Corporate Power Purchase Agreements and Renewable Energy Growth

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September 26, 2023

Abstract

Power purchase agreements (PPAs) are contracts that have become popular among private firms attempting to meet voluntarily adopted climate goals. Using data from the U.S. EIA and Energy Acuity, we construct a dataset on the electricity generation portfolios for U.S. counties over 1990-2021 and estimate two-way fixed effects regressions to explore the effects of spatially and temporally varying PPAs on the deployment of renewables. We find that, in contrast to the voluntary renewable energy certificate market, PPAs have influenced aggregate renewable generation capacity, although the effects are heterogeneous. PPAs signed by non-utility entities (e.g., corporations) generally have a smaller effect than those signed by utilities, but the effects vary by the type of renewable energy project (solar or wind) and spatially based on renewable resource potential, with non-utility PPAs appearing more flexibly used. For GHG accounting purposes, non-utility PPAs are therefore better treated as interventions outside of emissions inventories.

Key Words: Economics; Renewable Energy; Power Purchase Agreement; Public Goods; Public and Private Investment; Energy Transition

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This research was funded through an unrestricted grant from Salesforce to the Greenhouse Gas Management Institute. We thank Enverus, NREL, and Barry Solomon and Shan Zhou for access to data, and Karli Popko, Reid Melillo, Marie Amice, and Anthony Lopez for extensive help with data acquisition and additional information on using the renewable energy data. We would also like to thank Killian Daly, Mark Trexler, Malte Schäfer, Anders Bjørn, and participants at the U.S. Association for Energy Economics conference and GHG Scope 2 Workshop at Danish Technical University for constructive comments. All errors are our own.

1. Introduction

Some of the world's largest corporations are attempting to influence the future of the electricity grid. These attempts have partly been motivated by a desire to claim to be both buying and using "green power" and, by doing so, claim to have reduced both their disclosed corporate greenhouse gas (GHG) emissions and those of the overall electric power sector (Brander et al., 2018; Miller, 2020). Historically, these claims have been based on a variety of contractual arrangements with electricity generators utilizing renewable energy (RE) technologies. Such arrangements may involve wholesale electric power transactions, financial hedges on electricity prices, the claiming of RE "attributes," or a combination of these (Fedson et al., 2021).

Survey data show that the purchasing of unbundled renewable energy certificates (RECs), referred to as Guarantees of Origin in Europe, (RECs, hereafter) by corporations has been the dominant form of contractual arrangement in the voluntary green power market (IRENA, 2018; NREL, 2021; S&P Global, 2021). In the United States, this follows instructions from federal organizations that RE consumption claims by grid-connected retail electricity consumers should be made with RECs (FTC, 2012; NREL, 2015; EPA and GPP, 2017). However, studies of voluntary market RECs have shown that these "green energy" markets are unlikely to influence the amount of RE capacity built, and consequentially do not influence GHG emissions (Dagoumas and Koltsaklis, 2017; Gillenwater, 2013; Gillenwater et al., 2014; Hamburger and Harangozó, 2018; Andrews and Moss, 2023).

In this paper, we seek to test whether an increasingly popular alternative contractual arrangement, called a power purchase agreement (PPA), has influenced the deployment of renewables in the United States. In their original form, PPAs are used by load-serving entities (LSEs) (e.g., utility companies that distribute and sell power to retail consumers) to fulfill electricity load delivery obligations. LSEs pay an electricity generator according to a long-term pricing structure for supplying a specified amount of power at designated grid nodes and times in a contract called a "physical" PPA. In contrast, "virtual" PPAs are typically multi-year contracts that allow electricity generators to engage in financial hedging on wholesale electricity prices directly with end-use consumer companies (i.e., non-utilities) without altering physical power deliveries in wholesale or retail power markets.[1] In exchange, the non-utility entities in a virtual PPA typically also hope to receive long-term electricity pricing benefits as well as the stream of RECs issued to the RE generator.

An important element of PPAs is that they are voluntary. Hence, if they influence RE generation, non-utility PPAs could be a form of private provision of an impure public good. That is, the procurement of a good that generates private and public goods as a joint product (Kotchen, 2005; 2006)—power and/or pricing benefits—while concurrently displacing GHG emissions from fossil-fueled electricity generation. While PPAs are both used and structured in a variety of ways, the potential social benefits of PPAs center on increasing the competitiveness of RE sources. We describe some of the potential benefits as follows.

First, relative to voluntary market RECs, PPAs are more likely to influence investment in RE generation capacity as they typically provide a longer-term source of revenue to generators and are an intervention that can be legally secured at the project finance decision phase (Gillenwater, 2013). Hence, it is commonly assumed that PPAs de-risk RE projects and thereby enhance project developer access to project financing (Bjørn et al., 2022). Second, given the benefits of project de-risking, it is plausible that PPAs influence the development and expansion of critical infrastructure (e.g., transmission lines), which is a constraining factor to the development of RE (Haller et al., 2012; Zapata et al., 2023) and other energy commodities (Scott, 2023). Third, if PPAs make the development of new RE projects more likely, the additional projects that PPAs foster are likely to enhance experiential learning, as project developers learn to navigate administrative processes more efficiently and optimally design and site projects, thereby producing RE at lower levelized costs.[2]

Although it is frequently asserted that corporate and other non-utility PPAs accelerate the rate of renewable deployment,[3] at present there are no studies or empirical evidence demonstrating that they have influenced

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[1] Virtual PPAs represent the vast majority of PPAs between non-utility entities and RE projects (Kobus et al., 2021).

[2] Such efficiency gains have been observed in other stages of RE development, including wind turbine production (Covert and Sweeney, 2022) but also in other energy settings such as oil and gas drilling (e.g., Kellogg, 2011; Fitzgerald, 2015; and Covert, 2015).

[3] For example, see Amazon (2021), Apple (2022), and Google (2022).

the amount of RE generation capacity in the electric power system. In this paper, we address this gap in the literature by investigating whether PPAs have had an empirically discernible effect on the amount of RE generation capacity on the grid, including where and in what contexts PPAs signed by non-utility and utility entities influence RE development. To do this, we construct a large dataset on the electricity generation portfolios of U.S. counties over 1990-2021 and estimate two-way fixed effects regressions to explore the effects of spatially and temporally varying PPAs on the deployment of renewables.

Our results suggest that PPAs, as a combination of both physical and virtual types, are associated with an aggregate increase in both the deployment of RE capacity and the share of renewables, compared to counties absent such PPA activity. However, the effects are heterogeneous in three important ways. First, the effects of PPAs vary based on the power purchaser entity type, i.e., across non-utility, utility, and joint (non-utility and utility) power purchasers. Second, the effects vary based on whether the PPAs are signed for solar or wind projects. Third, the effects of PPAs across both entity and RE project type are sensitive to the renewable resource endowment of the area. These findings offer valuable insights into the efficacy of PPAs in providing public good benefits and may serve as an aid for the decision making of governmental policymakers and non-governmental initiatives seeking to accelerate investment in RE.

2. Background

Wholesale electricity markets encompass the large-scale generation and sale of electricity before it is distributed to end users in the retail electricity market by an LSE.[4] In vertically integrated power markets, utilities function as regulated monopolies and own generation, transmission, and distribution assets, serving as both generators and LSEs. Competitive wholesale power markets, on the other hand, operate with an Independent System Operator (ISO) or Regional Transmission Organization (RTO) that facilitates transactions between electricity generators and LSEs.

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[4] Retail electricity markets structure the transactions between LSEs and consumers (i.e., a household or a corporation paying a utility bill), whereas wholesale markets structure the transactions between electricity generators and LSEs.

Historically, a significant portion of U.S. electricity production relied on fossil fuels like coal, oil, and natural gas, imposing external costs on society such as health impacts from air pollution and GHG emissions contributing to climate change.[5] However, these externalities are not fully reflected in the price of electricity (Figure 1). In competitive markets, where the market price of electricity (P_m) does not account for negative externalities, electricity generation from fossil fuels exceeds the socially optimal level (Q*), resulting in a deadweight loss compared to an efficient resource allocation.

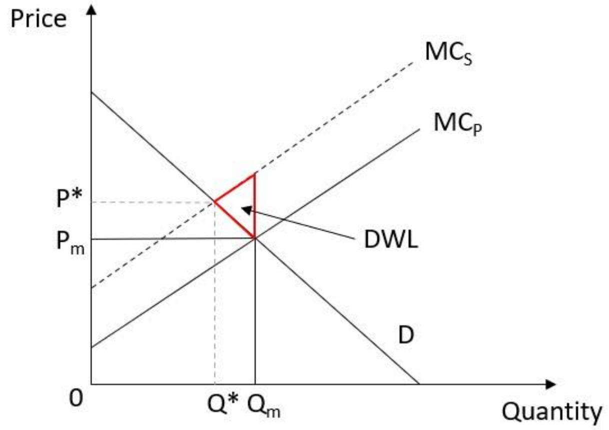

Figure 1. Externalities from electricity generated from fossil fuels.

Notes: A negative externality exists in the market for electricity generated from fossil fuels. It arises due to the disparity present between the private marginal cost (MC_P) and the social marginal cost (MC_S) of electricity production. In a competitive market, the industry produces until Q_m to maximize its producer surplus. However, this level of production is not efficient, given that the industry does not account for the social costs of environmental and health impacts from pollution. Hence, absent governmental control on emissions, a deadweight loss is imposed on society (area DWL) by the industry producing beyond Q*.

Backstop resource theory (Nordhaus, 1973) provides a framework for policymakers to consider these challenges and plan for a transition to a low-carbon economy. The theory follows that as traditional, lower-cost, and depletable resources become scarcer and costlier to extract (Hotelling, 1931), higher-cost "backstop" resources or technologies, such as renewables, are expected to become the primary energy source (Nordhaus, 1973). Figure 2 demonstrates the concept, showing the marginal cost and consumption profiles over time for a depletable resource alongside a renewable backstop resource. The "switch point"

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[5] Electricity generation alone accounts for about one quarter of all GHG emissions in the United States (EPA, 2022).

occurs when the marginal cost of extracting the depletable resource reaches the level of the renewable backstop resource, indicating the moment when society will shift to the renewable source indefinitely.

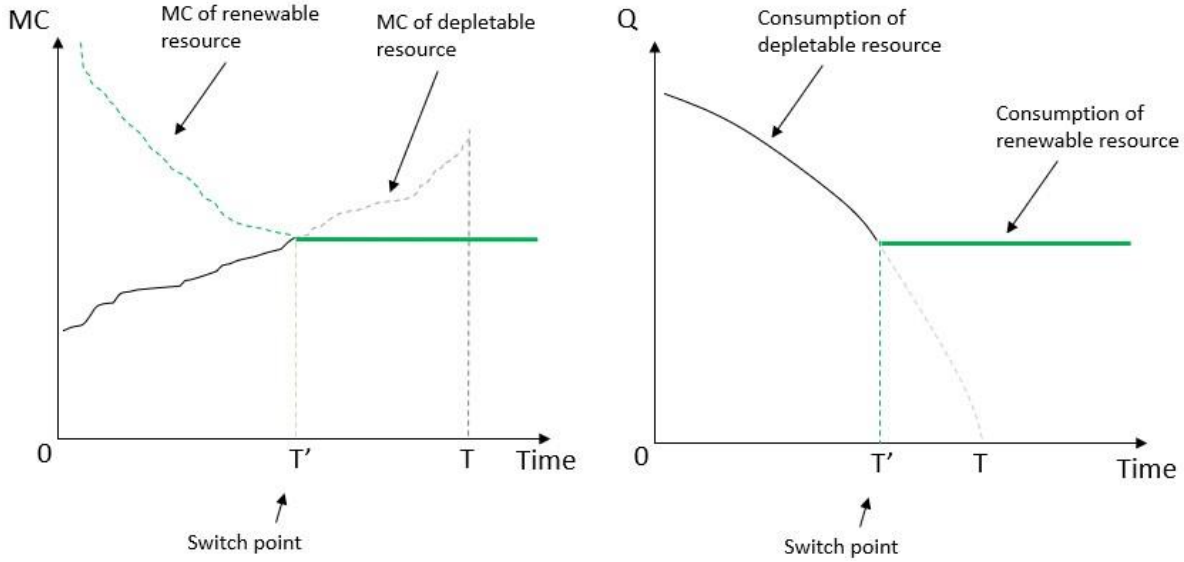

Figure 2. Extraction and marginal cost profiles for depletable and backstop resources.

