includes only PJM states. All regressions include state, year FE. Standard errors are clustered at the year level. REC price (t) variable is the first month price of the contemporaneous year and REC price ($t-1$) variable is the average price of the previous year (lagged value). The Binding variable has been adjusted to capture compliance for solar-specific requirements in states that have a separate requirement for solar.

individually transacted solar RECs from 2008 to 2020, averaging the monthly prices to the yearly level to make the time consistent with our main dataset. The 'Binding' variable is adjusted for states that have separate RPS target levels and compliance statuses for solar generation capacity.

We use the same specification as in Equation (1) using solar investment capacities as the dependent variable. Results are presented in Columns (1)-(3) in Table 3. Column (1) shows the result when not including the REC market variables. In Columns (2) and (3) regressions, we specify REC price variable interacted with our main variable, to capture differential impacts across vertical structure further being impacted by the REC market channel. We use the contemporaneous year's REC price (but of the first month) in Column (2) regression and one-year lagged REC price in Column (3).[42] Given that RECs can be traded between states within PJM, the standard errors are

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[42] Because new investments could affect the spot prices of RECs within the same year, we used the average monthly

clustered at the year level.[43]

Comparing the results of Column (1) to Columns (2) and (3), we find that the coefficient of our main variable, $VS\times$ Binding, changes from -60.96 to -69.26 and -80.83, respectively after adding the REC price control variables. This indicates a positive bias, since column (1) estimate is smaller in magnitude than in (2) and (3), which would occur if the REC market investment channel is not active and wholesale firms not making investment decisions based on REC market signals. It also implies that the results from our main estimation, which omits this variable due to data limitations, might be biased towards zero; the negative estimate for the $VS\times$ Binding variable would likely be larger in magnitude if REC market variables were included. However, note that the size of bias is not substantially large, so while our main analysis may have underestimated the true effect of vertical structure, the potential bias is not worrisome.

While the sample size is small to make a definitive statement about REC market channel investment, both the sign and the magnitude of bias from our small sample analysis hints on that the REC market investment channel may not be working properly and not serving as an alternative of contracting option. This may be attributed to the unattractive REC market conditions, which do not offer a reliable basis for wholesalers' investment decisions. For instance, REC prices are heavily influenced by the state's compliance status and can vary considerably.[44]. This is particularly true for solar renewable credits (SRECs). In our sample, SREC prices are significantly higher in binding years than in non-binding years, by about 24.7% on average. Moreover, Table 4 summarizes monthly SREC prices in the PJM market from 2008 to 2020, showing substantial volatility – from \$0 to about \$700/MWh, even within the same month.[45] The high variability in credit prices suggests that renewable project developers are unlikely to base their investment decisions solely on revenues from selling RECs in the spot market, as these revenues are uncertain and heavily influenced by a state's compliance status.

5 Conclusion

We have shown that the amounts of investment on renewable generation capacity as a consequence of the restrictions imposed by the Renewable Portfolio Standards policy largely differ depending on the market structure of the electricity sector in a given state. Vertical separation between the generation and the retail sectors tends to diminish the effectiveness of the policy rel-

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REC price of the first month (January) of each calendar year to avoid simultaneity in REC price determination.

[43] Most states require retailers to acquire credits issued within the same state, but some allow purchases from other states to meet RPS requirements. For example, Pennsylvania allows credits purchased within the PJM interconnection to be used for compliance (Abito et al. (2022)). Additionally, due to the small sample size, clustering at the state level would result in very small cluster sizes.

[44] `https://www.nrel.gov/docs/fy14osti/61042.pdf`

[45] A price of zero occurs when there is excess supply relative to demand (with very low or zero demand for credits).

Table 4: Summary Statistics: Solar Renewable Energy Credits (SREC) Price – PJM states

Price ($/MWh, monthly)	mean	med	min	max	s.d.	N
Weighted average price	181.25	156.49	0	654	145.23	1,594
Lowest price	76.14	16.75	0	648	107.39	1,594
Highest price	431.28	460	0	715	131.87	1,594

Notes: Data from PJM states only, 2008 - 2020.

ative to more vertically integrated markets. This finding is particularly relevant given the trend towards deregulation and restructuring witnessed in the US electricity sector over recent decades, often favoring vertical separation. While these reforms may have achieved their intended goals, this study suggests they may inadvertently hinder efforts to decarbonize the electricity sector through mechanisms such as RPS policies.

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Appendices

A Tables and Figures

Table A.1: Renewable investment and compliance using binary measure of vertical separation

	(1)	(2)	(3)	(4)
VS x Binding	-380.8*	-380.5*	-248.8***	-175.7***
	(194.0)	(195.9)	(86.64)	(62.13)
Binding	189.5	188.4	151.2**	89.98*
	(135.4)	(145.9)	(60.48)	(48.43)
RPS goal (GWh)		0.00210	0.000486	-0.00858
		(0.0255)	(0.0214)	(0.0256)
Net summer capacity (MW)			0.0926***	0.0954***
			(0.0295)	(0.0279)
Net generation (GWh)			-0.00703	-0.00824
			(0.00730)	(0.00744)
Renewable per cap. lag (GWh per MW)			-0.000324	0.00707
			(0.0160)	(0.0164)
Net flow lag (GWh)			1.300	0.219
			(3.693)	(3.763)
Constant	972.8***	970.8***	-3932.6***	-3838.4***
	(80.33)	(63.93)	(407.8)	(551.1)
N	388	388	388	388
Adj. R^2	0.49	0.49	0.62	0.62
Dep. var. mean	183.27	183.27	183.27	183.27
Market FE	✓	✓	✓	✓
State FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Dyn. Effects				✓

Standard errors in parentheses

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

Notes: Dependent variable: New renewable capacity (MW). The data combine EIA and FERC information, see main text for further details. For each state, only years when RPS policy had been put in place. Dynamic effects with a window +/-2 years. Standard errors clustered at the state level.

Table A.2: Renewable investment and compliance using a continuous measure of vertical separation (generation capacity)

	(1)	(2)	(3)	(4)
VS x Binding	-258.2	-257.2	-224.3**	-176.6**
	(166.7)	(169.0)	(103.2)	(72.91)
Binding	183.1	181.1	186.2**	134.6**
	(154.6)	(164.9)	(89.35)	(60.12)
RPS goal (GWh)		0.00297	-0.0000904	-0.00667
		(0.0208)	(0.0194)	(0.0221)
Net summer capacity (MW)			0.0935***	0.0935***
			(0.0322)	(0.0316)
Net generation (GWh)			-0.00640	-0.00614
			(0.00765)	(0.00743)
Renewable per cap. lag (GWh per MW)			-0.00664	-0.00465
			(0.0175)	(0.0162)
Net flow lag (GWh)			2.480	2.731
			(3.819)	(3.774)
Constant	1076.5***	1073.6***	-4143.1***	-4232.6***
	(63.11)	(51.07)	(484.1)	(607.9)
N	388	388	388	388
Adj. R^2	0.47	0.47	0.62	0.61
Dep. var. mean	183.27	183.27	183.27	183.27
Market FE	✓	✓	✓	✓
State FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Dyn. Effects				✓

Standard errors in parentheses

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

Notes: Dependent variable: New renewable capacity (MW). The data combine EIA and FERC information, see main text for further details. For each state, only years when RPS policy had been put in place. Dynamic effects with a window +/-2 years. Standard errors clustered at the state level.

