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How policy has shaped the emerging solar photovoltaic installation industry

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Abstract

Hundreds of state and local policies support the deployment of residential-scale solar photovoltaic systems in the United States. Policy differences across jurisdictions may explain differences in local photovoltaic industries, such as the number of competing installers, the distribution of market shares among those installers, and the market shares of large national-scale installers in local markets. This paper explores this hypothesis through a novel econometric model, the results of which suggest that various state and local policies indeed shape emerging photovoltaic industries. The results suggest that policies that generate higher customer electricity cost savings yield markets with more installers while higher levels of up-front photovoltaic subsidies produce markets with fewer installers. Further, both up-front subsidies and ongoing incentives yield markets where national-scale installers hold less market share. These results indicate that policies have long-term indirect impacts on photovoltaic markets by shaping nascent installation industries. Policymakers could use the results to identify and design policies that help raise infant installation industries to maturity.

Keywords

solar; industry; market structure; policy; incentives

1. Introduction

Global environmental challenges necessitate a transition toward energy systems based primarily on renewable energy resources (IPCC, 2018). However, existing energy systems are largely locked into fossil fuels due to large sunk investments in infrastructure and the political clout of incumbent industries (Arent, Arndt, Miller, Tarp, & Zinaman, 2017; Painuly, 2001; Sovacool, 2009; Unruh, 2000). A transition toward renewable energy-based systems will not occur rapidly enough to achieve meaningful climate change mitigation under existing and planned policies (Arent et al., 2017; IEA, 2017b). As a result, policymakers around the globe are exploring measures to support the growth of renewable energy technologies.

Residential-scale solar photovoltaic (PV) systems are one technology that has attracted considerable policy support (IEA, 2017a; NC CETC, 2018; Schmalensee et al., 2015). These small-scale systems, generally installed on rooftops, can produce enough electricity to match a typical home's annual electricity usage. The life-cycle emissions of PV are negligible relative to the life-cycle emissions of conventional electricity generators (Fthenakis, Kim, & Alsema, 2008). Hundreds of jurisdictions around the world have implemented policy measures to support residential solar photovoltaic (PV) market development (IEA, 2017a; NC CETC, 2018; Schmalensee et al., 2015). These policies include tax-financed measures such as up-front subsidies, tax credits, and production-based ($/kWh) incentives, as well as measures to increase the bill savings of rooftop PV adoption, such as net metering and feed-in tariffs. Several studies have analyzed how these policies affect PV adoption rates (Borenstein, 2017; Crago & Chernyakhovskiy, 2017; Hughes & Podolefsky, 2015; Sarzynski, Larrieu, & Shrimali, 2012). These policies may also affect firm formation and market structure the PV installation industry. Thousands of companies compete to install residential PV in the United States alone (O'Shaughnessy, 2018). Most of these companies operate at a scale of fewer than 10 systems installed per year, and many installers represent businesses that offer related services such as electrical contracting and roofing (O'Shaughnessy & Margolis, 2018). Some local markets comprise many installers while others comprise few. Local installers account for the majority of systems installed in some markets large national-scale installers dominate in other markets.

This study explores the effects that PV policies have had on the emerging PV installation industry, the role that local policies play in variations across local PV installation industries, and how these policy effects are leveraged to support renewable energy transitions towards PV and other technologies. Answers to these research questions are valuable because under-accounting for the effects of policy on industry can result in misleading policy analysis and inefficient policy implementation (Carlton & Loury, 1980; Katsoulacos & Xepapadeas, 1995; Markusen, Morey, & Olewiler, 1993; Spulber, 1985). To explore these research questions, an empirical model is developed and tested using data from the U.S. residential PV market. The dataset represents 572,414 systems installed in the United States from 2010 to 2016 and includes a rich set of control variables. The effects of policies are measured in terms of the number of competing installers, market concentration, and the market share of large national-scale installers. Results from an econometric model are used to establish general principles about the impacts of policy on the PV industry. Future research can explore the specific implications of those principles for PV policy design.