Notes: The figures above present the extraction and marginal cost profiles for a depletable resource, such as coal, natural gas, or oil, and those for a higher-cost backstop resource, such as wind or solar. Absent a backstop resource, the marginal cost of extracting the depletable resource will rise with cumulative extraction and the resource will be exhausted at time T. In the presence of a backstop resource, the depletable resource will be used until its marginal cost rises above that of the backstop resource at time T' (i.e., the switch point), and thereafter the backstop resource will be used indefinitely.

The social costs of climate change and the environmental benefits of RE have been extensively studied and highlight the need to shift forward the switch point to reduce emissions in the electricity sector (IPCC, 2007; 2018; Carleton and Hsiang, 2016; Nordhaus, 2017; Goulder, 2020). However, a major challenge in the RE transition is the higher overall cost of RE technologies like wind and solar compared to other sources.[6] To address this, various policy alternatives exist to enhance the competitiveness of renewables in supplying the electricity grid. Figure 3 illustrates two primary channels for policy intervention to achieve this goal: one *increases* the marginal cost of *depletable* resources, such as imposing taxes on GHG emissions, while the other *reduces* the marginal cost of *renewable* resources, such as through subsidies.

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[6] The overall cost considers the quality of the energy service provided (e.g., availability) and other barriers to new investment (e.g., project siting and power transmission access). However, intermittency, variability, and the ability of existing infrastructure to handle a large increase in renewable power contribute to cost challenges faced by renewables.

Both approaches make renewable substitutes more competitive and shift the switch point forward, facilitating the transition to RE.

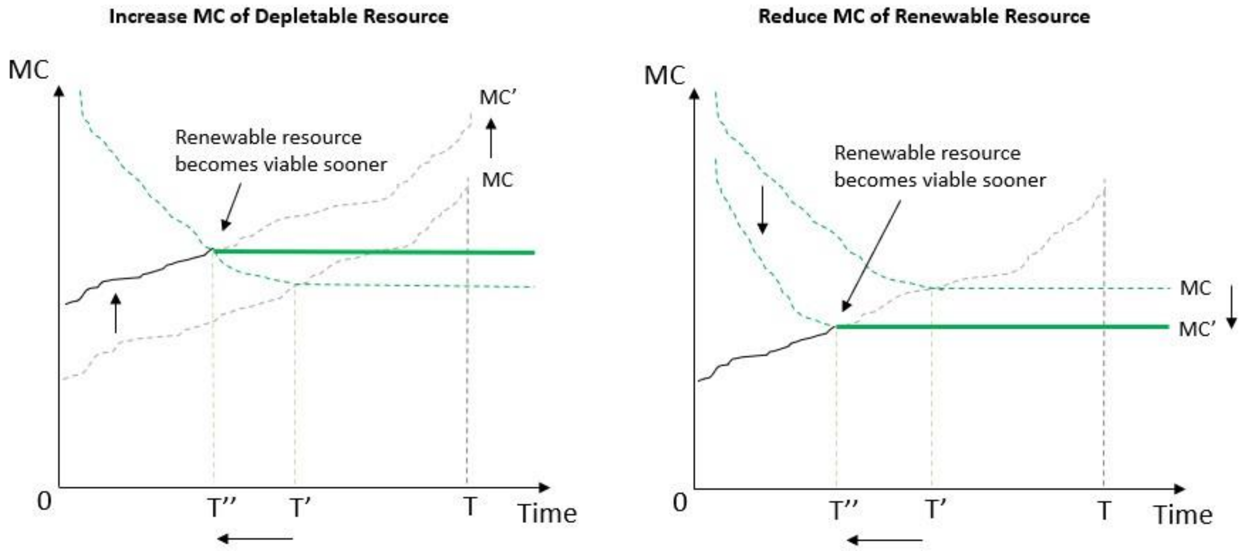

Figure 3. Switch points to backstop resource under policy alternatives that increase (reduce) the marginal cost profile for a depletable (backstop) resource.

Notes: The figures above present the marginal cost profiles for a depletable resource and a backstop resource under alternative policy arrangements that increase the competitiveness of renewable energy substitutes and encourage an earlier switch point, T''. At left, the figure shows how the switch point can be shifted forward in time via policies that increase the marginal cost of the depletable resource, such as through carbon taxes that reduce the competitiveness of fossil fuels. At right, the figure shows how the switch point can be shifted forward in time via policies that reduce the marginal cost of the backstop resource, such as through subsidies that encourage investment in the development of renewables. Under both cases, the backstop resource will be used indefinitely after the switch point.

One of the most common policy mechanisms used in the U.S. is the renewable portfolio standard (RPS), which mandate a growing percentage of electricity supplied by LSEs to come from renewable sources, promoting RE investment and reducing emissions from fossil-based generation (Upton and Snyder, 2017).[7] Studies have shown that RPS mandates do increase RE investment and reduce emissions (Wiser et al., 2016; Hollingsworth and Rudik, 2019; Fullerton and Ta, 2020; Barbose, 2021; Greenstone and Nath, 2021). Historically, RECs have served both as the primary RPS compliance instrument, as well as an accounting tool for claiming the purchase and/or use of RE by retail electricity end users (Gillenwater, 2008b).[8]

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[7] Thirty-nine states and Washington, D.C. have passed some form of an RPS, most of which are mandatory requirements for each LSE to meet the legislatively specified renewable generation quota.

[8] RECs are tradable certificates typically defined to represent property rights to a range of environmental, social, and/or other non-power attributes of RE generation (Gillenwater, 2008a; EPA, 2023).

Previous studies, however, have concluded that it is unlikely that past voluntary non-utility (i.e., retail) REC purchases have led to additional RE generation (e.g., Gillenwater, 2013; Gillenwater et al., 2014; Mulder and Zomer, 2016; Hamburger and Harangozó, 2018; Brander et al. 2018).[9]

Given that RE projects have higher capital costs compared to fossil fuel generation, they require proportionally more upfront financing, and the cost of capital (i.e., the required returns to debt and equity providers) can contribute a large proportion of the overall cost (Steffen, 2020).[10,11] Further, de-risking debt has been shown to yield two times larger savings than de-risking equity (Đukan and Kitzing, 2023). These features create scope for institutions, both public and private, to influence RE investment by voluntarily engaging in financial contracts tied to the amount of power generated by renewable projects. PPAs are an increasingly common instrument used to accomplish this (Kobus et al., 2021).

3. Data

We make use of data from several sources. The primary outcomes of interest relate to the electricity generation portfolio observed in U.S. counties over 1990-2021. Our panel dataset is used in an analysis to isolate the effect of new PPAs (associated with solar and wind electricity projects) on additions to RE generation capacity, conditional on a rich set of control terms. The datasets we use are described as follows.

3.1 Electricity Generation Capacity

We obtain data on annual electricity generation capacity from Form 860 of the U.S. Energy Information Administration (EIA) over 1990-2021.[12] These data are collected from power plants with 1 megawatt (MW) or more of combined nameplate capacity that report electricity generation capacity by generation

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[9] Bjørn et al. (2022) also shows that the use of RECs by companies with science-based targets has led to inflated reporting of the effectiveness of their voluntary mitigation efforts.

[10] Most costs for renewables are for the construction of the assets, whereas fuel receipts represent the largest share of costs for fossil fuel-based generation (Steffen, 2020).

[11] For example, the cost of financing solar photovoltaics in Germany ranges from 12-37% of total project costs (Egli et al., 2018), with this rising to 50% for projects in developing countries (Schmidt, 2014).

[12] Available at: https://www.eia.gov/electricity/data/eia860/.

technology at the generating unit level at the end of each year. Using details on the location of each generator and its primary fuel listed in EIA-Form 860, we initially transform the raw data from each generating unit into annual county-level measures of total capacity (in MW, inclusive of all fuels).[13]

We then create several outcomes of interest that relate to the annual RE generation capacity (in MW) in each county. The first is total RE capacity, calculated as the sum of capacity from all renewable sources.[14] Second, we create a term for the share of all renewables, calculated as the sum of all RE capacity divided by the sum of total electricity generation capacity from all generation types. Third, we create separate terms that reflect total solar and wind capacity, respectively. We initially focus on the two aggregated RE terms, given our interest in understanding the total effects of PPAs on the RE transition. Thereafter, we focus on the disaggregated terms in further analyses aimed at understanding how PPAs associated with solar and wind projects have influenced new renewable generation capacity from each generation type separately.

3.2 Power Purchase Agreements

We obtain data on PPAs from Enverus, a leading private provider of energy data.[15] The dataset includes details on over 5,000 PPAs signed over 1990-2021.[16] The PPAs correspond to specific solar and wind projects and were gathered from regulatory filings and news reports. The full data set includes several terms of interest to our analysis. First, geographic coordinates for each renewable project are provided, which we use to assign each project to a single U.S. county. Second, each record indicates whether the PPA corresponds to a solar or a wind project, the year the project became operational, and the amount of new generation capacity that was built. Lastly, “power purchaser” and “offtaker” terms are available for each

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[13] We restrict this dataset in several important ways to construct our final estimating dataset. First, we condition our sample to only include counties that had positive electricity generation capacity in at least one year of our sample. Second, we restrict our sample to counties on mainland United States. Lastly, given that some counties did not have positive electricity generation capacity in all years of our sample, we impose balance to the panel by specifying that a county had zero capacity during years in which no generation capacity data were available, or none were reported.

[14] Renewable sources include solar, wind, hydro, geothermal, and biomass fuels.

[15] The original dataset was compiled by Energy Acuity, who was acquired by Enverus in March 2021.

[16] Physical and virtual PPAs are not differentiated in our dataset so we do not consider their differences further, although it is likely that most utility PPAs are physical and most non-utility PPAs are virtual (Kobus et al., 2021).

PPA, which detail the name of the entity agreeing to purchase power from the project and the nature of the entity that is "off-taking" the electricity from the project, as outlined in the PPA.[17,18]

Given that our interest also lies in understanding whether PPAs signed by non-utility power purchasers differentially contribute to changes in the amount of renewable generation capacity than those signed by utility power purchasers, we use the power purchaser names provided to create several new terms for our analysis. First, using the set of all power purchaser names from all projects, we classify all power purchasing entities into one of three distinct entity types: utility, non-utility, and joint (in cases where a new RE project involves PPAs signed by both non-utility and utility entities).[19] Second, we create terms for the total amount of new electricity generation capacity (in MW) from solar and wind projects (all associated with PPAs), respectively, in each county in each year, irrespective of the power purchaser type. Lastly, we create the same set of terms across each of the three power purchaser entity types, such that we can test for differences in the effects of PPAs across both power purchaser and RE project type.

Tables 1a and 1b provide summary statistics of the raw data for solar and wind projects with a PPA by power purchaser type, respectively. Figures 4a and 4b depict the staggered nature of new solar and wind capacity corresponding to projects with a PPA by power purchaser type, respectively. Figures 5a and 5b provide a visual depiction of the spatial richness of all new solar and wind generation from projects with a PPA by power purchaser type, respectively.

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[17] Offtaker entities are categorized as commercial, utility, governmental, educational, energy market, other, or a combination of those designations.

[18] Several other terms are also available, including financial terms related to the project cost and the quantity, price, and duration that electricity will be purchased, along with details on the owner, developer, engineer, supplier, and financier. However, these details were not reported for most of the projects and are not used in our analysis.

[19] We classify non-utility entities as those encompassing commercial, educational, and government institutions.

Table 1a. Summary statistics for solar projects with a PPA, by power purchaser type over 1990-2021.

	Non-Utility Power Purchasers	Utility Power Purchasers	Joint Utility/Non-Utility Power Purchasers
Project Capacity (MW)	13.34	13.99	18.08
	(42.003)	(36.279)	(55.682)
Number of Power Purchasing Entities	1.07	1.19	2.18
	(0.424)	(0.602)	(0.819)
Year Project Became Operational	2014.83	2015.43	2016.3
	(3.800)	(3.469)	(3.515)
Project Cost (Million USD)	33.04	33.93	42.34
	(120.572)	(100.764)	(165.083)
Observations	2,473	1,374	261

Table 1b. Summary statistics for wind projects with a PPA, by power purchaser type over 1990-2021.