Table A.3: Renewable investment and compliance using a continuous measure of vertical separation (retail sales)

	(1)	(2)	(3)	(4)
VS x Binding	-451.0*	-451.7*	-276.3**	-212.1**
	(237.6)	(243.2)	(109.8)	(80.90)
Binding	200.8	202.0	152.5**	105.9**
	(139.8)	(152.9)	(62.97)	(40.74)
RPS goal (GWh)		-0.00184	-0.00117	-0.0101
		(0.0258)	(0.0212)	(0.0264)
Net summer capacity (MW)			0.0911***	0.0912***
			(0.0295)	(0.0283)
Net generation (GWh)			-0.00666	-0.00688
			(0.00725)	(0.00737)
Renewable per cap. lag (GWh per MW)			-0.0100	-0.0114
			(0.0188)	(0.0193)
Net flow lag (GWh)			1.185	0.953
			(3.835)	(4.106)
Constant	968.1***	969.8***	-3882.5***	-3852.6***
	(81.56)	(66.11)	(412.5)	(553.2)
N	388	388	388	388
Adj. R^2	0.49	0.49	0.62	0.61
Dep. var. mean	183.27	183.27	183.27	183.27
Market FE	✓	✓	✓	✓
State FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Dyn. Effects				✓

Standard errors in parentheses

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

Notes: Dependent variable: New renewable capacity (MW). The data combine EIA and FERC information, see main text for further details. For each state, only years when RPS policy had been put in place. Dynamic effects with a window +/-2 years. Standard errors clustered at the state level.

Table A.4: Staggered differences-in-differences analysis

	(1)	(2)
Overall ATT	100.98	29.26
	(79.72)	(59.54)
Average over 1-5 years post	31.61	−6.36
	(26.19)	(47.34)
N	940	940
Controls		✓

Notes: Dependent variable: New renewable capacity (MW). Callaway and Sant'Anna (2021) estimator. Standard errors in parentheses.

Table A.5: Alternative Capacity Payments (ACP): by state, year 2014

State	ACP payment ($/MWh)
CT	$55 (class 1 and class 2)
DC	$50 (Tier 1 and Solar), $10 (tier 2)
DE	$80 (non-solar), $500 (solar)
IL	Average rec price paid by IPA
MA	$73.7 (class 1 non-solar), $30.3 (class 2 existing re), $12.1 (class 2 -waste energy), $384 (class 1 solar -Srec 1 program), $316 (class 1 solar-SREC 2 program)
MD	$40 (tier 1 non-solar), $15 (tier 2), $50 (tier 1 solar)
ME	$70.9 (new renewables tier)
NH	$62.1 (class 1 new RE), $28.2 (class 1-thermal), $62.1 (class 2 -solar), $40.1 (class 3- existing biomass), $33.8 (class 4 – existing small hydro)
NJ	$50 (tier 1 and 2), $239 (solar)
OH	$61.0 (non-solar), $50 (solar)
OR	Established bi-annually by Oregon PUC ($110 for 2014 and 2015)
PA	$45 (tier 1 non-solar and tier 2), 2x market value of RECs (tier 1 solar)
RI	$73.9
TX	Financial penalty ($50/MWh)

Source: Heeter et al. (2014).

B Identification

In Section 4.3 we discuss the identification of the main parameter β with particular a focus on the Binding variable. As explained there, that variable, generated from the ex post compliance/non-compliance observations, can be formally represented as follows:

$$\text{Binding}_{s,t} = \mathbf{1}(G_{s,t} < \tau_{s,t} R_{s,t}).$$

The RPS target percentage $\tau_{s,t}$, is determined by state legislation independently of actual wholesale and retail market conditions. Moreover, the target levels are set and published in advance, allowing market participants to observe the targets for the coming years. The variable $R_{s,t}$ represents the total electricity sales within the state, which are determined by consumers and subject to various exogenous shocks. For this reason, the right-hand side of the inequality is exogenous from the investor's point of view.

$G_{s,t}$ represents the total annual generation from renewable sources, including the generation from newly installed capacities, Renewable $\text{Investment}_{s,t}$. Throughout this discussion, we refer to our dependent variable, Renewable $\text{Investment}_{s,t}$, as $Y_{s,t}$.

Now we argue that while the value of $G_{s,t}$ itself is not independent of $Y_{s,t}$, as it contains generation sourced from $Y_{s,t}$, the inequality condition that determines the Binding variable – an indicator function – is independent of $Y_{s,t}$. To clarify, let $G^*_{s,t}$ represent the total annual renewable generation *excluding* the generation from new capacities coming online in year t. Then, if $G_{s,t} < \tau_{s,t} R_{s,t}$, it follows that $G^*_{s,t} < \tau_{s,t} R_{s,t}$, meaning the same inequality condition that determines the Binding variable can be satisfied without $Y_{s,t}$.

Whether the inequality condition in the opposite direction, $G_{s,t} \geq \tau_{s,t} R_{s,t}$, which determines non-binding status, would also be preserved when excluding generation from $Y_{s,t}$ is less straightforward and difficult to confirm empirically due to data limitations. RPS compliance data reported by Barbose (2021) do not indicate by how much a fully complying state's generation level exceeds the RPS requirement, only reporting it as 100% compliance (i.e., $G_{s,t} = \tau_{s,t} R_{s,t}$). If we had data on the exact excess compliance amounts (e.g., 120% compliance), we could empirically verify whether the inequality would hold after excluding the generation from year t's renewable capacity. However, such data are unavailable. Another limitation is that we cannot measure the generation from newly invested renewable capacity ($Y_{s,t}$), as plant-level electricity generation data are not available for all states.

While we acknowledge that the inequality in the opposite direction (non-binding year) may not always hold without generation from $Y_{s,t}$, we empirically test whether the exogeneity condition holds for this case by regressing the Binding variable on Renewable Investment, $Y_{s,t}$. The results, shown in Table B.1, indicate no relationship between $Y_{s,t}$ and Binding, with the estimate being zero

Table B.1: Regression of Binding on Renewable Investment ($Y_{s,t}$)

	$\text{Binding}_{s,t}$
$Y_{s,t}$	8.16e-06
	(0.0000418)
N	388
Controls	✓
FEs (state, market, year)	✓

and statistically insignificant. This confirms that the exogeneity between the Binding variable and $Y_{s,t}$ is plausible in both directions of the inequality. Therefore, the Binding variable, as an indicator function, is exogenous ($\text{Binding}_{s,t} \perp\!\!\!\perp Y_{s,t}$).

C REC Channel Investment

As discussed in Section 4.5, if the REC market channel functions effectively, the presence of an attractive REC market is expected to increase the difference in RPS-driven investment patterns between vertically integrated and vertically separated structures, resulting in a more negative coefficient for the main variable of interest in the regression. On the other hand, if the REC market channel is not effective – meaning it is not a reliable source of investment for wholesale firms – the presence of an attractive REC market would have minimal effect or reduce the difference in RPS-driven investment, resulting in minimal change or a more positive coefficient for the main variable of interest.

From this, we know that while the REC market channel (Z) itself does not affect the contracting channel investment (Y) directly, it could change the differential effects across vertical structures, our main coefficient for $VS\times$ Binding (X). We can formalize this problem as

$$Y = \beta_0 + (\beta_1 + \beta_2 Z)\ X + \varepsilon,$$

where the effect of X could be affected by Z. If Z is present, the effect of X on Y is more intensified if β_1 and β_2 have the same sign, and more subdued if β_1 and β_2 have different signs.

Since we do not include Z in the analysis, we can assess the direction of the bias for β_1 in this case. We estimate the linear model

$$Y = b_0 + b_1 X + v \quad \text{where} \quad v = (\varepsilon + \beta_2 Z X).$$

Then the bias of b_1 would be represented by

$$\text{bias} = \frac{\text{Cov}(X, \beta_2 Z X)}{\text{Var}(X)} = \beta_2 \frac{\text{Cov}(X, ZX)}{\text{Var}(X)}.$$

The direction of bias depends on the sign of β_2 since the sign of the accompanying factor is positive because $\text{Var}(X) > 0$ and $\text{Cov}(X, ZX) > 0$. To see why, by expanding $\text{Cov}(X, ZX)$ we obtain

$$\begin{aligned}\text{Cov}(X, ZX) &= E[X^2Z] - E[X]E[ZX] \\ &= E[X^2]E[Z] - E[X]E[Z]E[X] \\ &= E[Z](E[X^2] - E[X]^2) \\ &= E[Z]\text{Var(X)} > 0,\end{aligned}$$

where the second line assumes $\text{Cov}(X, Z) = 0$ (weak version of independence), which holds because the REC price and $VS\times$ Binding are uncorrelated. Since Z, which is a price value, is positive, $E[Z] > 0$ and $\text{Var(X)} > 0$, making the entire expression positive.