This paper is structure as followed. Section 2 provides a brief review of literature on the impacts of policy on market structure. Section 3 describes the data and variables used for the empirical study. Section 4 provides descriptive statistics. Section 5 describes the empirical model and presents results. The paper concludes with a discussion of policy implications in Section 6.

2. Literature Review

The impacts of policies on industry are of broad interest in the business and industrial organization literature (Gao, 2021; Tirole, 1988). Understanding the impacts of policies on industry can inform policymaking to support local entrepreneurship (Fritsch & Mueller, 2007; Glaeser & Kerr, 2009), to drive economic recovery and growth (Castaño, Méndez, & Galindo, 2016), and to drive innovation in emerging industries (Doblinger, Dowling, & Helm, 2015), among other policy implications. U.S. PV policies to date have not been explicitly designed to affect industry. However, such policies can *indirectly* affect industry in numerous ways. Gao (2021) is the only study, to the author's knowledge, to directly examine these effects in the context of the PV installation industry. The author finds that local jurisdictions with more favorable regulatory environments are associated with higher levels of PV installation firm formation.

A large literature on institutional theory suggests that policy affects the conditions in which firms form and operate (Bruton, Ahlstrom, & Li, 2010; Su, Zhai, & Karlsson, 2014; Valdez & Richardson, 2013). Further, under the industrial evolution framework (Klepper & Graddy, 1990), any policy that increases customer valuation and prices should have two effects on emerging industries. First, higher prices signal higher potential profits and will induce more entrepreneurs to enter the emerging industry. Second, higher sustained prices will allow more firms to remain in the market after entering. In other words, high prices allow some relatively high-cost firms to continue to compete, though high-cost firms would be inefficient and forced to exit under a lower price regime.

Subsidies have been a common PV policy tool. The literature suggests that subsidies generally induce market entry (Burrows, 1979; Currier, 2015; Dunne, Klimek, Roberts, & Xu, 2013; Laincz, 2005), and can also increase the number of firms by allowing otherwise inefficient firms to remain in the market (Conrad & Wang, 1993), though subsidies can also discourage market entry in certain contexts (Chu, Furukawa, & Ji, 2016). Laincz (2005) shows that subsidies increase the number of firms, primarily because some otherwise inefficient firms remain in the market when production is subsidized. That study also shows that subsidies “stretch” the distribution of market shares—meaning that shares shift away from small firms and toward large firms. In Laincz’s study, the effects of the stretch in market shares dominates the effects of the increased number of firms, and subsidies increase market concentration. Gao (2021) finds only a weak relationship between PV firm formation and different PV subsidy levels.

Policy can also affect how firms scale, possibly causing redistributions of market shares between small and large firms. Any policy that imposes a compliance burden can potentially affect market concentration due to administrative economies of scale: Larger firms can spread compliance costs over a larger output base, thus policies with compliance costs tend to grant a competitive advantage to larger firms (Brock & Evans, 1985; Heyes, 2009; Verkuil, 1982).

This study directly tests theories developed in the existing literature through an econometric model. Specifically, by exploring the impacts of subsidies on the number of PV installers, this study directly tests the competing theories that subsidies foster larger numbers of firms (Burrows, 1979; Conrad & Wang, 1993; Currier, 2015; Dunne et al., 2013) versus the theory that subsidies stretch the distribution of market shares and result in fewer firms (Laincz, 2005). The econometric model also provides a direct test for the theory that compliance costs grant competitive advantages to larger firms (Brock & Evans, 1985; Heyes, 2009; Verkuil, 1982). Finally, the study builds on Gao (2021)—who explored impacts of policies on PV firm formation—by exploring the impacts of policies on a broader range of market structure metrics, namely market concentration, the number of firms, and the market shares of national-scale installers. Further, whereas Gao used dummy variables for the existence of incentives and net metering, this study uses continuous estimates of incentives and PV adopter bill savings to more precisely estimate the impacts of these policies on PV market structure.

3. Data and Variables

Customer-level data for systems installed in 2010-2016 are from the Lawrence Berkeley National Laboratory's *Tracking the Sun* dataset, Version 10 (Barbose & Darghouth, 2017). See O'Shaughnessy (2018) for more information about the raw data and data cleaning. Customer-level data are used to generate a balanced market-level panel dataset. Markets are defined according to the approach described in O'Shaughnessy et al. (2018).