	Non-Utility Power Purchasers	Utility Power Purchasers	Joint Utility/Non-Utility Power Purchasers
Project Capacity (MW)	106.67	116.18	105.99
	(120.52)	(97.116)	(98.756)
Number of Power Purchasing Entities	1.08	1.50	2.61
	(0.463)	(1.018)	(1.297)
Year Project Became Operational	2013.17	2012.04	2011.95
	(5.385)	(5.042)	(6.058)
Project Cost (Million USD)	197.45	216.95	200.66
	(225.052)	(196.067)	(202.480)
Observations	516	348	88

Notes: these tables present the sample mean for each variable, with the standard deviation below in parentheses. The bottom row in each table indicates the number of projects that the sample means and standard deviations are based on.

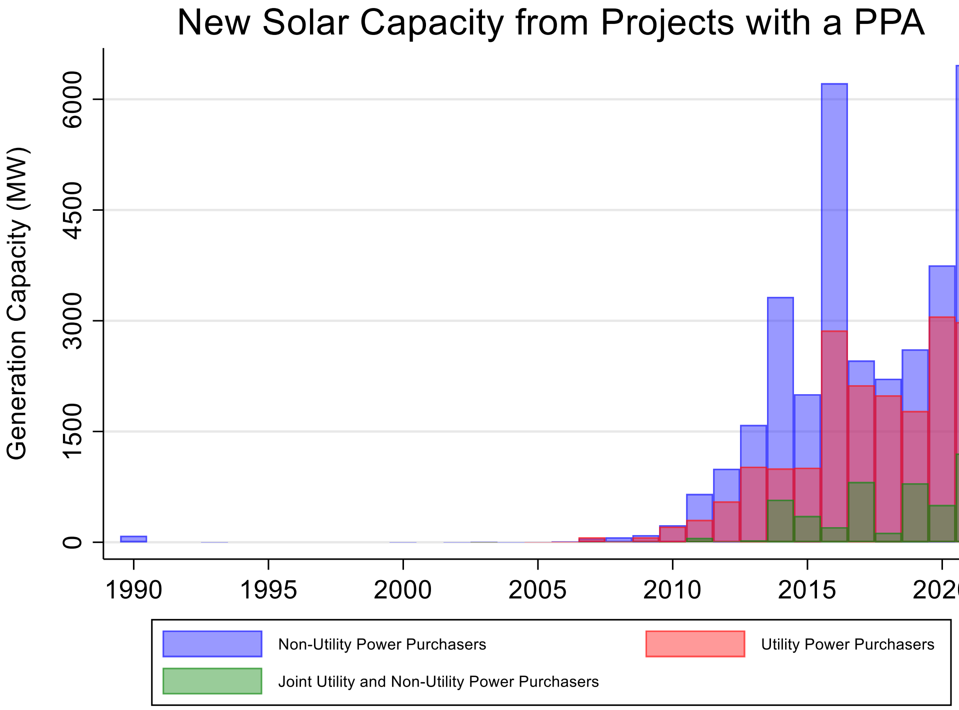

Figure 4a. New solar capacity from projects with a PPA, by power purchaser type over 1990-2021.

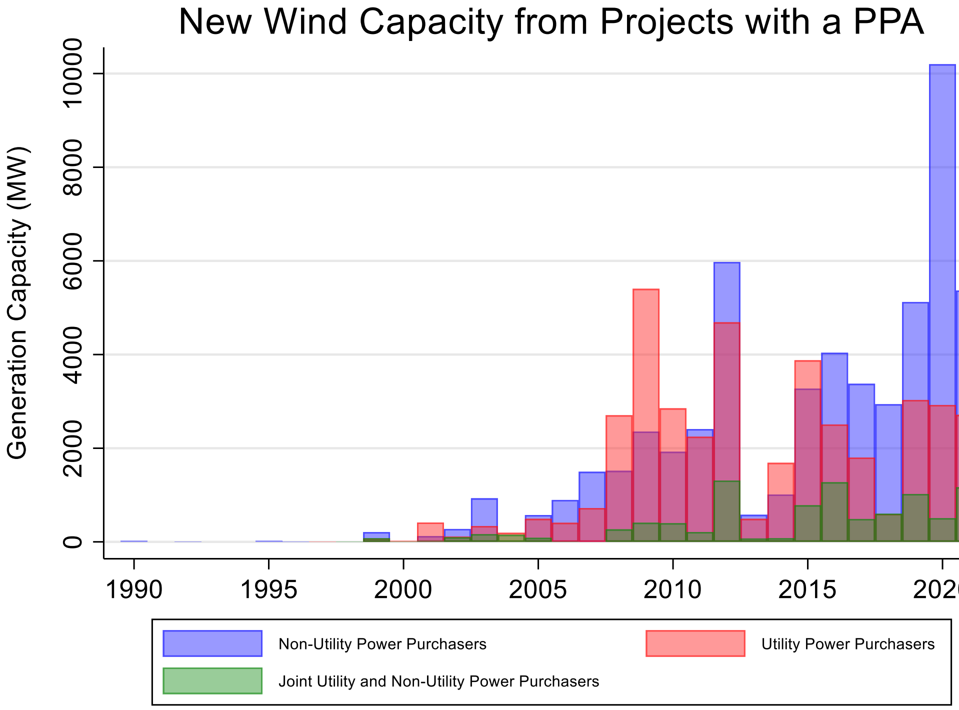

Figure 4b. New wind capacity from projects with a PPA, by power purchaser type over 1990-2021.

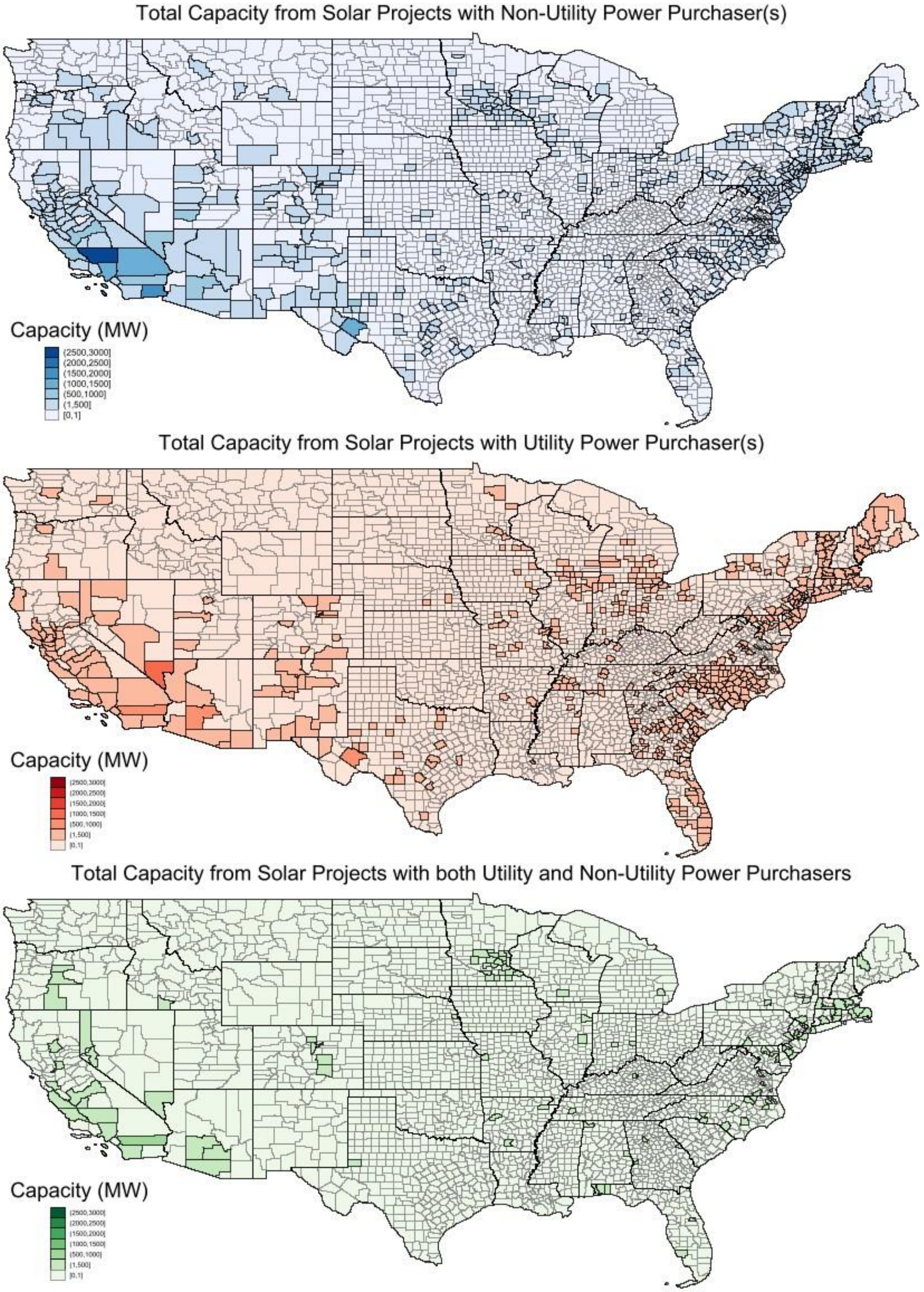

Figure 5a. Total county-level solar generation capacity from projects with a PPA, by power purchaser type over 1990-2021.

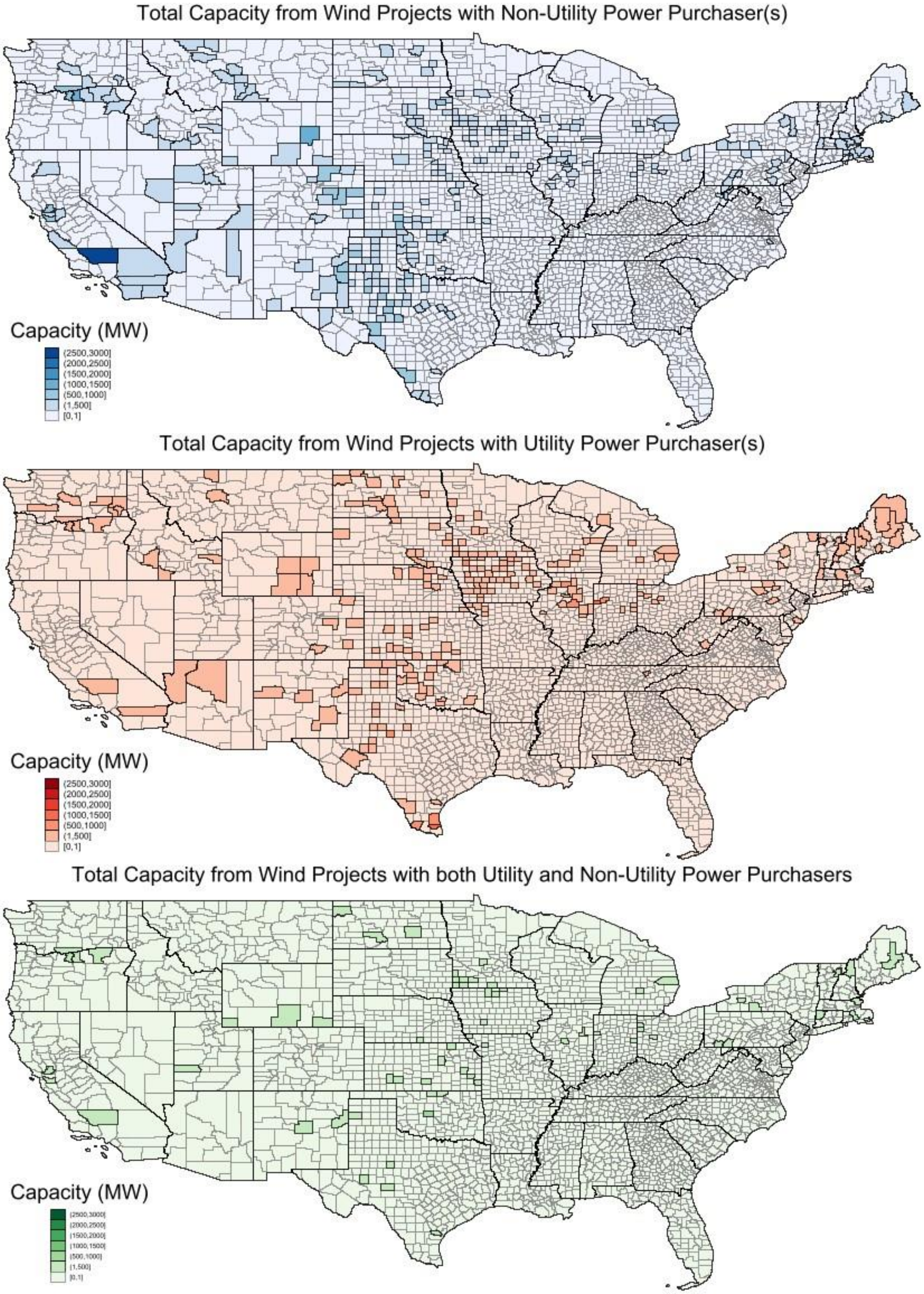

Figure 5b. Total county-level wind generation capacity from projects with a PPA, by power purchaser type over 1990-2021.