The bias expression can be further reduced to:

$$\text{bias} = \beta_2 \frac{E[Z]\text{Var}(X)}{\text{Var}(X)} = \beta_2 E[Z]$$

The sign of β_2 depends on the effectiveness of REC market channel, as discussed earlier. Thus, we can test whether the REC market channel has a crowding out effect (wholesalers viewing this as a reliable channel) or the opposite effect (REC market channel not working well). The former would be the case where signs of β_1 and β_2 are the same and the latter is where they have opposite signs. Since our coefficient β_1 has a negative sign, this indicates that bias will be negative if the REC market is working well, and bias is positive if not. In other words, if the former case, our main regression without REC market channel variable (Z) would estimate b_1 that is larger in magnitude than when including it, and if the latter case, the estimate would be smaller in magnitude than when including it.

Online Appendix

E.1 A Simple Model of Investment and Market Structure

We start with elements from the models in Coria and Jaraite (2024) and Brown and Sappington (2022) but with crucial differences to adapt it to the RPS policy.

Vertically separated. To gain tractability, we only consider the case of an upstream monopolist and a downstream monopolist. The downstream electricity retailer purchases its power from the upstream generator. The profits of the downstream firm are

$$\pi_D^{VS} = p_r q_D - p_w(1-\tau)q_D - p_c \tau q_D$$

where p_r is the retail price, p_w is the wholesale price, q_D is the quantity sold by the retailer and it is exogenous in the model, p_c is the price of a REC credit or the price established in a bilateral contract and exogenous to the model, $\tau \in [0,1)$ is the RPS requirement. The first term is simply the gross profits from selling q_D units of electricity. The second term is the cost associated with purchasing power that is not subject to the RPS regulation. The last term is the costs imposed by the regulation.

Note that *full compliance* occurs when the downstream firm can find enough τq_D units of renewable output through contracts or through the REC market:

$$\tau q_D \leq q_s,$$

where q_s is the amount of renewables output.

The policy is *binding* if that is not the case. In particular, when in the following equations we refer to the binding case we refer to the situation $\tau q_D = q_s$.

Upstream, the profits are different depending on the binding status:

$$\begin{aligned}
\text{Not binding: } \pi_U^{VS} &= p_w(1-\tau)q_D + \underbrace{p_c \tau q_D}_{\text{RPS revenue}} - \underbrace{c_f(q_D - q_s) - c_s(q_s)}_{\text{variable costs}} - C_{VS}(I_{VS}) \\
\text{Binding: } \pi_U^{VS} &= p_w(q_D - q_s) + \underbrace{p_c q_s}_{\text{RPS revenue}} - \underbrace{c_f(q_D - q_s) - c_s(q_s)}_{\text{variable costs}} - C_{VS}(I_{VS})
\end{aligned}$$

where $q_f = q_D - q_s$ is the quantity of electricity from fossil fuels, c_f and c_s are the variable cost functions for fossil fueled power plants and for renewable plants, and $C_{VS}(I_{VS})$ is the cost of investing in I_{VS} units of renewables capacity. If there are more retailers or more upstream firms we just need to take this into account with aggregate quantities and capacity constraints within a proper competition model.

If we take the first order condition of the upstream firm with respect to the investment amount and remembering that q_D is a constant:

$$\begin{aligned} \text{Not binding: } \left(c_f'(q_D - q_s) - c_s'(q_s)\right)\frac{\partial q_s}{\partial I_{VS}} + \tau q_D \frac{\partial p_c}{\partial q_s}\frac{\partial q_s}{\partial I_{VS}} &= C_{VS}'(I_{VS}) \\ \text{Binding: } \left(-p_w + p_c + c_f'(q_D - q_s) - c_s'(q_s)\right)\frac{\partial q_s}{\partial I_{VS}} + q_s \frac{\partial p_c}{\partial q_s}\frac{\partial q_s}{\partial I_{VS}} &= C_{VS}'(I_{VS}) \end{aligned} \quad (2)$$

where the second term on the LHS is negative if we assume $\frac{\partial p_c}{\partial q_s} < 0$ and $\frac{\partial q_s}{\partial I_{VS}} > 0$. The first inequality captures a scarcity effect in which if there is plenty of renewable output, the price of RECs would decrease. The second inequality represents that investing in renewable capacity increases renewable output. We can further assume that $c_s'(q_s) = 0$ but this is irrelevant for what follows.

Vertically integrated. Now there is only one firm with profits function

$$\pi^{VI} = p_r q_D + p_w \underbrace{[q_f + q_s - q_D]}_{\text{=0 if closed mkt}} + \underbrace{p_c[q_s - \tau q_D]}_{\text{credits sold}} - c_f(q_D - q_s) - c_s(q_s) - C_{VI}(I_{VI})$$

and a different investment costs function $C_{VI}(I_{VI})$.

Note that *full compliance* occurs when $q_s - \tau q_D > 0$ and the policy is just *binding* when $q_s - \tau q_D = 0$.

Taking the first order condition with respect to the investment amount:

$$\begin{aligned} \text{Not binding: } \left(p_c + c_f'(q_D - q_s) - c_s'(q_s)\right)\frac{\partial q_s}{\partial I_{VI}} + (q_s - \tau q_D)\frac{\partial p_c}{\partial q_s}\frac{\partial q_s}{\partial I_{VI}} &= C_{VI}'(I_{VI}) \\ \text{Binding: } \left(c_f'(q_D - q_s) - c_s'(q_s)\right)\frac{\partial q_s}{\partial I_{VI}} &= C_{VI}'(I_{VI}). \end{aligned} \quad (3)$$

Similarly to the VS case, assume that $\frac{\partial p_c}{\partial q_s} < 0$ and $\frac{\partial q_s}{\partial I_{VI}} > 0$.

Comparing optimal investment amounts. Suppose that one extra unit of renewable capacity produces the same additional amount of output regardless of the market structure, in other words assume that

$$\frac{\partial q_s}{\partial I_{VS}} = \frac{\partial q_s}{\partial I_{VI}}.$$

Subtract Equation 3 from Equation 2:

$$\begin{aligned} \text{Not binding: } -p_c\frac{\partial q_s}{\partial I_{VI}} + (2\tau q_D - q_s)\frac{\partial p_c}{\partial q_s}\frac{\partial q_s}{\partial I_{VI}} &= C_{VS}'(I_{VS}) - C_{VI}'(I_{VI}) \\ \text{Binding: } (-p_w + p_c)\frac{\partial q_s}{\partial I_{VI}} + q_s\frac{\partial p_c}{\partial q_s}\frac{\partial q_s}{\partial I_{VI}} &= C_{VS}'(I_{VS}) - C_{VI}'(I_{VI}) \end{aligned} \quad (4)$$

The LHS of the Not binding expression above is guaranteed to be negative since $\frac{\partial p_c}{\partial q_s} < 0$ and if we assume that τ cannot be too small:

$$\tau > \frac{q_s}{2q_D}.$$

The LHS of the Binding expression is negative if the inverse elasticity of REC prices with respect to renewables output is bounded from above by a negative number

$$\frac{q_s}{p_c}\frac{\partial p_c}{\partial q_s} < \frac{p_w - p_c}{p_c},$$

which is achieved if $p_c > p_w$. That is consistent with the observation that if the policy is binding, the value of RECs is most likely higher than that of the non-regulated electricity output. The inequality above can be interpreted as follows. The inverse elasticity cannot be too close to 0 because that would indicate that the REC price does not react too much to changes in renewable output, and if that was the case, then more investment in renewable capacity would have no effect whatsoever on the value of a REC.

Relationship between investment costs. Therefore, for both the Not binding and the Binding case we have

$$C'_{VS}(I_{VS}) < C'_{VI}(I_{VI}). \tag{5}$$

We make the following assumptions regarding the two cost functions. (1) the cost functions are increasing,

$$C'_i(\cdot) > 0$$

for $i \in \{VS, VI\}$, and (2) the investment costs under vertically separated structures C_{VS} increase faster than the investment costs under vertically integrated markets C_{VI}, or equivalently

$$C'_{VS}(x) \geq C'_{VI}(x) \tag{6}$$

for any given level of investment x. Assumption (2) would hold if marginal investment costs in vertically separated markets increase substantially more as the investment size grows than in vertically integrated markets since the latter have a higher monopsony power and ability to bargain.