Put simply, the approach draws market lines based on the spatial distribution of installers, creating market boundaries based on price determination rather than arbitrary jurisdictional lines. The algorithm applied to the customer-level dataset resulted in 1,416 unique markets. By way of comparison, there are about 700 counties and 10,000 zip codes in the Tracking the Sun dataset, so that the installer-based market definition results in markets sized somewhere between counties and zip codes. To ensure that the panel data are balanced, markets without at least one system installed per year from 2010 to 2016 were dropped. The final dataset comprises 534 unique markets based on 572,414 residential PV systems installed from 2010 to 2016 in 11 states.

The data are used to generate three industry variables (Table 1). The three industry variables defined in Table 1 are all aspects of PV *market structure*, a term broadly used to describe various industrial characteristics (Tirole, 1988). The Herfindahl-Hirschman Index (HHI), equal to the sum of squared market shares, is the most common metric used to measure market concentration (Weiss, 1989). HHI takes on a maximum value of 1 in a fully monopolized market and approaches zero as markets become less concentrated. The market share of national-scale installers is a variable of particular interest in the context of emerging PV markets. Though local businesses represent the vast majority of PV installers, a few companies have grown to serve customers around the country. These national-scale installers are generally more capable of offering PV leases, and they are increasingly offering to finance customer-owned systems through PV loan products (Litvak, 2017). For the purposes of this study, a national-scale installer is an installer that is active in all five of the largest state markets: Arizona, California, Massachusetts, New Jersey, and New York. Only five installers meet this criterion, yet these installers account for about 39 percent of the systems installed in the dataset. A national-scale installer market share variable is tested, defined as the percentage of systems installed in a market in a given year by national-scale installers.

Table 1. Market structure variables (dependent variables)

Variable	Description
# of installers	Number of installers with at least one system installed in a given market in a given year
HHI	Sum of squared market shares in a given market in a given year. Takes on a maximum value of 1 for a fully concentrated monopoly market and approaches 0 for un-concentrated markets.
% national	Percentage of market share held by national-scale installers, defined as an installer that is active in Arizona, California, Massachusetts, New Jersey, and New York

The data are used to generate independent policy variables. The variables are grouped into four dimensions: policies that act via regulated electric utility rates (bill savings); policies that generate up-front financial incentives for adoption (subsidies); policies that generate long-term financial incentives for adoption (ongoing incentives); and policies that determine how rooftop PV is purchased (leasing):

- **Bill savings**: Electricity bill savings are the primary monetary value of PV adoption (Nemet et al., 2017). The magnitudes of bill savings are policy outcomes in that state utility regulators oversee the rate designs that determine bill savings from PV adoption. In certain jurisdictions, bill savings may also include payments for PV output exported to the grid, known as net metering in the United States. Net metering, in particular, is a policy in that state regulators have often required utilities to provide it. As of the end of 2017, 38 states and Washington, DC required utilities to offer net metering programs, and 7 states required utilities to offer some other type of grid export compensation (Proudlove, Lips, Sarkisian, & Shrestha, 2018). Bill savings are estimated based on retail electricity rate information from the Utility Rate Database and estimated system output based on data from the National Solar Radiation Database. Bill savings include savings accruing through net metering credits.
- **Subsidies:** Most states and many sub-state jurisdictions offer up-front subsidies to PV adopters (NC CETC, 2018; Tian et al., 2016).[1] Subsidies are typically distributed as rebates based on system size ($/W). These rebates are issued to the system owner, meaning the homeowner for owned systems or the third-party

[1] Arguably the most important PV subsidy in the United States is the federal investment tax credit, which is worth 30 percent of the installed system cost. Because the federal investment tax credit does not vary across jurisdictions, it is excluded from our study.

system owner in the case of leased systems. Subsidy values are reported directly in Tracking the Sun.