3.3 Controls

Isolating the effect of PPAs on RE growth requires conditioning our estimates on other potentially confounding factors that are correlated with RE growth. These include, but are not limited to, factors related to demographic conditions in each county, regulations associated with transitioning localities away from the use of fossil fuels, and local access to natural gas resources that compete with renewables as a technology for electricity generation. We also use data on renewable resource endowments in heterogeneity analysis to characterize how the effects of non-utility and utility PPAs may vary based on the resource potential of a county. We describe these data and their sources in the following subsections.

3.3.1 Demographic Controls

We obtain data on several demographic terms that are known to affect the adoption of renewables. These include annual county-level population estimates from the U.S. Census, which we convert to densities given that population density is correlated with both prevailing and constraining factors for RE development.[20,21] For example, the siting of renewable facilities poses several challenges. Firstly, to achieve economies of scale that reduce average per-unit electricity costs, wind energy production facilities must be sited in areas with more open space and where wind patterns are left uninterrupted by physical structures (e.g., less densely populated areas). Solar facilities, on the other hand, are typically more flexible and can be sited in both urban (e.g., rooftop solar) and rural (e.g., ground mounts or solar farms) areas, given that uninhibited access to sunlight can be found. Secondly, spatial and temporal mismatches between renewable resource availability and electricity demand can challenge grid reliability (Tong et al., 2021). Thirdly, the environmental benefits of RE capacity are location sensitive, and are lower in areas with congestion in transmission lines (Hitaj, 2015; Fell et al. 2021; Millstein et al., 2021). Lastly, while public support for RE development remains high, wind energy projects are sometimes met by local opposition, indicating that

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[20] Barnea and Barnea (2021) find evidence of a strong negative correlation between population density and RE capacity in Germany; and that solar is the more predominant RE source in more densely populated areas.

[21] County-level population data available at: https://www2.census.gov/programs-surveys/popest/datasets/.

wind may represent a locally unwanted land use in some cases (Mueller and Brooks, 2020).[22] Together, these factors make it important to account for spatially and temporally varying population nuclei.

We also gather data on average annual county-level income from the U.S. Internal Revenue Service (IRS), given that higher income areas are presumably more able and likely to be willing to accept higher electricity bills to consume green energy (Salim and Rafiq, 2012).[23] Finally, we gather data on annual county-level unemployment rates from the Bureau of Labor Statistics (BLS), given findings of a mixed relationship (i.e., positive and negative) between the consumption of renewable and non-renewable energy and unemployment (Saboori et al., 2022) and RE support policies and unemployment (Rivers, 2013).[24]

3.3.2 Renewable Energy Regulation Controls

RPS requirements have been shown to influence the amount of renewable development (Barbose, 2021) and electricity prices (Greenstone and Nath, 2021) in an area. To avoid attributing changes in the electricity portfolio due to RPS requirements as attributable to PPAs, we use data from Zhou and Solomon (2021) on the annual relative stringency of RPS requirements for each state. We use these data to create two control terms. The first reflects the relative stringency of the own state renewable requirements, where an increasing degree of RPS stringency is likely to impose pressure on LSEs to increase the development of renewable projects. The second reflects the average RPS stringency of neighboring states. We include this second term given that neighboring states may impose pressure on firm and consumer behavior, out of state REC imports, or own-state government RPS decisions via a peer effects channel. Such policy spillovers have been found in other settings, including state fiscal policies and government expenditures (Case et al., 1993),

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[22] One disamenity potentially associated with opposition to wind farms includes higher incidences of suicide among populations exposed to low-frequency noise radiation from wind turbines (Zhou, 2020). Other factors influencing opposition to RE development appear to be those related to potential effects on land and land-use values (Gross, 2020). For example, Carlisle et al. (2015) finds survey evidence suggesting concerns over potential effects of solar farm proximity on property values. Several empirical studies have also found positive microclimate effects of wind turbines on down-wake crop yields (Kaffine, 2019), but negative effects on down-wake wind generating facilities (Kaffine and Worley, 2010; Lundquist et al., 2019), suggesting that coordinated siting of turbines is important to minimize local external costs.

[23] County-level income data available at: https://www.irs.gov/statistics/soi-tax-stats-county-data/. Note that we had to forecast the income data for 2021, given that it was not yet available from the IRS.

[24] County-level unemployment data available at: https://www.bls.gov/lau/.

government expenditures on flex-fuel vehicles and E85 fuel stations (Corts, 2010), cap-and-trade programs and leakage in carbon emissions (Fell and Maniloff, 2018), state regulations and wind energy patenting (Fu et al., 2018), and neighboring state/country RE production (Shahnazi and Shabani, 2020). Importantly, this set of terms also absorbs changes in RPS stringency (positive or negative) due to changing state government administrations over time.

3.3.3 Competing Resource Controls

The U.S. electricity generation portfolio has been distorted in recent years by the boom in unconventional shale gas development, which forestalled the viability of renewables (Butner and Scott, 2022). We gather data on two terms that capture the influence of readily available natural gas supplies as competitors to generation from renewables. Our first measure for these influences is borrowed from Bartik et al. (2019), who use spatially varying data on geological quality, termed prospectivity, within each county, and interact this term with the timing of the initiation of hydraulic fracturing technology across space. Specifically, the prospectivity term represents an indicator for whether a county is within the top quartile of prospectivity within the set of counties within a shale play, and the term representing the timing of the initiation of hydraulic fracturing represents the year in which the technology became deployed in a given shale basin.[25,26] Together, these terms reflect the exogenous timing that shale gas abundance became economical in certain regions. Our second measure of these influences comes from annual state-level citygate natural gas prices from the EIA.[27] Given the evolution of the natural gas pipeline network that brings shale gas to more distant markets, citygate natural gas prices provide a more localized measure of the degree of price competition facing the rollout of renewables, including in areas where shale gas resources may not be as prevalent.

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[25] Note: a basin refers to a region where geological forces have caused the rock layers to form a rough bowl shape, with the center then filled in by layers of sediment. A shale play is part of a basin where oil and gas molecules are trapped in tight pore spaces; and reflect the part of geology targeted by extraction firms when attempting to produce unconventional oil and gas.

[26] Data on county-level shale prospectivity and basin-level timing of hydraulic fracturing initiation available at: https://www.aeaweb.org/articles?id=10.1257/app.20170487.

[27] A citygate is a point (measuring station) at which a distributing gas utility receives gas from a natural gas pipeline company or transmission system. Our data, which reflect state-level average citygate prices in each year (dollars per thousand cubic feet), are available at: https://www.eia.gov/dnav/ng/NG_PRI_SUM_A_EPG0_PG1_DMCF_A.htm.

3.3.4 Renewable Resource Endowments

The resource potential (or endowment) for solar and wind resources varies significantly across space. To understand how PPAs may enhance the development of renewables, particularly in areas that may not have otherwise received renewable projects, we acquire data from the U.S. National Renewable Energy Laboratory (NREL) on both the solar and wind resource potential in each county. Since resource potential is unlikely to vary substantially over our sample period, our data reflect the annual average resource potential in each county over 1990-2020, which reasonably approximates the long-term resource endowment at each location.[28]

The solar resource endowment is represented by the global horizontal irradiance (GHI) estimate of the National Solar Radiation Database maintained by NREL. GHI is calculated by:

$$GHI = DNI \times \cos(SZA) + DHI,$$

where DNI is the direct normal irradiance, SZA is the solar zenith angle, and DHI is the diffuse horizontal irradiance (Sengupta, 2021). GHI represents a combined value for solar radiation experienced by a location that comes directly from the sun and is reflected from the surrounding environment, both of which are collected by photovoltaic arrays, which we assume as our standard solar technology. Figure 6a shows the spatial distribution of county-level solar resource potential across space in the United States.

The wind resource endowment is represented by the 100-meter wind speed estimate of the Wind Integration National Dataset maintained by NREL. The 100-meter wind speed is the interpolated wind speed at 100 meters above ground level, which is roughly the height of a modern wind turbine (Draxl et al., 2015). Figure 6b shows the spatial distribution of county-level wind resource potential across space in the United States.

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[28] A finer temporal resolution of wind and solar resource data would capture more of the short-term variability of resource potential at each location, but this advantage would be negated by the geographic averaging at the county level. When examining the potential of a given location for renewable resource endowment, aggregated values are more indicative of long-term potential than short-term fluctuations would indicate. The use of raw solar and wind resource potential also allows the variable to be technology-agnostic instead of layering in changing efficiencies over time. These changes are better represented by the levelized cost of RE.

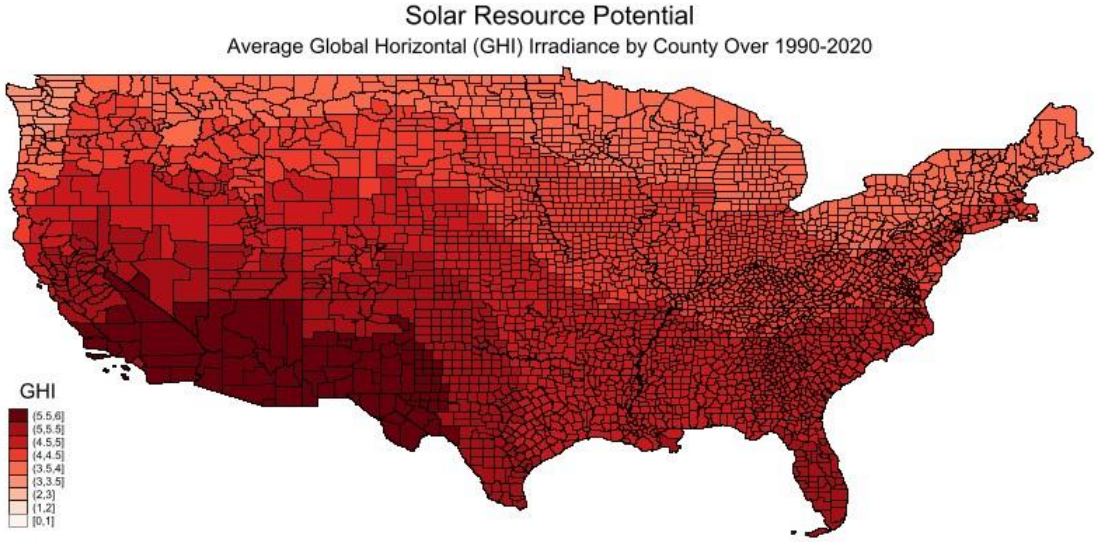

Figure 6a. Solar resource potential by county. Resource potential is estimated using data from NREL on average annual global horizontal irradiance by county over 1990-2020.