By combining Equation 5 with Equation 6 we get

$$C'_{VS}(I_{VS}) < C'_{VI}(I_{VI}) \leq C'_{VS}(I_{VI})$$

and therefore, by assumption (1), $I_{VS} < I_{VI}$. In other words, the investment under the VS market structure is lower than in the vertically integrated case.

If the two cost functions are identical, assumption (1) alone and Equation 5 takes us to the exact same conclusion.

The role of the RPS requirement τ. The LHS of Equation 4 in the Not binding case can be rewritten as follows

$$2q_D\frac{\partial p_c}{\partial q_s}\frac{\partial q_s}{\partial I_{VI}}\tau + (\text{terms that do not depend on } \tau)$$

and we know that the whole expression is negative. In addition, the slope $2q_D\frac{\partial p_c}{\partial q_s}\frac{\partial q_s}{\partial I_{VI}}$ is negative itself.

Since the slope is negative, an increase in τ makes the whole expression more negative while approaching the Binding case. This has for consequence that as τ increases, there is a larger difference between the two types of investment: $I_{VS} \ll I_{VI}$.

E.2 Identifying Contracting Channel Investment

EIA Form 860 contains the list of power plants along with the name of the plant's owner. There are two types of owners appearing in the data: Independent Power Producers (IPPs) and Electric Utilities. Since the electric utilities are the companies operating in the retail sector, we can sort out the generators that are owned by electric utilities, namely the generators directly invested and operated by the downstream retailer, from this EIA dataset. The generation capacities sorted out in this way are referred to as vertically integrated investments.

However, electric utilities also actively contract with the IPPs to invest in renewable capacity. These contracted generation assets are not directly invested by the utilities, and for that reason, IPPs are listed as their owners in the EIA Form 860. Therefore, we cannot sort out such contracted assets solely from the EIA data.

To complement the EIA and to find the contracting relationships, we use the FERC Form 1 data. The FERC Form 1 data, *yearly purchased power and exchanges* section, lists the companies from which electric utilities purchase electricity. The form includes information such as the name of the power plant owner, the type of contract (e.g., LU indicates a long-term agreement), and the name of the retail company that set up the contract. We can verify from this form that retail companies do contract with and purchase a substantial amount of electricity from IPP invested renewable assets, through long-term purchasing agreements.

For example, PG&E (Pacific Gas Electric Co.), one of the electric utilities in California, owns many power plants that appear in the EIA Form. However, FERC Form 1 data show that the company has purchasing contracts with renewable generators not listed as owned by PG&E in the EIA Form. Examples include *Mega Renewables*, *EDF Renewables*, *Pristine Sun*, *Alamo Solar*,*Agua Caliente Solar*, *AV solar ranch*, and *Bear Creek Solar*. These facilities do appear in the EIA Form 860, but PG&E is not listed as their owner, and they are part of IPP investments. This suggests that the directly invested capacity (vertical integration case, with owner listed as the retail company) is the lower bound of retail company's total contracting channel investment.

We cross-checked using the retail company's compliance reports to make sure that the FERC Form 1 information accurately captures the contracting relationship between the retail company (electric utility) and the IPP invested renewables. Figure E.1 is an excerpt from the RPS compliance report filed by one of the electric utilities in Arizona, APS (Arizona Public Service), in 2016. The table shows a list of renewable resources acquired by APS either through direct investment (ownership = 'APS') or by contracting (ownership = '3rd party PPA'). A substantial amount of generation used for compliance comes from third-party PPA, which are capacities invested by IPPs.

Steps We identified renewable generation assets contracted with each major electric utilities from the FERC Form 1 data. Since the FERC data itself does not contain basic information about the generation assets, such as the nameplate capacity, we matched each assets in the FERC Form to the EIA dataset. Since there is no common identifier that links the FERC data and the EIA data, we manually matched the names of generation assets in both datasets. For example, *Alamo Solar* is listed as contracted assets of PG&E in the FERC data, and we found Alamo Solar from the EIA dataset and encoded the basic information.

While the FERC dataset enables us to identify the contractual relationship as well as the exact identities of the firms and generators involved, there are limitations to this data. First, not all retail companies appear in the dataset. In our analysis, we restrict the sample to retailers with at least 5% of the retail market share (based on residential customers). Even so, not all retailers file the FERC Form, leaving some out. Another issue is that some electric utilities appear to contract with major IPPs rather than with individual renewable assets. For example, an electric utility might have contracts only with large IPPs that supply a diverse set of generation sources (e.g., Exelon, Calpine, NextEra), including renewables, or with large IPPs that specialize in renewable asset investments (e.g., Avangrid, Brookfield Renewables, Iberdrola Renewables). In these cases, we assume that the large IPPs contract with or invest in renewables on behalf of the electric utilities. For these utilities, we cannot separate out contracting channel investments and instead use statewide renewable additions as the main variable.

E.3 Additional Factors Affecting RPS Compliance

E.3.1 Spillover Effect: Out-of-state Investment

The RPS policy in one state can influence renewable investment in neighboring states if compliance is possible using out-of-state renewable generation (Hollingsworth and Rudik (2019)). A retail company (electric utility) in one state can contract with out-of-state renewable generation assets that are planned for construction to source electricity from those plants once they are operational. While Hollingsworth and Rudik (2019) examined the cross-state spillover of electricity generated from renewable assets, FERC data allow us to analyze spillovers in invested capacities across states. From the contract data, we can identify which out-of-state power plants are tied to a state's electric utilities through purchasing power agreements, thereby establishing a link between power plants