- **Ongoing incentives:** Some jurisdictions offer ongoing production-based incentives paid per unit of system output. Ongoing incentives include revenue from solar renewable energy certificates. Ongoing incentives are estimated according to reported incentive levels and estimated system output based on the National Solar Radiation Database. Lifetime financial values for bill savings and ongoing incentives are converted to net present values and normalized by PV system size in terms of watts (W) installed: $/W. However, though the units are expressed in $/W, bear in mind that ongoing incentives are in effect paid out over time, as distinguished from subsidies which are paid out immediately before or soon after PV installation.
- **Leasing:** PV adoption entails a large up-front investment on a similar order as purchasing a new vehicle. Similar to the vehicle market, the PV industry developed a leasing model that allows customers to purchase PV output while avoiding the large up-front investment. In the context of PV, adopters can "lease" a third-party owned PV system by making monthly payments ($/month) or by buying PV output at a contractual rate ($/kilowatt-hour).[2] Unlike the

[2] In the parlance of the PV industry, the volumetric purchase model is known as a power purchase agreement (PPA) and differs in substantive ways from a lease model. However distinctions between

vehicle market, PV leases are restricted by state laws that generally prohibit retail electricity sales by entities other than utilities and licensed electricity suppliers. These regulations have historically prevented PV installers from offering leasing models (Beck & Martinot, 1994; Drury et al., 2012; Kollins, Speer, & Cory, 2010). However, beginning in the 2000s, some states amended or interpreted utility laws in ways that allowed PV leasing (Drury et al., 2012). 26 states and Washington, DC have now interpreted or amended regulations to explicitly allow PV leases, 9 states explicitly prohibit or restrict leases, and the remainder have no explicit PV leasing policy (Proudlove et al., 2018). The leasing policy variable takes on a value of 1 if the state allows leasing and 0 if otherwise (determined by the presence or absence of leased systems in the data).

4. Descriptive Statistics

This section provides descriptive statistics of the market structure and policy variables to contextualize the econometric results. Summary statistics for these variables, as well as control variables used in the regression described in Section 5, are provided in Table 2. Focusing first on the dependent variables, Figure 1 illustrates the distributions of the

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leases and PPAs are not important for the purposes of this study. For simplicity, all third-party owned PV financing products are referred to as lease products.

three market structure variables. All three distributions skew toward low values. About 98 percent of markets have fewer than 100 installers. About 64 percent of markets have an HHI below 0.25, the threshold above which the U.S. Department of Justice considers markets to be concentrated. The distribution of national-scale installer market shares exhibits a mode around 0 percent, representing markets where national-scale installers had no sales. National-scale installers hold less than 50 percent market share in about 80 percent of markets.

Table 2. Summary statistics for regression variables

Variable	Mean	SD	Min	Max	Source
Dependent market structure variables					
number of installers	23.1	27.06	1	378	Calculated
HHI	0.25	0.21	0.03	1.00	Calculated
% national-scale	26.1	24.1	0	100	Calculated
Policy variables					
bill savings ($/W)	2.79	1.22	0.54	5.42	URDB
subsidies ($/W)	0.84	0.94	0.00	6.93	TTS
ongoing incentives ($/W)	0.56	0.98	0.00	2.91	TTS
leasing	0.87	0.34	0	1	Calculated
Control variables					
sales tax ($/W)	0.07	0.09	0.00	0.31	TTS
market size (x1,000 systems)	153.13	436.08	1	11,773	Calculated
entry pool (x1,000 companies)	1.95	6.32	0.001	179.97	Census
labor cost index	851.29	125.93	515.75	1,278.3	BLS
household density (1,000hh/mi^2)	1.09	1.91	0.00	20.67	Census
% population > bachelor's degree	35.98	15.80	3.88	85.0	Census
% population income >100k	33.87	14.06	0	72.7	Census

Sources: TTS=Tracking the Sun ; URDB=Utility Rate Database; BLS=U.S. Bureau of Labor Statistics