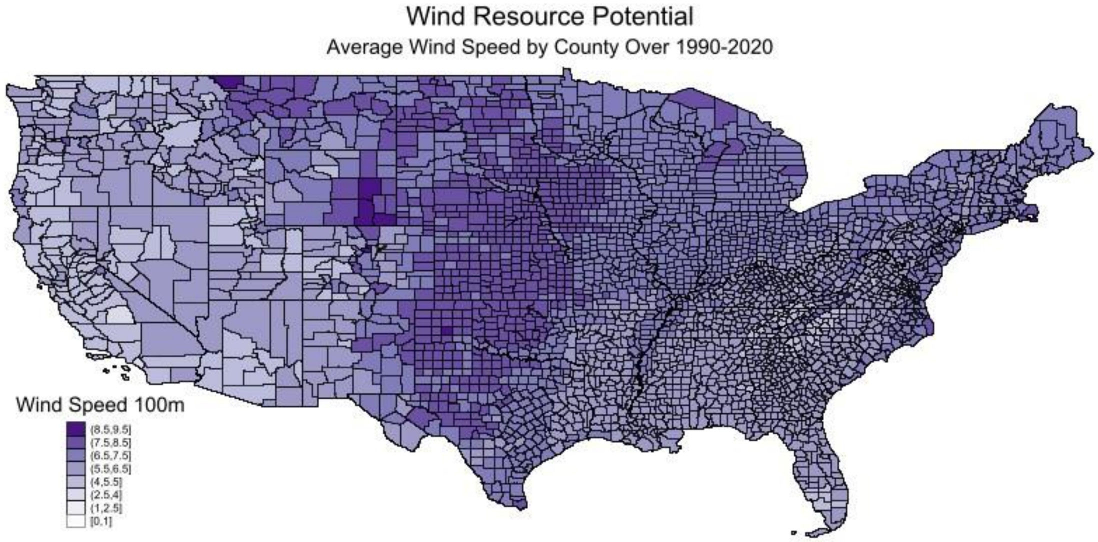

Figure 6b. Wind resource potential by county. Resource potential is estimated using data from NREL on average 100-meter wind speed by county over 1990-2020.

4. Empirical Approach

Using data on county-level electricity generation capacity over 1990-2021, we use a two-way fixed effects strategy that leverages the spatially and temporally varying nature of new capacity from renewable projects associated with PPAs (PPA capacity, hereafter) to estimate their association with additions to RE generation capacity.[29] The primary outcomes of interest include the total RE generation capacity, total RE capacity share, and wind and solar generation capacity separately.[30] For RE capacity outcome y in county i and year t, our baseline estimating equation is:

$$y_{it} = \beta Cap_{All\ PPAs_{it}} + \boldsymbol{X\delta} + \gamma_i + \lambda_t + \epsilon_{it}. \tag{1}$$

The variable of interest in this specification is $Cap_{All\ PPAs}$, which reflects the total capacity from all new PPA capacity, irrespective of power purchaser type and including both solar and wind projects. We also include a vector of control terms, $\boldsymbol{X}$, which reflect county-level demographic conditions, state-level energy regulations, and county and state level access to competing fuels for electricity generation. Lastly, we include sets of county and year fixed effects, γ_i and λ_t, to control for average differences in renewable investment and other factors affecting renewable investment across space, and time-specific confounders common to all counties, respectively.[31] The coefficient of interest is β, which measures the aggregate effect of an additional MW of capacity from projects associated with PPAs on the RE capacity outcome of interest.

We then decompose the aggregate PPA term and specify similar regressions to separately estimate the contributions to capacity from non-utility, utility, and joint (non-utility and utility) PPAs. For these models, our estimating equation becomes:

$$y_{it} = \beta_1 Cap_{NonUtil\ PPAs_{it}} + \beta_2 Cap_{Util\ PPAs_{it}} + \beta_3 Cap_{Joint\ PPAs_{it}} + \boldsymbol{X\delta} + \gamma_i + \lambda_t + \epsilon_{it}. \tag{2}$$

This specification is similar to (1) but includes power-purchaser-specific PPA capacity terms, and the same sets of controls, $\boldsymbol{X}$, and fixed effects, γ_i and λ_t. The coefficients on the PPA capacity terms provide an

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[29] RE projects in the sample include new capital investments in generation capacity at greenfield sites as well as repowering to increase capacity at existing sites.

[30] Note that we define total RE capacity as capacity from solar, wind, hydro, geothermal, and biomass sources.

[31] The county fixed effects should capture the influence of time-invariant terms, such as wind and solar resource potential, and the year fixed effects, for example, should capture the influence of federal wind production tax credits and solar investment tax credits that do not vary across counties.

estimate of the effect of an additional unit of PPA capacity (solar and/or wind) from non-utility, utility, and joint (non-utility and utility) power purchasers, respectively, on the RE capacity outcome of interest.

Lastly, we further disaggregate the power-purchaser-specific PPA terms based on the nature of the RE project (i.e., solar and wind), and estimate separate specifications for solar and wind outcomes, respectively. Hence, $\forall g \in \{solar, wind\}$, we estimate:

$$y_{git} = \beta_1 Cap_{NonUtil\ PPAs_{git}} + \beta_2 Cap_{Util\ PPAs_{git}} + \beta_3 Cap_{Joint\ PPAs_{git}} + \boldsymbol{X\delta} + \gamma_i + \lambda_t + \epsilon_{it}. \quad (3)$$

The coefficients on these terms provide an estimate of the effect of an additional MW of solar (wind) PPA capacity by power purchaser type on the solar (wind) capacity outcome of interest. In additional heterogeneity analyses, we also estimate the same sets of regressions in (3) but include interactions between the PPA capacity terms and an indicator for whether a given county has above (below) median renewable resource potential for each renewable resource type.

5. Results

This section reports the effects of PPAs on changes to the county-level U.S. renewable electricity portfolio. We separately report four main types of effects: (1) the effects of total new PPA capacity; (2) the effects of total new PPA capacity by power purchaser entity type; (3) the effects of solar PPA capacity by power purchaser entity type; and (4) the effects of wind PPA capacity by power purchaser entity type. We also estimate the same sets of regressions using the share of renewables as the outcome (results available in the online appendix). Additionally, for the effects exclusively focusing on additions to solar and wind generation capacity, we report results from heterogeneity analyses that show how the effects of PPAs vary by county-level renewable resource endowment.

The main results are presented in Tables 2-5. For each model, we include in column 1 an initial baseline specification that includes the terms corresponding to PPA capacities, a set of county fixed effects to control for average differences in renewable investment and other factors affecting renewable investment across space, and a set of year fixed effects to control for time-specific confounders common to all counties. In column 2, we include the natural log of income, natural log of population density, and unemployment rate terms to capture any effects from demographic influences in each county on changes in RE infrastructure. In column 3, we add two RPS terms, which control for the RPS stringency of the own state and the average RPS stringency of neighboring states, respectively.[32] In column 4, we add two further controls for competing resource availability, which include an indicator term that reflects the exogenous timing that hydraulic fracturing became economical in counties with top quartile endowments of shale gas, and a term that the reflects annual average state-level citygate natural gas prices.

Positive coefficients on the PPA capacity terms indicate a positive effect on total RE capacity. Further, for coefficients estimated to be greater (and statistically different) than one, these effects indicate that PPAs, in aggregate, are associated with additionality in aggregate RE capacity additions (i.e., that an additional MW of PPA capacity generates a proportionally larger response, or accelerated growth, in new RE capacity).[33]

5.1 Results: All PPAs on Total Renewable Energy Development

Looking at Table 2, we begin by estimating the effect of all newly contracted PPA capacity on total RE capacity. The outcome is inclusive of capacity from all renewable sources—solar, wind, hydro, geothermal, and biomass fuels—and the PPA capacity term is inclusive of capacity from all wind and solar projects associated with PPAs from all power purchaser entity types (i.e., utility, non-utility, and joint non-utility and utility). We find a highly statistically significant coefficient on the PPA capacity term in all columns. In our preferred specification, column 4, we estimate that an additional MW of PPA capacity leads to a

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[32] In other specifications, we also included the average RPS stringency of REC-eligible states based on each state's RPS regulatory compliance rules. However, the results were not statistically significant at any meaningful level and given that we observe little temporal variation in state-level compliance REC eligibility rules, we omit these terms from our regressions.

[33] Note, this conceptual framing of "additionality" differs from the binary causation framing used in the carbon offset project field, as this study investigates the aggregate effect of aggregate PPA activities, rather than the effect of each individual PPA intervention (Gillenwater, 2012). Hence, we consider these aggregate effects to be on the intensive margin (i.e., changes in the level that existing RE project development activities are undertaken). We are unable to investigate the extensive margin (i.e., the effect of PPAs on the likelihood that each renewable project is developed), given that unfunded projects are unobserved to us.

1.497 MW increase in total RE capacity ($p < .01$). Given that this coefficient is both greater and statistically different than one ($p < .05$), it suggests that PPAs are associated with some additionality in new RE capacity.

Table 2. Fixed effects model results for total renewable capacity regressed on total new capacity from all renewable projects associated with a PPA.

	(1)	(2)	(3)	(4)
PPA Capacity (All)	1.516***	1.515***	1.505***	1.497***
	(0.2504)	(0.2512)	(0.2473)	(0.2490)
ln(Income)		28.431*	28.067*	23.871
		(16.0540)	(16.1477)	(16.1830)
ln(Population Density)		-14.657	-14.191	-13.976
		(15.4638)	(15.5057)	(15.5061)
Unemployment Rate		-108.295	-102.564	-109.201
		(69.4288)	(68.0293)	(67.9759)
Own-State RPS Stringency			1.590***	1.592***
			(0.3326)	(0.3372)
Avg RPS Stringency in Neighboring States			4.755***	4.767***
			(1.5739)	(1.5779)
Top Shale County X Frac Viability				17.221
				(13.7413)
Citygate Natural Gas Price				6.656***
				(0.9356)
County FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
N	74016	74016	74016	74016
# Counties	2313	2313	2313	2313
R-Squared	0.202	0.203	0.210	0.213

* p<0.10, ** p<0.05, *** p<0.01
Robust standard errors in parentheses.

Notes: the estimating dataset contains a panel of counties with at least one MW or more of electricity generation capacity in at least one year over 1990-2021. The outcome reflects the total capacity from renewables in each county-year, including solar, wind, hydro, geothermal, and biomass. The PPA capacity term reflects the total capacity in each county-year from PPAs for wind and solar projects from all power purchaser types. The income and population density terms, in their natural log form, and the unemployment rate term, reflect annual values in each county. The RPS stringency terms reflect the annual RPS stringency in the own state and the average annual RPS stringency in neighboring states, respectively. The interaction term "Top Shale County X Frac Viability" is equal to 1 for all years after unconventional oil and gas production became economically viable in top-quartile shale counties, using data from Bartik et al. (2019). The citygate natural gas price term reflects the annual average state-level price that distributing gas utilities receive from a natural gas pipeline company or transmission system.

The only other coefficients with statistical significance include those for each of the RPS stringency terms and the citygate natural gas price term ($p < .01$). The coefficient on the own-state RPS stringency term suggests that a one-unit increase in a state's RPS stringency leads to a 1.592 MW increase in RE capacity, whereas a one-unit increase in the average RPS stringency in neighboring states leads to a 4.767 MW increase, suggesting that some RE capacity investments out of state may be used by LSEs for RPS compliance and/or state-level peer effects potentially influence the development of renewables. Among the competing resource terms, only the coefficient on the citygate natural gas price term is statistically significant ($p < .01$) and suggests that a one-dollar increase (per thousand cubic feet) in annual state-level natural gas prices leads to a 6.656 MW increase in RE capacity. Among the demographic terms, the coefficient on the natural log of county-level income is positive and marginally statistically significant in columns 2 and 3 ($p < .10$) but is not significant when including the competing resource terms. The coefficients on the natural log of population density and unemployment rate terms are negative and not statistically significant at any meaningful level.[34]

We interpret these findings as supportive evidence that PPAs, in the aggregate, have enhanced the RE transition.

5.2 Results: All PPAs by Power Purchaser Entity Type on Total Renewable Energy Development

In Table 3, we estimate the effects of total PPA capacity disaggregated by power purchaser entity type on total renewable capacity. We find highly statistically significant coefficients on each of the PPA capacity terms in all columns. In our preferred specification, column 4, we estimate that an additional MW of non-utility PPA capacity leads to a 1.569 MW increase in total RE capacity ($p < .01$), and that this effect is statistically different than one ($p < .05$), suggesting additionality at an aggregate scale. We also estimate that an additional MW of utility PPA capacity leads to a 1.394 MW increase in total RE capacity ($p < .01$), and that of joint (non-utility and utility) PPA capacity leads to a 1.348 MW increase total RE capacity ($p < .01$). However, neither of these coefficients are statistically different than one ($p > .10$), which suggests that an additional MW of PPA capacity from utility and joint entities is associated with a mechanical response in new RE capacity (i.e., a proportional relationship exists between RE capacity and PPAs, on average).

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[34] In Appendix Table A, we report the results from models that regress the share of RE capacity on the same sets of controls as in Table 2. The results are qualitatively similar and provide evidence that PPAs are associated with an increasing share of renewable generation in U.S. counties.