Figure E.1: Renewable Investment: IOU vs. IPP

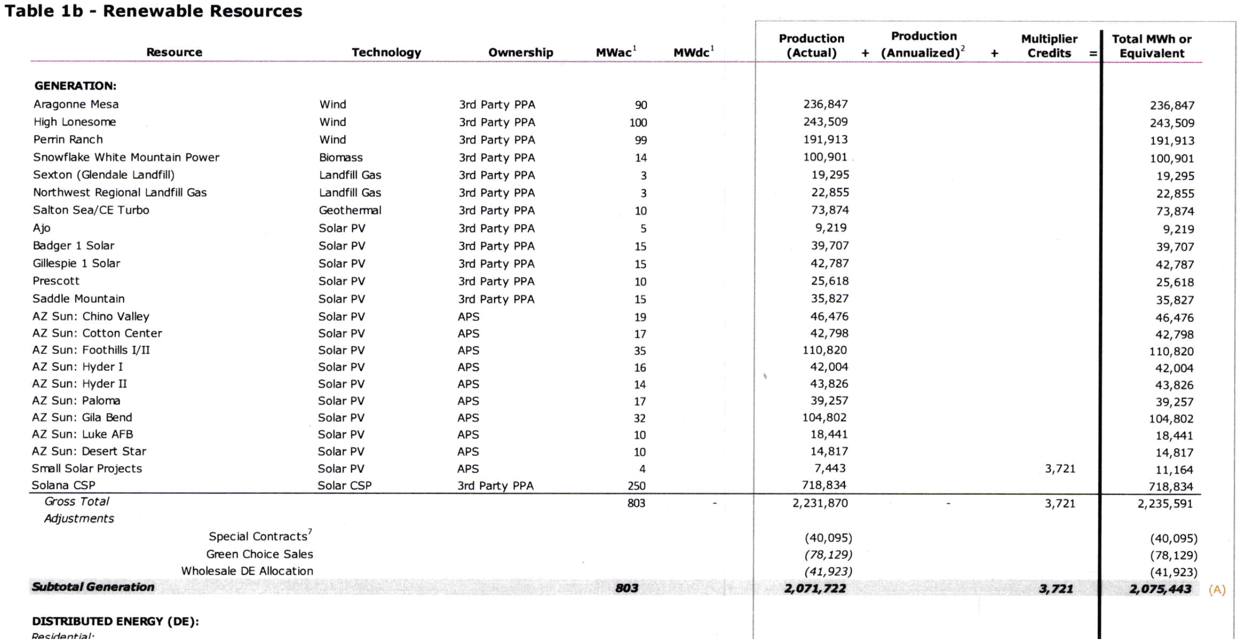


Table 1b - Renewable Resources

Resource	Technology	Ownership	MWac[1]	MWdc[1]	Production (Actual) +	Production (Annualized)[2] +	Multiplier Credits =	Total MWh or Equivalent
GENERATION:								
Aragonne Mesa	Wind	3rd Party PPA	90		236,847			236,847
High Lonesome	Wind	3rd Party PPA	100		243,509			243,509
Perrin Ranch	Wind	3rd Party PPA	99		191,913			191,913
Snowflake White Mountain Power	Biomass	3rd Party PPA	14		100,901			100,901
Sexton (Glendale Landfill)	Landfill Gas	3rd Party PPA	3		19,295			19,295
Northwest Regional Landfill Gas	Landfill Gas	3rd Party PPA	3		22,855			22,855
Salton Sea/CE Turbo	Geothermal	3rd Party PPA	10		73,874			73,874
Ajo	Solar PV	3rd Party PPA	5		9,219			9,219
Badger 1 Solar	Solar PV	3rd Party PPA	15		39,707			39,707
Gillespie 1 Solar	Solar PV	3rd Party PPA	15		42,787			42,787
Prescott	Solar PV	3rd Party PPA	10		25,618			25,618
Saddle Mountain	Solar PV	3rd Party PPA	15		35,827			35,827
AZ Sun: Chino Valley	Solar PV	APS	19		46,476			46,476
AZ Sun: Cotton Center	Solar PV	APS	17		42,798			42,798
AZ Sun: Foothills I/II	Solar PV	APS	35		110,820			110,820
AZ Sun: Hyder I	Solar PV	APS	16		42,004			42,004
AZ Sun: Hyder II	Solar PV	APS	14		43,826			43,826
AZ Sun: Paloma	Solar PV	APS	17		39,257			39,257
AZ Sun: Gila Bend	Solar PV	APS	32		104,802			104,802
AZ Sun: Luke AFB	Solar PV	APS	10		18,441			18,441
AZ Sun: Desert Star	Solar PV	APS	10		14,817			14,817
Small Solar Projects	Solar PV	APS	4		7,443		3,721	11,164
Solana CSP	Solar CSP	3rd Party PPA	250		718,834			718,834
Gross Total			803	-	2,231,870	-	3,721	2,235,591
Adjustments								
Special Contracts[7]					(40,095)			(40,095)
Green Choice Sales					*(78,129)*			(78,129)
Wholesale DE Allocation					*(41,923)*			(41,923)
Subtotal Generation			***803***		***2,071,722***		***3,721***	***2,075,443*** (A)
DISTRIBUTED ENERGY (DE):								
Residential:								

Notes: This is taken from APS (Arizona Public Service)'s RPS compliance report filed for 2016. Table shows a list of renewable resources acquired either through direct investment (ownership = 'APS') or by contracting (ownership = '3rd party PPA').

and electric utilities (retailers).

Summary of Capacities by Retailer State We established a link between a specific renewable generator and electric utility (retail company), along with the capacity size, and the year in which the generators became operational. We then summarized the average size of renewable capacities contracted by electric utilities in each state where these utilities are located.

Table E.1 summarizes the in-state and out-of-state capacities. From the RPS Years columns (using sample years after RPS enactment), about 80% of the capacity amounts contracted by retail companies in California (with an average size of 825.7 MW) are constructed within the same state, while 20% (with an average size of 266 MW) are located out-of-state, sourced from five nearby states. In contrast, retail companies in Oregon primarily contract with out-of-state generators, with about 90% of the contracted capacity amounts (average size of 238.8 MW) located outside Oregon.

Summary of Capacity Amounts by the Renewable Plant's State We also summarize the capacities by the states where the renewable power plants that contracted with retailers are located,

Table E.1: Average In-state, Out-of-state Contracted Capacities: By Retailer's State

	Full Sample				RPS Years			
State (retail)	In-state (MW)	Out-state (MW)	% out	# states	In-state (MW)	Out-state (MW)	%out	# states
AZ	117.02	58.12	0.3	2	117.02	58.12	0.3	2
CA	775.73	243.99	0.2	7	825.69	266.08	0.2	5
CO	218.55	49.17	0.2	3	230.32	94.00	0.3	2
DE	11.30	89.25	0.9	2	11.30	89.25	0.9	2
IA	112.93	21.50	0.2	1	112.93	21.50	0.2	1
IL	.	199.70	.	1	.	199.70	.	1
MA	15.00	52.28	0.8	4	15.00	52.28	0.8	4
MI	68.39	4.00	0.1	1	113.72	.	.	0
MN	82.97	90.90	0.5	3	78.75	90.90	0.5	3
MO	.	300.00	.	1	.	.	.	0
NC	212.99	29.19	0.1	3	285.54	32.40	0.1	2
NH	27.73	.	.	0	33.53	.	.	0
NM	88.21	160.49	0.6	2	72.72	186.73	0.7	2
NV	97.73	108.00	0.5	1	96.54	108.00	0.5	1
NY	10.75	.	.	0	.	.	.	0
OH	81.00	600.30	0.9	1	81.00	600.30	0.9	1
OR	59.82	314.55	0.8	6	37.63	238.80	0.9	3
RI	5.03	.	.	0	3.50	.	.	0
VT	5.00	52.67	0.9	2	5.00	77.00	0.9	1
WA	504.49	132.53	0.2	4	68.58	18.50	0.2	1
WI	11.10	175.00	0.9	1	11.10	175.00	0.9	1
N	21							

Notes: This table presents in-state and out-of-state contracted capacities by state, summarized from our FERC identified contracted capacity data. *State* (retail) denotes the state in which a retail company with data entries in the FERC dataset is located. Capacities of power plants (solar and wind only) contracted with a retailer in the state are summed over the years at the state level. The *Full sample* summary includes all years in the sample, while *RPS years* covers the years after the state has enacted the RPS policy. *In-state capacity* refers to the total capacity of contracted generators located within the retailer's state, and *Out-state capacity* refers to the total capacity of contracted generators located outside the retailer's state. *# states* indicates the number of these outside states, and *% out* shows the percentage of out-of-state capacities relative to the total contracted capacities.

as shown in Table E.2. The table displays the average size of renewable generation capacities in each state contracted with in-state retailers (in-state MW) and out-of-state retailers (out-of-state MW). Based on the RPS Years columns, generators in states like California, Colorado, North Carolina, and Ohio are mostly contracted to in-state retailers, whereas those in other states have roughly half or more of their capacities contracted with out-of-state retailers.

Summary and Discussion This basic summary of contract data shows that sourcing renewables is not restricted to the state level but can be expanded to cover neighboring states, indicating a possible spillover of state-level policy. There is substantial heterogeneity in cross-state contracting patterns: some states source only within their own state, some rely exclusively on other states, and many have varying proportions of both.

The determination of a state's compliance hinges on the inclusion of renewable generation from out-of-state sources. Consequently, a state is deemed non-compliant if, even after accounting for renewable electricity generated outside its borders, it fails to meet the RPS requirement. Hence, our assumption that all in-state capacities brought online during a non-compliant year contribute to RPS compliance, heavily influenced by RPS policies, remains valid despite the presence of the spillover effect.

Nevertheless, the actual size of new investments induced by the state's RPS policy will be under/over-measured if the spillover effect is not accounted for. For example, if a retailer in California contracts with a solar plant in Arizona to comply with the RPS policy, the solar capacity in Arizona is driven by the RPS policy in California, not by the policy in Arizona. Thus, the actual capacity induced by California's RPS policy is under-measured, while that of Arizona is over-measured.

Using contract-level data addresses the spillover issue by including capacities contracted by retailers in the state, regardless of their sourcing locations. In other words, we account for all capacities contracted with retail companies in California, irrespective of where these assets are located. For instance, solar capacity in Arizona contracted by a California retailer will be included in California's RPS-induced capacity. This approach helps mitigate potential under- or over-measurement of capacities associated with the state's RPS policy.