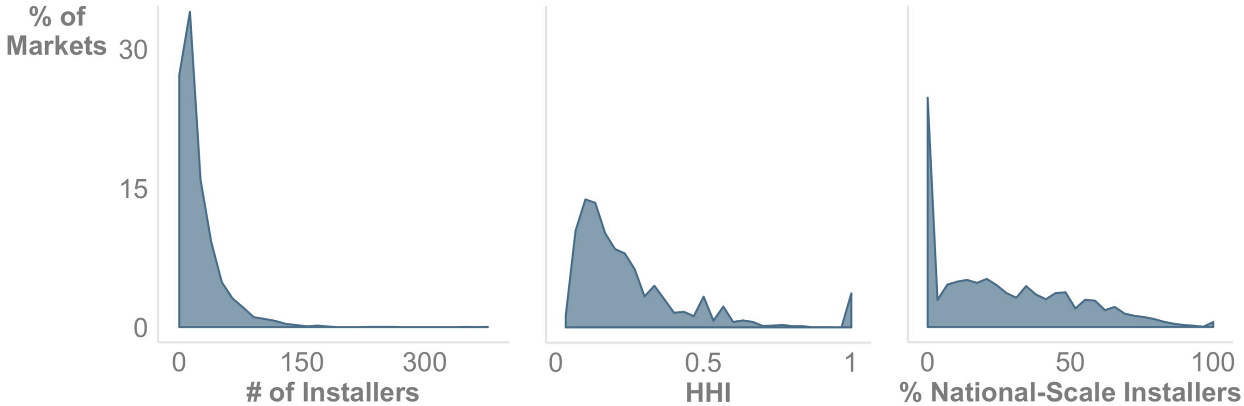

Figure 1. Distributions of Market Structure Variables

Moving to the independent variables, Figure 2 displays distributions for the values of the three financial incentives. Bill savings are generally higher in value than the other incentives are. Bill savings exceed $2/W in about 64 percent of markets, compared to about 24 percent of markets for ongoing incentives and 12 percent of markets for subsidies. The cluster of markets centering around $4/W of bill savings primarily represents markets in California, where high volumetric rates and full retail rate net metering increase the value of bill savings for California customers. Ongoing incentives exhibit a bimodal distribution, with a cluster of zero or low ongoing incentive levels corresponding to markets without any ongoing incentives and a relatively low-value production-based incentive in Florida. The cluster of observations around $2.5/W corresponds to solar renewable energy certificate programs in Massachusetts and New Jersey. State PV rebates have generally declined over time by program design. As a result, subsidy levels declined from 2010 to 2016 (Figure 3). In contrast, bill savings and ongoing incentive levels increased slightly over the study period, largely because customers bought increasingly larger PV systems over time, which increased system output and the sum of bill savings and solar renewable energy certificate revenues.

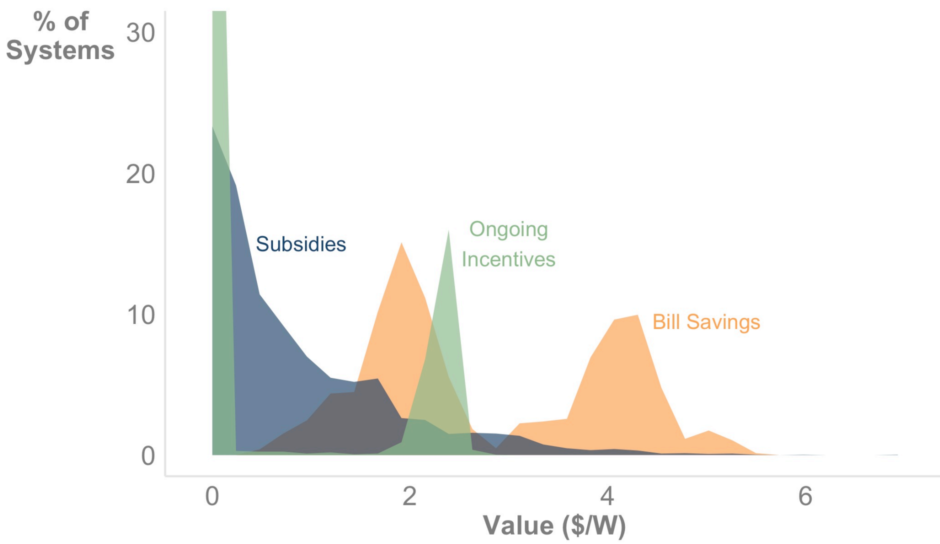

Figure 2. Distributions of Incentive Levels. ***Note: Y-axis is cropped for visual simplicity; the mode of observations for ongoing incentives exceeds 30 percent.***