Table 3. Fixed effects model results for total renewable capacity regressed on total new capacity from all renewable projects associated with a PPA, by power purchaser entity type.

	(1)	(2)	(3)	(4)
PPA Capacity (Non-Utility)	1.591***	1.591***	1.578***	1.569***
	(0.2875)	(0.2881)	(0.2837)	(0.2862)
PPA Capacity (Utility)	1.409***	1.405***	1.401***	1.394***
	(0.2479)	(0.2492)	(0.2463)	(0.2469)
PPA Capacity (Joint)	1.357***	1.360***	1.349***	1.348***
	(0.2228)	(0.2231)	(0.2182)	(0.2183)
ln(Income)		28.602*	28.225*	24.043
		(16.0487)	(16.1434)	(16.1765)
ln(Population Density)		-14.736	-14.269	-14.054
		(15.4941)	(15.5362)	(15.5362)
Unemployment Rate		-109.510	-103.765	-110.354
		(69.8699)	(68.4643)	(68.4055)
Own-State RPS Stringency			1.591***	1.594***
			(0.3334)	(0.3380)
Avg RPS Stringency in Neighboring States			4.735***	4.747***
			(1.5667)	(1.5704)
Top Shale County X Frac Viability				17.163
				(13.7513)
Citygate Natural Gas Price				6.635***
				(0.9402)
County FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
N	74016	74016	74016	74016
# Counties	2313	2313	2313	2313
R-Squared	0.203	0.204	0.210	0.213

* p<0.10, ** p<0.05, *** p<0.01
Robust standard errors in parentheses.

Notes: the estimating dataset contains a panel of counties with at least one MW or more of electricity generation capacity in at least one year over 1990-2021. The outcome reflects the total capacity from renewables in each county-year, including solar, wind, hydro, geothermal, and biomass. The PPA capacity terms reflect the total capacity in each county-year from PPAs for wind and solar projects with non-utility, utility, and joint (utility and non-utility) power purchasers, respectively. The income and population density terms, in their natural log form, and the unemployment rate term, reflect annual values in each county. The RPS stringency terms reflect the annual RPS stringency in the own state and the average annual RPS stringency in neighboring states, respectively. The interaction term "Top Shale County X Frac Viability" is equal to 1 for all years after unconventional oil and gas production became economically viable in top-quartile shale counties, using data from Bartik et al. (2019). The citygate natural gas price term reflects the annual average state-level price that distributing gas utilities receive from a natural gas pipeline company or transmission system.

The only other coefficients with statistical significance include those for each of the RPS stringency terms and the citygate natural gas price term ($p < .01$), with similar effects as those described in the previous subsection. Among the demographic terms, the coefficient on the natural log of county-level income is positive and marginally statistically significant in columns 2 and 3 ($p < .10$) but is not significant when including the competing resource terms. The coefficients on the natural log of population density and unemployment rate terms are negative and not statistically significant at any meaningful level.[35]

We interpret these findings as supportive evidence that PPAs, in the aggregate, have enhanced the RE transition, but the likelihood of additionality associated with PPAs varies by power purchaser entity type. These results are intuitive if, for example, utility PPAs are fewer in number but have larger capacities, and non-utility PPAs are smaller but more spatially distributed, including in areas with less preexisting capacity.

5.3 Results: Solar PPAs by Power Purchaser Entity Type on Solar Development

In Table 4, we estimate the effects of solar PPA capacity disaggregated by power purchaser entity type on total solar capacity. The outcome is inclusive of capacity from solar sources only, and the PPA capacity terms are inclusive of capacity from all new solar projects associated with PPAs by power purchaser entity type. We find highly statistically significant coefficients on each of the solar PPA capacity terms in all columns. In our preferred specification, column 4, we estimate that an additional MW of non-utility solar PPA capacity leads to a 1.583 MW increase in total solar capacity ($p < .01$). We also estimate that an additional MW of utility solar PPA capacity leads to a 2.285 MW increase in total solar capacity ($p < .01$), and that of joint (non-utility and utility) solar PPA capacity leads to a 1.888 MW increase ($p < .01$). Given that each of these coefficients is also statistically different than one ($p < .01$) and that each of these effects are not statistically different from one another ($p > .10$ for each pair), this suggests that PPAs, irrespective of power purchaser entity type, are associated with some additionality in total solar capacity.[36,37]

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[35] In Appendix Table B, we report the results from models that regress the share of renewables on the same sets of controls. The results are qualitatively similar, but the effect is largest for utility PPAs.

[36] In these specifications, all coefficients on the control terms are highly statistically significant except for the citygate natural gas price and unemployment rate terms. We find negative correlations between total solar capacity and income and the indicator between top shale county and hydraulic fracturing viability, and positive correlations with both own-state RPS and average neighboring state RPS stringencies, respectively.

[37] In Appendix Table C, we report the results from models that regress the share of solar on the same sets of controls. The results are qualitatively similar, but the effect on solar share is largest for utility PPAs.

Table 4. Fixed effects model results for total solar capacity regressed on total new capacity from solar projects associated with a PPA, by power purchaser entity type.

	(1)	(2)	(3)	(4)
Solar PPA Capacity (Non-Utility)	1.604***	1.598***	1.582***	1.583***
	(0.1312)	(0.1310)	(0.1290)	(0.1290)
Solar PPA Capacity (Utility)	2.300***	2.289***	2.284***	2.285***
	(0.5489)	(0.5446)	(0.5399)	(0.5398)
Solar PPA Capacity (Joint)	1.915***	1.904***	1.888***	1.888***
	(0.4557)	(0.4528)	(0.4490)	(0.4488)
ln(Income)		-9.000**	-9.204**	-8.498**
		(4.2057)	(4.2281)	(4.1507)
ln(Population Density)		23.595***	23.939***	23.865***
		(5.9225)	(5.9706)	(5.9513)
Unemployment Rate		-37.867	-35.088	-35.234
		(24.9792)	(24.2948)	(24.2552)
Own-State RPS Stringency			0.591***	0.594***
			(0.1372)	(0.1377)
Avg RPS Stringency in Neighboring States			2.226***	2.231***
			(0.7722)	(0.7734)
Top Shale County X Frac Viability				-3.623**
				(1.6160)
Citygate Natural Gas Price				-0.329
				(0.2394)
County FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
N	74016	74016	74016	74016
# Counties	2313	2313	2313	2313
R-Squared	0.291	0.294	0.300	0.300

* p<0.10, ** p<0.05, *** p<0.01
Robust standard errors in parentheses.

Notes: the estimating dataset contains a panel of counties with at least one MW or more of electricity generation capacity in at least one year over 1990-2021. The outcome reflects the total solar capacity in each county-year. The PPA capacity terms reflect the total new capacity in each county-year from solar projects associated with a PPA and non-utility, utility, and joint (utility and non-utility) power purchasers, respectively. The income and population density terms, in their natural log form, and the unemployment rate term, reflect annual values in each county. The RPS stringency terms reflect the annual RPS stringency in the own state and the average annual RPS stringency in neighboring states, respectively. The interaction term "Top Shale County X Frac Viability" is equal to 1 for all years after unconventional oil and gas production became economically viable in top-quartile shale counties, using data from Bartik et al. (2019). The citygate natural gas price term reflects the annual average state-level price that distributing gas utilities receive from a natural gas pipeline company or transmission system.

These results corroborate the findings that PPAs, in the aggregate, have enhanced the RE transition. These results are intuitive if non-utility PPAs are smaller, but more spatially distributed, i.e., leading to smaller additions to solar capacity in a larger number of areas, particularly those that utilities are unlikely to reach.

5.4 Results: Wind PPAs by Power Purchaser Entity Type on Wind Development

In Table 5, we estimate the effects of wind PPA capacity disaggregated by power purchaser entity type on total wind capacity. The outcome is inclusive of capacity from wind sources only, and the PPA capacity terms are inclusive of capacity from all new wind projects associated with PPAs by power purchaser entity type. We find highly statistically significant coefficients on each of the wind PPA capacity terms in all columns. In our preferred specification, column 4, we estimate that an additional MW of non-utility wind PPA capacity leads to a 1.100 MW increase in total wind capacity ($p < .01$). We also estimate that an additional MW of utility wind PPA capacity leads to a 0.919 MW increase in total wind capacity ($p < .01$), and that of joint (non-utility and utility) wind PPA capacity leads to a 0.911 MW increase total wind capacity ($p < .01$). However, none of these three effects are statistically different than one.[38,39]

Table 5. Fixed effects model results for total wind capacity regressed on total new capacity from wind projects associated with a PPA, by power purchaser entity type.

	(1)	(2)	(3)	(4)
Wind PPA Capacity (Non-Utility)	1.121***	1.112***	1.111***	1.100***
	(0.0838)	(0.0856)	(0.0850)	(0.0854)
Wind PPA Capacity (Utility)	0.944***	0.927***	0.926***	0.919***
	(0.0930)	(0.0935)	(0.0933)	(0.0930)
Wind PPA Capacity (Joint)	0.920***	0.915***	0.918***	0.911***
	(0.1969)	(0.1964)	(0.1959)	(0.1951)
ln(Income)		54.835***	54.667***	48.505***
		(13.6386)	(13.6949)	(14.1120)
ln(Population Density)		-50.254***	-50.081***	-49.690***
		(10.8601)	(10.9170)	(10.9430)
Unemployment Rate		19.821	22.214	17.146
		(52.6743)	(52.1378)	(52.1288)
Own-State RPS Stringency			0.749***	0.739***
			(0.2546)	(0.2569)
Avg RPS Stringency in Neighboring States			2.040**	2.027**
			(0.9740)	(0.9743)
Top Shale County X Frac Viability				28.075**
				(13.3914)
Citygate Natural Gas Price				6.907***
				(0.7810)
County FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
N	74016	74016	74016	74016
# Counties	2313	2313	2313	2313
R-Squared	0.133	0.140	0.143	0.149

* p<0.10, ** p<0.05, *** p<0.01
Robust standard errors in parentheses.

Notes: the estimating dataset contains a panel of counties with at least one MW or more of electricity generation

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[38] In these specifications, all coefficients on the control terms are highly statistically significant except for citygate natural gas price term unemployment rate terms. We find negative correlations between total wind capacity and income and the indicator between top shale county and hydraulic fracturing viability, and positive correlations with both own-state RPS and average neighboring state RPS stringencies, respectively.

[39] In Appendix Table D, we report the results from models that regress the share of wind on the same sets of controls. The results are qualitatively similar, but the effect on wind share is largest for utility PPAs.

capacity in at least one year over 1990-2021. The outcome reflects the total wind capacity in each county-year. The PPA capacity terms reflect the total new capacity in each county-year from wind projects associated with a PPA and non-utility, utility, and joint (utility and non-utility) power purchasers, respectively. The income and population density terms, in their natural log form, and the unemployment rate term, reflect annual values in each county. The RPS stringency terms reflect the annual RPS stringency in the own state and the average annual RPS stringency in neighboring states, respectively. The interaction term "Top Shale County X Frac Viability" is equal to 1 for all years after unconventional oil and gas production became economically viable in top-quartile shale counties, using data from Bartik et al. (2019). The citygate natural gas price term reflects the annual average state-level price that distributing gas utilities receive from a natural gas pipeline company or transmission system.

These results corroborate the findings that wind PPAs, in the aggregate, have enhanced the RE transition. However, they reveal a mechanical (i.e., proportional) relationship between wind capacity and PPAs from each entity type, or in other words, that additionality is less likely for wind PPAs. Yet, the effects of utility and joint PPAs on the share of wind capacity are larger than those for non-utility PPAs. These findings are intuitive if, for example, wind projects are larger in scale and thus face greater siting issues, while also being costlier to finance, which utilities are more suited to encumber compared to non-utility entities alone.

5.5 Results: Heterogeneity Analysis for Solar and Wind PPAs by Power Purchaser Entity Type and Resource Endowment

In this subsection, we report the results from heterogeneity analyses to further understand where PPAs from each entity type have influenced changes to the U.S. RE portfolio. We estimate the same general specifications as those in Tables 4 and 5, but we now interact the PPA capacity terms for each entity type with terms that indicate whether the county has above (below) median solar and wind resource potential, respectively. Hence, the results indicate the influence of PPAs, by entity type, based on the resource potential of projects' locations.