However, it is important to note that these data do not capture spillovers related to unbundled RECs. Retailers can also meet compliance by purchasing unbundled RECs from other states. If new capacity is built outside the state to supply credits to buyers within the state, this investment occurs through the REC market channel. While we have included net interchange data – reflecting the net flow of imports between states – to account for some spillover related to physical electricity generation, this does not fully address the limitation because the unbundled REC trading does not

Table E.2: Average In-state, Out-of-state Contracted Capacities: By Plant's State

	Full Sample				RPS Years			
State(plant)	In-state(MW)	Out-state(MW)	%out	#states	In-state(MW)	Out-state(MW)	%out	# states
AZ	117.02	151.12	0.6	1	117.02	149.34	0.6	1
CA	775.73	75.60	0.1	5	825.69	75.60	0.1	5
CO	218.55	.	.	0	230.32	.	.	0
CT	.	28.45	.	1	.	28.45	.	1
DE	11.30	11.80	0.5	1	11.30	11.80	0.5	1
GA	.	1.00	.	1	.	.	.	0
IA	112.93	243.33	0.7	3	112.93	143.33	0.6	2
ID	.	83.07	.	3	.	96.40	.	2
IN	.	800.00	.	2	.	800.00	.	2
MA	15.00	4.50	0.2	1	15.00	5.00	0.2	0
MD	.	40.00	.	1	.	40.00	.	1
ME	.	52.66	.	1	.	52.66	.	1
MI	68.39	149.00	0.7	1	113.72	149.00	0.6	1
MN	82.97	21.50	0.2	1	78.75	21.50	0.2	1
MT	.	124.10	.	2	.	102.25	.	1
NC	212.99	.	.	0	285.54	.	.	0
ND	.	11.90	.	1	.	11.90	.	1
NH	27.73	48.00	0.6	1	33.53	48.00	0.6	1
NJ	.	4.00	.	1	.	.	.	0
NM	88.21	270.77	0.8	2	72.72	95.00	0.6	1
NV	97.73	113.91	0.5	2	96.54	125.44	0.6	2
NY	10.75	.	.	0	.	.	.	0
OH	81.00	.	.	0	81.00	.	.	0
OK	.	199.00	.	1	.	199.00	.	1
OR	59.82	251.12	0.8	2	37.63	318.50	0.9	1
PA	.	46.70	.	2	.	46.70	.	2
RI	5.03	25.00	0.8	1	3.50	25.00	0.9	1
SC	.	14.61	.	1	.	12.20	.	1
SD	.	175.05	.	1	.	175.05	.	1
UT	.	208.67	.	1	.	264.58	.	1
VT	5.00	.	.	0	5.00	.	.	0
WA	504.49	684.65	0.6	2	68.58	90.00	0.6	1
WI	11.10	.	.	0	11.10	.	.	0
WY	.	110.67	.	2	.	86.00	.	1
N	35							

Notes: This table presents in-state and out-of-state contracted capacities by state, summarized from our FERC identified contracted capacity data. State (plant) denotes the state in which a contracted renewable power plant is located. Capacities of power plants (solar and wind only) that are contracted are summed over the years at the state level. The *Full sample* summary includes all years in the sample, while *RPS years* covers the years after the state has enacted the RPS policy. *In-state* capacity refers to the total capacity of power plants contracted with retailers located in the same state as the generators, while *Out-state* capacity refers to the total capacity of power plants contracted with retailers located outside the plant's state. *# states* indicates the number of these outside states where contracted retailers are located, and *% out* shows the percentage of out-of-state capacities relative to the total contracted capacities.

involve physical electricity flow into the grid and is thus not captured by net interchange variations. Nevertheless, since our analysis assumes the REC market channel investments are unaffected by vertical structure, the inability to separately account for this channel's investments will not critically impact our main empirical results.

E.3.2 Other Policies Affecting Renewable Investment

It is important to recognize that while the RPS policy is the oldest at the federal level in the US, other incentives for renewable generation have been put in place in some states and at the federal level in recent years. Two such policies are the feed-in-tariffs and the Federal Tax Investment Credit, respectively. However, the main difference between those policies and the RPS is that the former do not represent a mandate and impose no obligations on stakeholders, whereas the RPS policy stipulates an obligation. Abroad, other countries have adopted policies to incentivize the investment on renewables assets as well. A similar policy to the RPS exists in Sweden and Norway, the Electricity Certificate System (`https://t.ly/FkoCq`, see Coria and Jaraite (2024) for a study on this policy) as well as in China (Wang et al. (2021)). The feed-in-tariffs is a particularly prominent policy in Europe and Canada but it is not market-based. These tariffs offer a fixed production subsidy ensured over extended periods, providing stability and certainty for investors (Lamp and Samano (2023)). In Germany, feed-in-tariffs are the main incentive for small installations but for utility-scale assets, firms must bid in federal-level renewable energy auctions to get the right to realize the investment and to determine the level of support they will receive (Lamp et al. (2024)).

E.3.3 Interconnection costs

Interconnection cost can be a determinant of the renewable investment decision. However, our analysis does not specifically consider the interconnection issues or bottlenecks for the following reasons. First, the interconnection cost is a small part of the total investment cost. Using Laurence Berkeley Lab's estimate of median interconnection cost of $50,000/MW, we can calculate that for a wind power plant of 70MW (Laurel Hill Wind Farm, in PA), the interconnection cost takes up roughly 1/50 of the total construction cost. And for a solar project of 20MW (Tinton Hills Solar, PA), the interconnection cost takes up 1/80 of the construction cost. Given the small size, this cost is not a critical barrier for renewable projects to enter.

Recent studies by the Berkeley lab report that interconnection requests have increased recently, and currently, there is a long queue of interconnection requests which could slow down the investment process (Joachim et al. (2023)). Typically, a renewable project developer requests an interconnection study even before it secures finance for the project. Securing the finance and developing a viable plan for construction is more challenging than completing the interconnection studies. Indeed, once the developers secure finance through a long-term contract with the demand side (electric utilities or others), they receive priority over other smaller, uncertain projects in the queue.

Historically, the percentage of projects that requested interconnection studies and eventually completed construction has been low (around 30 percent), so having a long queue or higher average interconnection cost does not necessarily mean that developers face a significant hurdle in their process. Studies show this completion rate was consistently low over time, even when the number of renewable investments was very small (when the renewable boom was yet there). Suppose the elongated interconnection process is a critical barrier and matters to investment. In that case, we should have seen a higher completion rate for years with less renewable entry competition, but we don't. Many of those projects in the queue would never have been completed anyway. The average increase in the interconnection cost also masks the fact that many unattractive projects have requested interconnection, most of which would not be completed. The less attractive project (located too far away from the transmission lines) receives a high estimate of interconnection cost, forcing them to opt out of the investment process. This is not necessarily a bad outcome from an economic perspective, as we can sort out the inefficient projects. For these reasons, our analysis does not specifically consider or worry about the interconnection queue or cost.

E.3.4 REC market data

Unfortunately, we do not have good data on REC prices in every market. We do have data for the PJM market. In Section 4.5, we show the potential direction of bias that arises from omitting the REC market data.

E.4 Additional Tables and Figures

Table E.3: Renewable investment, RPS enactment, and market structure

	(1)	(2)
VS	28.15	82.06
	(47.87)	(53.50)
After RPS	52.45	31.12
	(38.96)	(37.00)
After RPS × VS	-89.05	-93.59*
	(70.52)	(54.92)
Net summer capacity (MW)		0.0185*
		(0.0106)
Net generation (GWh)		-0.00324
		(0.00259)
Renewable per cap. lag (GWh per MW)		0.0287***
		(0.0107)
Net flow lag (GWh)		-0.270
		(1.606)
Constant	788.0***	200.4
	(33.12)	(233.0)
N	1000	1000
Adj. R^2	0.41	0.44
Dep. var. mean	129.80	129.80
Market FE	✓	✓
Year FE	✓	✓

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: Dependent variable: New renewable capacity (MW). Years before and after RPS enactment in each state. Only states that enacted an RPS policy at some point. Using a continuous measure of vertical separation (retail sales). The data combine EIA and FERC information, see main text for further details. Standard errors clustered at the state level.