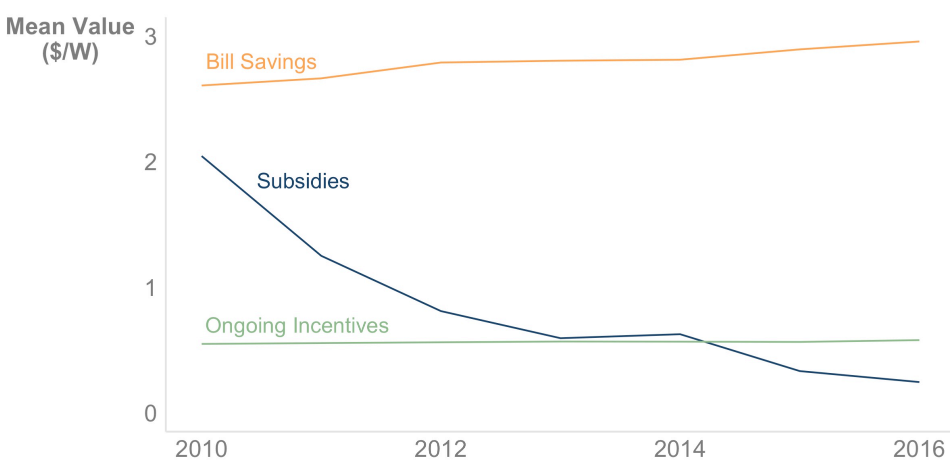

Figure 3. Mean Incentive Levels by Year

5. Multi-Level Model

Given the nested geographic nature of the data and the potential for interaction between policies at different levels, a multi-level model was developed to test the effects of PV policies on market structure. Multi-level models can be used with panel data by treating each observation as a first-level unit and the subject as a second-level unit (Goldstein, 1999). In this case, the first level comprises systems, the second level comprises markets, and the third level comprises states. States are added as a third-level unit, given that state-level policies play a key role in the values of the policy variables. Let MS denote one of the three dependent market structure variables (N, HHI, % markets share of national-scale installers). The effects of policy on market structure is tested according to the following model:

$$MS = \mathbf{POL}\alpha + \boldsymbol{X}\beta + \mathcal{Y} + \varepsilon_{ml} \quad (1)$$

Where $\mathbf{POL}$ is a vector of the policy variables defined in Section 3, $\boldsymbol{X}$ is a matrix of control variables, $\mathcal{Y}$ is year-level fixed effect controlling for variation over time (e.g., changing attitudes about PV over time), and ε_{ml} is a multi-level error term capturing the random effects of observations nested within markets within states. The coefficient α can be interpreted as the effects of policy on market structure within markets within states. Summary statistics for the variables in Equation (1) are provided in Table 2. See Table S1 in the Supplementary Information for complete definitions for the control variables.

5.1 Model Results

Table 3 provides the results of the model in Equation (1) for each of the three dependent market structure variables: the number of installers, HHI, and the market share of national-scale installers. The multi-level models were implemented using the lme4 package in R (Bates, Mächler, Bolker, & Walker, 2015), with marginal R^2 estimates calculated using the Multi-Model Inference (MuMIn) package in R (Bartón, 2018).