Table 6 reports the heterogeneity results for solar PPA capacity. We find that the influence of PPAs varies significantly by power purchaser entity type across the distribution of resource potential. In column 4, our preferred specification, we find that non-utility solar PPAs have a moderately different degree of influence in counties with above and below-median solar resource potential. For counties with below median resource potential, an additional MW of non-utility solar PPA capacity leads to a 1.233 MW increase in total solar capacity ($p < .01$, which is not significantly different than one, $p = .106$), and for counties with above-median resource potential, we find they have they have a total effect of 1.598 MW on solar capacity, which is statistically different than one (i.e., 1.233 MW plus an additional 0.365 MW increase in total solar capacity, $p < .10$). This result suggests that while there is a mechanical relationship between PPAs and solar capacity in areas with lower resource potential, the additional benefits of non-utility solar PPAs are driven by those signed in areas with greater resource potential.

For utility solar PPAs, we find that their influence varies more considerably based on the resource potential of the county. In column 4, we find that an additional MW of utility solar PPA capacity in counties with below median resource potential is associated with a 0.533 MW increase in solar capacity ($p < .01$), an effect that is statistically different than one ($p < .01$). One potential explanation for this effect being less than one is that existing utility-scale solar projects may undergo repowering (or decommissioning of aging projects before reconstruction), and thus experience lower generation capacity while new capacity is added (Wyatt, 2020). For counties with above median resource potential, we find a much larger effect. We estimate that an additional MW of utility solar PPA capacity in these counties leads to a total effect of 2.332 MW, which is statistically different than one (i.e., 0.533 MW plus an additional 1.799 MW increase in total solar capacity, $p < .01$). These results suggest that the influence of utility solar PPAs is almost entirely driven by those in areas with greater solar resource potential, which is intuitive if utility projects are larger in scale and tend to be located in areas with more solar exposure.

For joint (non-utility and utility) solar PPAs, we also find that their influence varies across the distribution of resource potential. As with both non-utility and utility PPAs, we find that an additional MW of joint solar PPA capacity has a positive and statistically significant effect in counties with below median resource potential. The effect is estimated at 0.694 MW ($p < .01$) and is not statistically different than one ($p = .102$). For counties with above median solar resource potential, we estimate that an additional MW of joint PPA capacity leads to a total effect of 1.915 MW, which is statistically different than one (i.e., 0.694 MW plus an additional 1.221 MW increase in total solar capacity, $p < .05$). Intuitively, each of these effects lies between the effects for non-utility and utility PPAs.

Although we show that the additional benefits are predominantly driven by PPAs signed in areas with greater resource potential, the effects for both non-utility and joint solar PPAs are larger in magnitude than those for utility PPAs in counties with below median resource potential. Whereas the effects for utility and joint solar PPAs are largest for projects in counties with above median resource potential.

Table 6. Fixed effects model results for total solar capacity regressed on total new capacity from solar projects associated with a PPA, by power purchaser entity type and median county-level solar resource potential.

	(1)	(2)	(3)	(4)
Solar PPA Cap (Non-Utility)	1.290***	1.278***	1.236***	1.233***
	(0.1492)	(0.1455)	(0.1433)	(0.1438)
Solar PPA Cap (Non-Utility) X Above Median Solar Potential	0.328	0.334*	0.361*	0.365*
	(0.2045)	(0.2023)	(0.2026)	(0.2035)
Solar PPA Cap (Utility)	0.622***	0.629***	0.535***	0.533***
	(0.0832)	(0.0825)	(0.1127)	(0.1141)
Solar PPA Cap (Utility) X Above Median Solar Potential	1.722***	1.705***	1.796***	1.799***
	(0.5721)	(0.5666)	(0.5775)	(0.5782)
Solar PPA Cap (Joint)	0.886***	0.865***	0.698***	0.694***
	(0.2172)	(0.2141)	(0.1865)	(0.1870)
Solar PPA Cap (Joint) X Above Median Solar Potential	1.052**	1.063**	1.217**	1.221**
	(0.5250)	(0.5230)	(0.5205)	(0.5209)
ln(Income)		-9.368**	-9.600**	-8.855**
		(4.2414)	(4.2669)	(4.1825)
ln(Population Density)		23.497***	23.840***	23.763***
		(5.8842)	(5.9298)	(5.9098)
Unemployment Rate		-37.166	-34.285	-34.406
		(24.8986)	(24.2089)	(24.1643)
Own-State RPS Stringency			0.610***	0.614***
			(0.1407)	(0.1412)
Avg RPS Stringency in Neighboring States			2.264***	2.269***
			(0.7757)	(0.7769)
Top Shale County X Frac Viability				-3.818**
				(1.6234)
Citygate Natural Gas Price				-0.367
				(0.2446)
County FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
N	74016	74016	74016	74016
# Counties	2313	2313	2313	2313
R-Squared	0.293	0.295	0.302	0.302

* p<0.10, ** p<0.05, *** p<0.01
Robust standard errors in parentheses.

Notes: the estimating dataset contains a panel of counties with at least one MW or more of electricity generation capacity in at least one year over 1990-2021. The outcome reflects the total solar capacity in each county-year. The PPA capacity terms reflect the total new capacity in each county-year from solar projects associated with a PPA and non-utility, utility, and joint (utility and non-utility) power purchasers, respectively. These PPA capacity terms are interacted with a dummy indicator that reflects whether the county is endowed with above-median solar resource potential. The income and population density terms, in their natural log form, and the unemployment rate term, reflect annual values in each county. The RPS stringency terms reflect the annual RPS stringency in the own state and the average annual RPS stringency in neighboring states, respectively. The interaction term "Top Shale County X Frac

Viability" is equal to 1 for all years after unconventional oil and gas production became economically viable in top-quartile shale counties, using data from Bartik et al. (2019). The citygate natural gas price term reflects the annual average state-level price that distributing gas utilities receive from a natural gas pipeline company or transmission system.

In Table 7, we report the heterogeneity results for wind PPA capacity. In column 4, our preferred specification, we estimate that an additional MW of non-utility wind PPA capacity in counties with below median wind resource potential leads to a 1.311 MW increase in total wind capacity ($p < .01$), an effect that is marginally statistically different than one ($p = .098$). However, given insignificance on the interaction term for counties with above median resource potential ($p > .10$), we find no differential influence of non-utility wind PPAs across the distribution of resource potential. Further, unlike our results in Table 5, we do not find statistical significance on the coefficients for utility wind PPA capacity in counties with above nor below median resource potential ($p < .10$). For joint (non-utility and utility) wind PPA capacity, we only find significance on the interaction term. That is, we estimate an additional MW of joint PPA capacity leads to a 0.989 MW increase in total wind capacity in counties with above median wind resource potential (i.e., -0.371 MW plus an additional 1.36 MW increase in total wind capacity, $p < .01$). We offer potential explanations for these results in the following section.

Table 7. Fixed effects model results for total wind capacity regressed on total new capacity from wind projects associated with a PPA, by power purchaser entity type and median county-level wind resource potential.

	(1)	(2)	(3)	(4)
Wind PPA Cap (Non-Utility)	1.307***	1.317***	1.311***	1.311***
	(0.1904)	(0.1906)	(0.1868)	(0.1883)
Wind PPA Cap (Non-Utility) X Above Median Wind Potential	-0.233	-0.257	-0.251	-0.268
	(0.2124)	(0.2114)	(0.2079)	(0.2082)
Wind PPA Cap (Utility)	1.910	1.930	1.929	1.901
	(1.2819)	(1.2837)	(1.2747)	(1.2786)
Wind PPA Cap (Utility) X Above Median Wind Potential	-1.018	-1.057	-1.057	-1.036
	(1.2850)	(1.2854)	(1.2763)	(1.2801)
Wind PPA Cap (Joint)	-0.372	-0.384	-0.366	-0.371
	(0.4096)	(0.4085)	(0.4026)	(0.4015)
Wind PPA Cap (Joint) X Above Median Wind Potential	1.374***	1.380***	1.363***	1.360***
	(0.4571)	(0.4559)	(0.4507)	(0.4494)
ln(Income)		55.538***	55.365***	49.165***
		(13.4149)	(13.4714)	(13.9299)
ln(Population Density)		-50.822***	-50.644***	-50.266***
		(10.4426)	(10.4977)	(10.5214)
Unemployment Rate		22.409	24.782	19.743
		(50.5769)	(50.1282)	(50.0541)
Own-State RPS Stringency			0.746***	0.735***
			(0.2531)	(0.2552)
Avg RPS Stringency in Neighboring States			2.024**	2.010**
			(0.9548)	(0.9542)
Top Shale County X Frac Viability				28.326**
				(13.3953)
Citygate Natural Gas Price				6.890***
				(0.7838)
County FEs	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
N	74016	74016	74016	74016
# Counties	2313	2313	2313	2313
R-Squared	0.135	0.142	0.145	0.151

* p<0.10, ** p<0.05, *** p<0.01
Robust standard errors in parentheses.

Notes: the estimating dataset contains a panel of counties with at least one MW or more of electricity generation capacity in at least one year over 1990-2021. The outcome reflects the total wind capacity in each county-year. The PPA capacity terms reflect the total new capacity in each county-year from wind projects associated with a PPA and non-utility, utility, and joint (utility and non-utility) power purchasers, respectively. These PPA capacity terms are interacted with a dummy indicator that reflects whether the county is endowed with above-median wind resource potential. The income and population density terms, in their natural log form, and the unemployment rate term, reflect annual values in each county. The RPS stringency terms reflect the annual RPS stringency in the own state and the average annual RPS stringency in neighboring states, respectively. The interaction term "Top Shale County X Frac Viability" is equal to 1 for all years after unconventional oil and gas production became economically viable in top-quartile shale counties, using data from Bartik et al. (2019). The citygate natural gas price term reflects the annual average state-level price that distributing gas utilities receive from a natural gas pipeline company or transmission system.

6. Conclusions and Policy Implications

In this paper, we provide new insights into the role of PPAs in enhancing the RE transition in the United States. Broadly, our results suggest that PPAs, in aggregate, have a non-mechanical relationship with additions to new RE capacity. In other words, for an average U.S. county that secures a unit of PPA capacity, we find an associated change in total RE capacity that is not only positive, but larger and statistically different than one (MW). This finding alone is important as it suggests that PPAs provide some additional benefits beyond their contracted capacity. Upon exploring the effects on the share of renewables, we find that counties receiving PPAs are associated with a statistically significant increase in RE share compared to those without. We also show the effects of PPAs are heterogeneous in three important ways.

First, and unlike the null effect for voluntary REC markets, our results indicate that the overall emergence and growth in non-utility PPA transactions has influenced new RE investment—counties receiving non-utility PPAs, on average, exhibit an overall positive and non-mechanical increase in total RE capacity and a positive increase in the share of renewables. The results for utility and joint PPAs also suggest they are associated with increases in total RE capacity and RE share, however, their effects on total RE capacity are not statistically different than one, and thus appear more mechanical in nature. Our results also suggest that utility PPAs are associated with the largest impact on RE share, as the point estimate is both larger and statistically different than the effects for non-utility and joint PPAs.[40]

Second, we explore how the effects for entity specific PPAs vary across solar and wind projects. For solar development, we find that non-utility PPAs are associated with an increase in solar capacity that is non-mechanical, as the estimated coefficient (1.583 MW) is statistically different than one. However, we find larger effects for both utility and joint PPAs (2.285 and 1.888 MW, respectively), which we consider to be

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[40] We find these results intuitive if, for example, renewable projects associated with utility PPAs are larger in scale and fewer in number, and those associated with non-utility and joint PPAs are smaller in scale but larger in number and more spatially distributed. Further, as shown in Table 5 and discussed below, the aggregate effects for utility and joint PPAs are likely driven by a relative lack of additionality created by wind PPAs, with RPSs playing a more influential role in wind development.

intuitive. For example, if utility-scale solar projects tend to be larger in capacity, it is unsurprising that the effect for utility PPAs is largest, and the effect for joint PPA capacity lies between those for utility and non-utility PPAs. These results suggest that solar PPAs, irrespective of entity type, stimulate additional development beyond the project's capacity. However, some of the differences across entity type may be due, in part, to differences in the typical type of PPA used by each group (i.e., physical versus virtual PPA).