Table E.4: [EIA data] Fossil-fueled powered plants investment, RPS enactment, and market structure

	(1)	(2)
VS	-276.4*	-107.9
	(162.9)	(113.9)
After RPS	31.21	58.89
	(55.06)	(48.24)
After RPS × VS	301.2**	145.4
	(132.2)	(139.5)
Net summer capacity (MW)		0.0280*
		(0.0167)
Net generation (GWh)		-0.00340
		(0.00419)
Renewable per cap. lag (GWh per MW)		-0.0313
		(0.0240)
Net flow lag (GWh)		-1.326
		(2.444)
Constant	1156.7***	74.68
	(46.80)	(296.3)
N	1000	1000
Adj. R^2	0.27	0.31
Dep. var. mean	292.00	292.00
Market FE	✓	✓
Year FE	✓	✓

Standard errors in parentheses

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

Notes: Dependent variable: New fossil capacity (MW). Years before and after RPS enactment in each state. Only states that enacted an RPS policy at some point. Using a continuous measure of vertical separation (retail sales). EIA data only. Standard errors clustered at the state level.

Table E.5: [EIA data] Renewable investment and compliance using binary measure of vertical separation

	(1)	(2)	(3)	(4)
VS x Binding	-336.4*	-337.3*	-207.2**	-196.6**
	(179.8)	(183.1)	(87.29)	(75.59)
Binding	148.3	151.5	118.8*	118.5**
	(116.7)	(130.6)	(59.54)	(56.51)
RPS goal (GWh)		-0.00591	-0.00646	-0.0119
		(0.0314)	(0.0283)	(0.0293)
Net summer capacity (MW)			0.0793**	0.0797**
			(0.0349)	(0.0326)
Net generation (GWh)			-0.00450	-0.00497
			(0.00852)	(0.00844)
Renewable per cap. lag (GWh per MW)			-0.00487	-0.000747
			(0.0150)	(0.0169)
Net flow lag (GWh)			2.028	1.608
			(4.893)	(4.860)
Constant	802.6***	808.3***	-3765.8***	-3672.1***
	(69.85)	(54.33)	(444.4)	(579.6)
N	388	388	388	388
Adj. R^2	0.48	0.48	0.60	0.59
Dep. var. mean	176.02	176.02	176.02	176.02
Market FE	✓	✓	✓	✓
State FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Dyn. Effects				✓

Standard errors in parentheses

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

Notes: Dependent variable: New renewable capacity (MW). EIA data only. For each state, only years when RPS policy had been put in place. Dynamic effects with a window +/-2 years. Standard errors clustered at the state level.

Table E.6: [EIA data] Renewable investment and compliance using a continuous measure of vertical separation (generation capacity)

	(1)	(2)	(3)	(4)
VS x Binding	-209.3	-210.9	-172.8	-212.5**
	(158.7)	(162.7)	(109.1)	(88.00)
Binding	131.0	134.4	139.3	173.1**
	(138.8)	(152.8)	(92.83)	(76.07)
RPS goal (GWh)		-0.00499	-0.00682	-0.0122
		(0.0267)	(0.0264)	(0.0273)
Net summer capacity (MW)			0.0799**	0.0795**
			(0.0373)	(0.0364)
Net generation (GWh)			-0.00394	-0.00364
			(0.00882)	(0.00861)
Renewable per cap. lag (GWh per MW)			-0.0103	-0.00883
			(0.0152)	(0.0150)
Net flow lag (GWh)			3.045	3.385
			(4.903)	(4.794)
Constant	895.1***	900.0***	-3944.5***	-3992.8***
	(59.42)	(48.04)	(515.3)	(608.1)
N	388	388	388	388
Adj. R^2	0.47	0.46	0.59	0.59
Dep. var. mean	176.02	176.02	176.02	176.02
Market FE	✓	✓	✓	✓
State FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Dyn. Effects				✓

Standard errors in parentheses

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

Notes: Dependent variable: New renewable capacity (MW). EIA data only. For each state, only years when RPS policy had been put in place. Dynamic effects with a window +/-2 years. Standard errors clustered at the state level.

Table E.7: [EIA data] Renewable investment and compliance using a continuous measure of vertical separation (retail sales)

	(1)	(2)	(3)	(4)
VS x Binding	-400.8*	-404.3*	-237.3**	-237.5**
	(222.0)	(228.7)	(106.4)	(95.63)
Binding	159.3	165.2	122.6*	132.6**
	(121.6)	(137.8)	(61.37)	(55.72)
RPS goal (GWh)		-0.00947	-0.00791	-0.0130
		(0.0318)	(0.0283)	(0.0296)
Net summer capacity (MW)			0.0780**	0.0774**
			(0.0347)	(0.0334)
Net generation (GWh)			-0.00421	-0.00400
			(0.00844)	(0.00835)
Renewable per cap. lag (GWh per MW)			-0.0130	-0.0129
			(0.0164)	(0.0161)
Net flow lag (GWh)			1.885	2.149
			(4.954)	(5.013)
Constant	797.8***	806.3***	-3715.8***	-3727.5***
	(71.76)	(57.13)	(441.6)	(580.6)
N	388	388	388	388
Adj. R^2	0.49	0.48	0.60	0.59
Dep. var. mean	176.02	176.02	176.02	176.02
Market FE	✓	✓	✓	✓
State FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Dyn. Effects				✓

Standard errors in parentheses

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

Notes: Dependent variable: New renewable capacity (MW). EIA data only. For each state, only years when RPS policy had been put in place. Dynamic effects with a window +/-2 years. Standard errors clustered at the state level.

Table E.8: [EIA data] Fossil-fueled plants investment and compliance using binary measure of vertical separation

	(1)	(2)	(3)	(4)
VS x Binding	404.9	402.1	231.6	313.1
	(313.1)	(311.1)	(273.1)	(248.5)
Binding	-114.9	-104.9	-135.2	-260.5**
	(81.47)	(82.07)	(126.0)	(101.5)
RPS goal (GWh)		-0.0184	-0.0442	-0.00752
		(0.0386)	(0.0599)	(0.0600)
Net summer capacity (MW)			0.0699	0.0576
			(0.0578)	(0.0531)
Net generation (GWh)			-0.0357**	-0.0356**
			(0.0140)	(0.0133)
Renewable per cap. lag (GWh per MW)			-0.0220	-0.0275
			(0.0833)	(0.0906)
Net flow lag (GWh)			-9.692	-8.370
			(12.86)	(12.71)
Constant	1318.0***	1335.5***	4726.4***	5317.5***
	(91.46)	(105.2)	(1716.7)	(1625.7)
N	388	388	388	388
Adj. R^2	0.34	0.34	0.38	0.40
Dep. var. mean	324.25	324.25	324.25	324.25
Market FE	✓	✓	✓	✓
State FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Dyn. Effects				✓

Standard errors in parentheses

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

Notes: Dependent variable: New fossil capacity (MW). EIA data only. For each state, only years when RPS policy had been put in place. Dynamic effects with window +/-2 years. Using a discrete measure of vertical separation (binary). Standard errors clustered at the state level.

Table E.9: [EIA data] Fossil-fueled plants investment and compliance using a continuous measure of vertical separation (generation capacity)

	(1)	(2)	(3)	(4)
VS x Binding	342.0	335.9	195.5	316.5
	(292.9)	(291.4)	(255.5)	(213.5)
Binding	-149.9	-137.2	-159.6	-307.4*
	(141.5)	(144.5)	(175.6)	(159.2)
RPS goal (GWh)		-0.0187	-0.0438	-0.0209
		(0.0344)	(0.0580)	(0.0553)
Net summer capacity (MW)			0.0692	0.0677
			(0.0598)	(0.0556)
Net generation (GWh)			-0.0364**	-0.0379**
			(0.0145)	(0.0138)
Renewable per cap. lag (GWh per MW)			-0.0159	-0.0238
			(0.0799)	(0.0890)
Net flow lag (GWh)			-10.82	-10.94
			(11.55)	(10.90)
Constant	1211.0***	1229.4***	4925.5***	5308.3***
	(63.93)	(69.49)	(1599.8)	(1553.0)
N	388	388	388	388
Adj. R^2	0.34	0.34	0.38	0.39
Dep. var. mean	324.25	324.25	324.25	324.25
Market FE	✓	✓	✓	✓
State FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Dyn. Effects				✓

Standard errors in parentheses

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

Notes: Dependent variable: New fossil capacity (MW). EIA data only. For each state, only years when RPS policy had been put in place. Dynamic effects with window +/-2 years. Using a continuous measure of vertical separation (generation capacity). Standard errors clustered at the state level.