Table 3. Econometric model results

	(1) Y=# installers	(2) Y=HHI	(3) Y=%national
bill savings ($/W)	9.39*	-0.07*	-8.25*
	(0.88)	(0.01)	(0.95)
subsidies ($/W)	-3.36*	0.03*	-1.41*
	(0.46)	(0.01)	(0.65)
ongoing incentives ($/W)	-2.24	-0.03	-10.07*
	(1.64)	(0.02)	(2.54)
leasing	1.56	-0.11*	13.14*
	(0.79)	(0.01)	(1.09)
sales tax ($/W)	-74.76*	-0.55*	26.67*
	(5.1)	(0.07)	(7.27)
market size	0.01*	0.00	0.01*
	(0.00)	(0)	(0.002)
entry pool	1.32*	0.00	-0.43*
	(0.11)	(0.001)	(0.14)
labor cost index	-0.02*	0.00*	0.02*
	(0.004)	(0.00)	(0.004)
household density	0.76*	0.00	0.44
	(0.26)	(0.002)	(0.24)
% higher than bachelor's degree	-0.09	0.00	-0.24*
	(0.05)	(0.001)	(0.05)
% income >$100k	0.31*	0.00*	0.11
	(0.06)	(0.001)	(0.06)
constant	14.14*	0.55*	1.38
	(4.7)	(0.05)	(6.47)
R^2	0.66	0.31	0.33
N	3,738	3,738	3,738

*Notes: * p<0.05 based on profiled confidence intervals, standard errors shown in parentheses*

5.1.1 Bill savings

The models suggest that a $1/W increase in bill savings is associated with an increase of about 9 installers, a 0.07 point reduction in HHI, and an 8 percentage point drop in the market share of national-scale installers. These results accord with industrial evolution theory (Klepper & Graddy, 1990). Higher bill savings increase customer incentives for adoption and should, all else equal, increase customer willingness to pay and PV prices. Higher PV prices and higher potential profits may induce more entrepreneurs to enter these markets and may allow some high-cost installers to remain in these markets, both effects contributing to a higher number of installers. The fact that higher bill savings also reduce market concentration suggest that bill savings reduce the competitive advantages of large installers.

5.1.2 Subsidies and ongoing incentives

Subsidies have nearly the opposite effects as bill savings: A $1/W increase in subsidies is associated with a reduction of about 3 installers, a 0.03 point increase in HHI, and a 1.4 percentage point drop in national-scale installer market share. These results are consistent with findings from Laincz (2005), who finds that subsidies tend to shift market shares from small to large firms. Further, the results are consistent with theories that policies that entail compliance costs (e.g., compliance with subsidy program requirements) tend to favor larger firms. A $1/W increase in ongoing incentives is associated with a 10 percentage point reduction in the market share of national-scale installers. Because the regressions control for market size, another way to interpret this result is that installers tend to operate at a smaller scale in markets with higher bill savings and at a larger scale in markets with higher subsidies. In other words, policies that increase bill savings by $1/W yield markets with more and smaller installers while subsidies of the same amount yield markets with fewer and larger installers, all else equal.

Bill savings and subsidies vary in one key way that could explain the divergent regression results: Bill savings are a relatively stable value from year to year whereas subsidies decline in value by policy design. Further, subsidies have declined in an inconsistent manner across different jurisdictions, making it difficult for installers operating across jurisdictions to predict future subsidies in different markets. The relative stability of bill savings versus the short-term and inconsistent nature of subsidies may affect installer strategies in ways that explain the incongruent effects of the two policies on industry. Bill savings and subsidies are generally viewed as demand-side incentives. However, these incentives may also reduce supply-side customer acquisition costs, given that installers may need to invest less time convincing prospective customers to adopt when those customers stand to gain more from adoption. Customer acquisition costs account for about 12 percent of total residential PV system costs (Fu, Feldman, Margolis, Woodhouse, & Ardani, 2017), and—unlike other soft costs—customer acquisition costs have generally increased over time (Mond, 2017). Due to the short-term nature of subsidy programs, installers face a limited window in which to take advantage of subsidized customer acquisition. As a result, installers in subsidized markets may seek to acquire more customers while customer acquisition is cheap, allowing them to secure a strong market position before customer acquisition becomes costlier. Put another way, subsidies may induce installers to focus on market shares and on growing their business, consistent with the results in this study showing that higher subsides are associated with more concentrated markets with fewer and larger installers.