For wind development, we also find that PPAs for each entity type are associated with an increase in wind capacity. However, the effects are smaller in magnitude, and purely mechanical as the estimated coefficients are not statistically different than one. This finding suggests that PPAs signed for wind projects, in general, are less likely to be associated with additional wind development. We find this result unsurprising, given that wind projects tend to be much larger in capacity and less flexible than say, solar projects, which can be a myriad of sizes and are less constrained by environmental and other factors related to siting issues.

To provide further descriptive evidence of the effects of PPAs, and whether they appear complementary or substitutionary for other renewable energy policies (Kotchen et al., 2001), in Figures 7a and 7b we plot average county-level solar and wind capacities over time, separating counties into groups that received (did not receive) a PPA during our sample period and those in states with (without) an RPS. In each figure, we observe that counties receiving a PPA, irrespective of RPS status, have developed a significantly greater degree of solar and wind capacity than counties that never received a PPA. In general, the trend in RE capacity appears correlated with average state RPS stringency for wind, and lags RPS stringency for solar. Initially, RPS compliance by utilities was met largely with investments in wind capacity (i.e., intuitively in advance of RPS compliance deadlines), while expansion of solar capacity did not widely occur until the technology became increasingly cost competitive (see Figure 8).

Figure 7a, showing changes in solar capacity over time, also exhibits a complementarity between PPAs and RPS status. The largest degree of additions is observed in counties that received a PPA and are in an RPS state. Yet, counties that received a PPA but are in a non-RPS state still experienced a much larger degree of solar capacity than counties absent a PPA. For wind capacity in Figure 7b, this complementarity does not appear as prevalent. Irrespective of RPS status, counties receiving a PPA experienced a much greater degree of wind development than counties without. However, unlike the case for solar, when comparing wind capacities among counties receiving a PPA, there is no stark divergence between wind capacities in counties in RPS states vs. counties in non-RPS states. This suggests that RPSs appear to be the primary driver of additions to wind capacity, but PPAs are potentially a substitute.

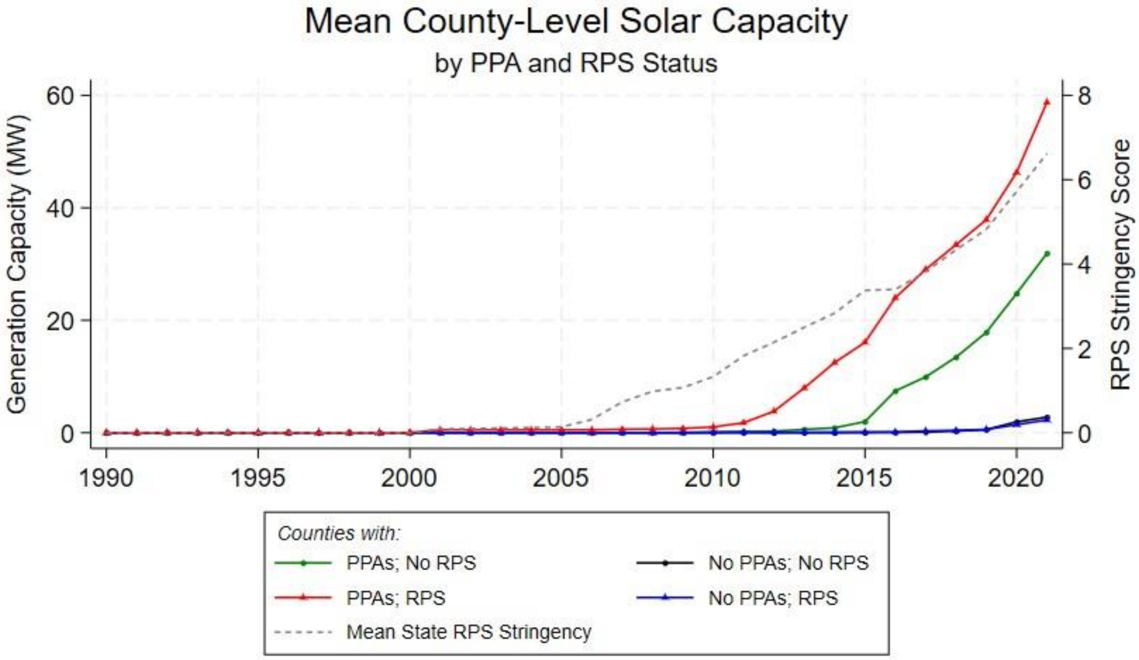

Figure 7a. Mean county-level solar capacity over time. In each figure, the data are separated into counties that received (did not receive) a PPA of any type during our sample period and counties in states with (without) RPS.

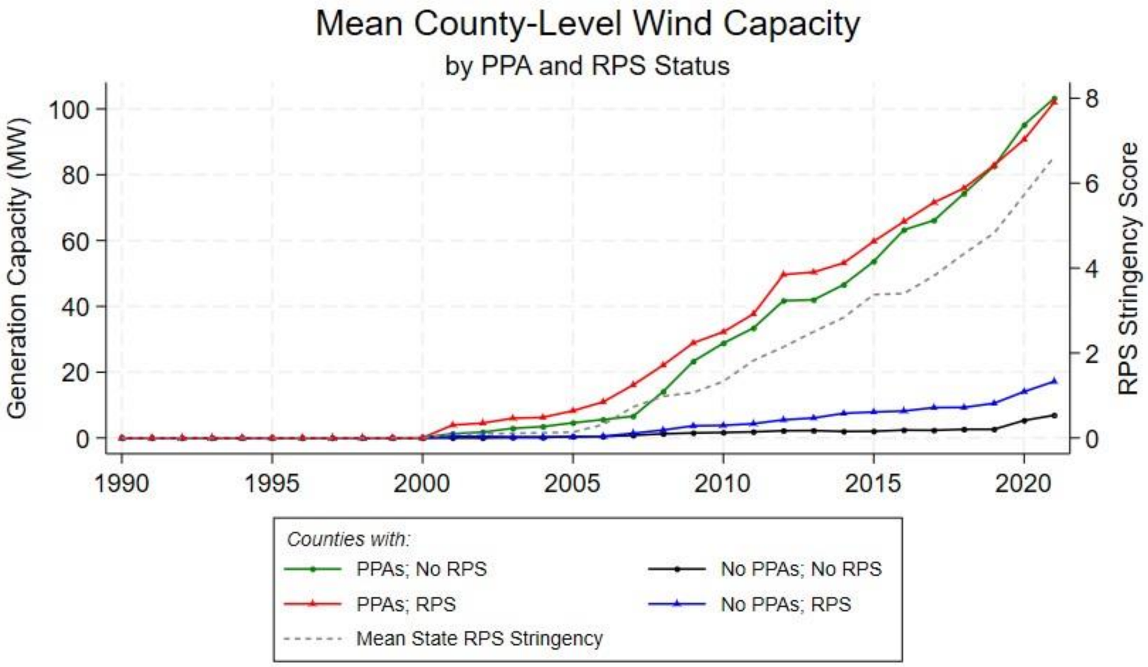

Figure 7b. Mean county-level wind capacity over time. In each figure, the data are separated into counties that received (did not receive) a PPA of any type during our sample period and counties in states with (without) RPS.

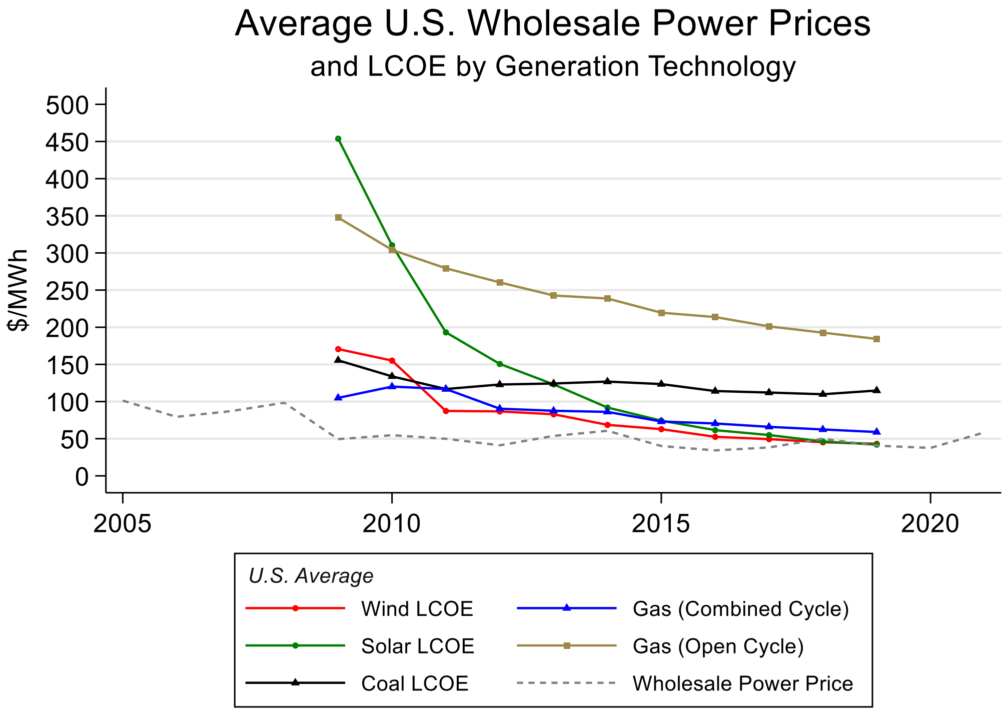

Figure 8. Mean U.S. peak wholesale power prices and LCOE by generation technology over time (in 2021

dollars). Wholesale power price data from U.S. EIA and LCOE data from Lazard, available in Breeze (2021).[41]

Lastly, we explore how the effects of PPAs across both entity and RE project type are sensitive to county-level renewable resource endowment. For solar development, we find that the influence of non-utility PPAs in counties with below median resource potential is positive, but mechanical in nature. Whereas in counties with above median resource potential, the effects are statistically greater than one, suggesting some additional benefits accrue for PPAs signed in these areas. For utility PPAs, we find their effects are much more starkly dependent on resource potential. In counties with below median solar potential, the effect of utility PPAs is small and statistically less than one, but for counties with above median resource potential, the effect is the largest of all entities (statistically different that one), suggesting the additional benefits of utility PPAs in these areas are much larger. Unsurprisingly, these findings suggest that the additional benefits of solar PPAs are predominantly a function of resource potential, but the magnitudes suggest non-utility PPAs are more flexibly used in practice—compared to PPAs signed by other entity types, non-utility PPAs appear more frequently and thus have been more impactful in areas with less resource potential.

For wind development, we find that the influence of non-utility PPAs does not vary across the distribution of wind resource potential. That is, the coefficient on the non-utility PPA capacity term is statistically significant, but the coefficient on the interaction term is statistically insignificant, suggesting the effects are not different in counties with above (below) median resource potential. For utility PPAs, we find no statistical significance for the effects in counties with below nor above median resource potential. We believe these results are partly attributable to the limited number observations of wind PPAs in our dataset.[42] Further, as shown in Figure 7b, it appears wind capacity additions are predominantly driven by RPSs, in which case utility wind projects in particular may be more likely to develop regardless of whether a PPA is

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[41] Peak wholesale power price data available at: https://www.eia.gov/electricity/wholesale/#history.

[42] For example, Table 1b shows only 516 non-utility wind PPA observations (compared to 2,473 for solar), 348 utility wind PPA observations (compared to 1,374 for solar), and 88 joint wind PPA observations (compared to 261 for solar).

present. This claim is also corroborated by the findings in Table 5a, which suggest the average effects for wind PPAs are merely mechanical for each entity type.

Collectively, our results contribute to the growing discussion on new channels, such as non-utility PPAs, to enhance the RE transition of the electric power sector. Previous studies in green energy finance have made a theoretical case that non-utility PPAs drive additional RE capacity (Bjørn et al., 2022), and some reporting initiatives (UKGBC, 2021) and regulatory support mechanisms (European Commission, 2023) have promoted the use of PPAs based on the assumption that all PPAs achieve additionality. This paper is therefore important for providing the first empirical evidence on the validity of this assumption. However, the findings should not be interpreted to support causal claims that each RE project or MW of RE capacity associated with a non-utility PPA achieves additionality. Instead, our results suggest that the collective emergence and growth in non-utility PPA transactions is associated with growth in overall RE investment. Given that non-utility PPAs demonstrate greater flexibility in their usage, incentivizing investment in non-utility PPAs might be conducive to enhancing the expansion of RE into areas where it may otherwise take longer to develop.

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