Table E.10: [EIA data] Fossil-fueled plants investment and compliance using a continuous measure of vertical separation (retail sales)

	(1)	(2)	(3)	(4)
VS x Binding	559.1*	554.3*	411.8	468.5
	(322.0)	(321.4)	(271.3)	(296.4)
Binding	-158.3*	-150.2	-194.8	-291.2**
	(86.96)	(91.04)	(135.1)	(115.2)
RPS goal (GWh)		-0.0130	-0.0411	0.00179
		(0.0396)	(0.0613)	(0.0636)
Net summer capacity (MW)			0.0720	0.0614
			(0.0565)	(0.0512)
Net generation (GWh)			-0.0357**	-0.0349**
			(0.0139)	(0.0129)
Renewable per cap. lag (GWh per MW)			-0.0128	-0.00493
			(0.0780)	(0.0777)
Net flow lag (GWh)			-8.555	-7.612
			(12.65)	(11.74)
Constant	1344.4***	1356.1***	4503.2**	4872.0***
	(89.04)	(99.33)	(1692.3)	(1450.4)
N	388	388	388	388
Adj. R^2	0.35	0.34	0.39	0.41
Dep. var. mean	324.25	324.25	324.25	324.25
Market FE	✓	✓	✓	✓
State FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Dyn. Effects				✓

Standard errors in parentheses

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

Notes: Dependent variable: New fossil capacity (MW). EIA data only. For each state, only years when RPS policy had been put in place. Dynamic effects with window +/-2 years. Using a continuous measure of vertical separation (retail sales). Standard errors clustered at the state level.

Table E.11: Wind plants investment and compliance using a continuous measure of vertical separation (retail sales)

	(1)	(2)	(3)	(4)
VS x Binding	-290.1	-281.3	-128.1**	-96.46
	(172.9)	(171.4)	(57.86)	(68.24)
Binding	81.23*	66.13	52.53*	19.83
	(44.49)	(41.50)	(27.21)	(38.41)
RPS goal (GWh)		0.0243**	0.0248***	0.0159
		(0.0108)	(0.00784)	(0.00969)
Net summer capacity (MW)			0.0176**	0.0191**
			(0.00780)	(0.00893)
Net generation (GWh)			0.00678***	0.00643***
			(0.00114)	(0.00108)
Renewable per cap. lag (GWh per MW)			-0.0146	-0.0166
			(0.0165)	(0.0170)
Net flow lag (GWh)			8.870***	8.845***
			(2.080)	(2.194)
Constant	394.6***	372.7***	-2875.9***	-2919.6***
	(26.00)	(27.70)	(301.9)	(384.5)
N	388	388	388	388
Adj. R^2	0.48	0.48	0.55	0.54
Dep. var. mean	135.84	135.84	135.84	135.84
Market FE	✓	✓	✓	✓
State FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Dyn. Effects				✓

Standard errors in parentheses

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

Notes: Dependent variable: New wind-powered capacity (MW). The data combine EIA and FERC information, see main text for further details. For each state, only years when RPS policy had been put in place. Dynamic effects with window +/-2 years. Using a continuous measure of vertical separation (retail sales). Standard errors clustered at the state level.

Table E.12: Solar plants investment and compliance using a continuous measure of vertical separation (retail sales)

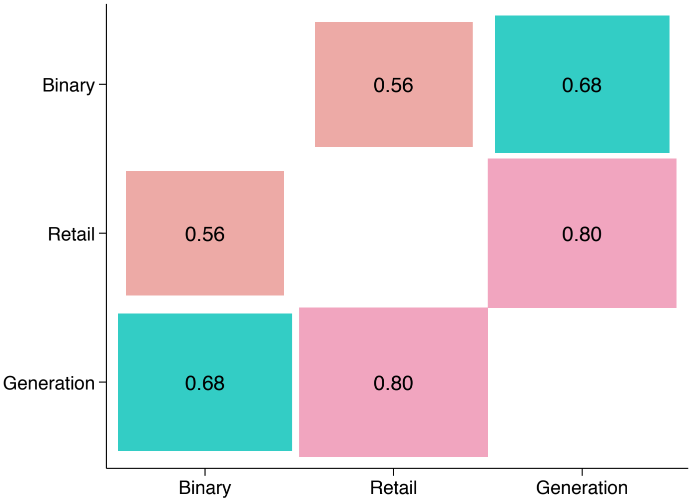
	(1)	(2)	(3)	(4)
VS x Binding	-161.5	-171.0	-148.8**	-117.0**
	(128.6)	(141.7)	(69.04)	(48.09)
Binding	120.0	136.3	100.4**	87.10**
	(108.1)	(127.8)	(46.41)	(35.58)
RPS goal (GWh)		-0.0261	-0.0259	-0.0259
		(0.0292)	(0.0239)	(0.0253)
Net summer capacity (MW)			0.0735**	0.0722**
			(0.0316)	(0.0310)
Net generation (GWh)			-0.0134*	-0.0133*
			(0.00744)	(0.00750)
Renewable per cap. lag (GWh per MW)			0.00444	0.00511
			(0.0107)	(0.0101)
Net flow lag (GWh)			-7.690*	-7.895*
			(3.897)	(3.926)
Constant	573.3***	596.8***	-1007.5**	-934.9**
	(63.87)	(48.97)	(467.4)	(451.5)
N	388	388	388	388
Adj. R^2	0.33	0.33	0.56	0.56
Dep. var. mean	47.24	47.24	47.24	47.24
Market FE	✓	✓	✓	✓
State FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Dyn. Effects				✓

Standard errors in parentheses

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

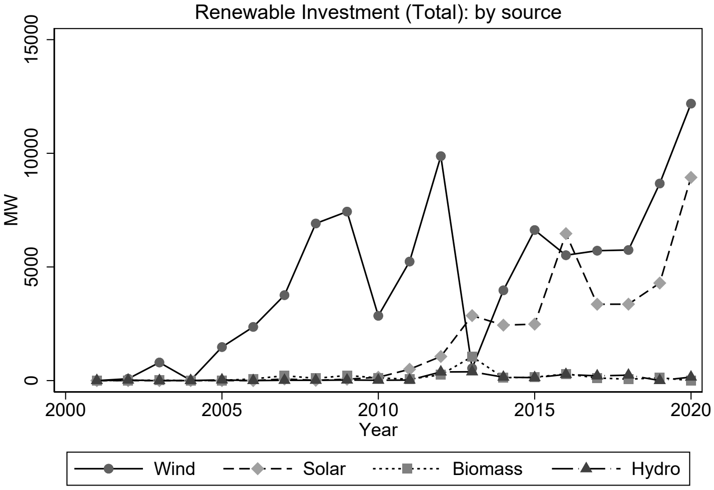
Notes: Dependent variable: New solar-powered capacity (MW). The data combine EIA and FERC information, see main text for further details. For each state, only years when RPS policy had been put in place. Dynamic effects with window +/-2 years. Using a continuous measure of vertical separation (retail sales). Standard errors clustered at the state level.

Figure E.2: Correlation matrix of different Vertical Separation measures



Notes: Pairwise correlations between our three measures of vertical separation: a binary classification (as it has been commonly assumed in the literature), a measure using generation capacity, and a measure using retail sales volume.

Figure E.3: Renewable Investment: by Energy Source



Notes: The capacity sum shows a national summary of new renewable capacity additions by year and by energy source.