Some empirical evidence supports the hypothesis that short-term subsidies cause installers to focus on their market shares rather than their margins. Several studies show that installers pass the value of subsidies through to customers as opposed to using the subsidies to increase their margins (Dong, Wiser, & Rai, 2018; Pless & van Benthem, 2017). Bielen et al. (2019) show that installers pass the value of subsidies through to customers but tend to increase prices on customers with higher bill savings. These results provide a plausible explanation for the outcomes of the current study. Installers in subsidized markets focus on increasing market share, resulting in market concentration, while higher bill savings allow installers to earn higher profits, attracting more installers to enter and resulting in less market concentration. Future research could further explore this hypothesis, perhaps through installer surveys.

At least two other explanations exist for why subsidies result in markets with fewer and larger installers. First, installers need to invest time and effort to complete paperwork and complete various steps to ensure that their systems qualify for subsidies. These compliance costs may exhibit returns to scale and favor larger installers. Second, some subsidy programs only administer subsidies for systems installed by "eligible" installers. For instance, major subsidy programs such as the California Solar Initiative and NY-Sun maintain databases of subsidy-eligible installers. Installer eligibility requirements may pose market barriers to smaller installers that do not meet eligibility criteria, thus favoring larger installers.

Another interesting result is that higher subsidies and ongoing incentives are associated with markets where national-scale installers hold less market share. Local subsidies and incentives may somehow favor local installers. Local installers may "learn" to navigate subsidy and ongoing incentive programs more efficiently than national-scale installers. Further, customers may prefer to work with local installers, and that subsidies reduce the effective price of PV enough to allow customers to choose local installers and forego any potential cost savings associated with national-scale installers. Alternatively, subsidies and incentive programs may favor local installers by design. For instance, rebate program websites may list qualified local installers, or local Solarize programs may work with local installers to help customers take advantage of rebates.[3]

[3] In a Solarize program, a community group contracts with an installer or installers to install systems on multiple homes.

Conversely, national-scale installers may struggle to navigate different requirements in different subsidy programs, creating transaction costs that must be passed through to customers. The provision of subsidies and ongoing incentives may therefore support the development of local PV installation industries, allowing local installers to establish their businesses before national-scale installer systems flood the market. This hypothesis is an area for further research.

5.1.3 Leasing

The models suggest that policies to allow PV leasing are associated with a 0.1 point reduction in HHI and a 13 percentage point increase in the market share of national-scale installers. The former effect is difficult to explain. When treated as separate markets, the market for leased PV is significantly more concentrated than the market for customer-owned PV (O'Shaughnessy, 2018). The second result agrees with expectations. PV leases tend to be offered, almost exclusively, by large installers with enough scale and capital to own leased systems or access low-cost tax equity to finance leased systems (Mauritzen, 2017; Schmalensee et al., 2015). As a result, implementing policies to allow leasing may open markets to national-scale installers, consistent with the model's result. Again, this result is consistent with theories that policies that entail compliance costs (e.g., costs of securing financing for leases) tend to favor larger firms.

The result that lease-enabling policies yield less concentrated markets is puzzling. When analyzed as separate markets, markets for leased PV are more concentrated than markets for customer-owned PV, primarily due to the higher economies of scale involved in PV leasing (O'Shaughnessy, 2018). Hence policies to enable leasing would be expected to yield more rather than less concentrated markets. One possibility is that policies to enable leasing increase PV demand overall, such that an increase in market size and the number of installers offsets the effects from any re-distribution of market shares. To test this, the regression in Equation (1) was re-run with the standard deviation of market shares as the dependent variable and the number of installers on the right-hand side. The coefficient on leasing was statistically significant and positive, suggesting that lease-enabling policies cause a re-distribution of market shares toward larger installers that may not be reflected in the effects of lease-enabling policies on HHI. Another possibility is that the leasing variable exhibits too little within-market variation to produce the true effect, given that leasing is allowed or prohibited at the state level.

5.1.4 Control variables

The interpretations on the effects of the control variables are mostly straightforward. Among the more interesting results are those on sales taxes and the entry pool variable. Markets with higher sales taxes are associated with fewer installers and higher national-scale installer market shares, suggesting that sales taxes may stymy local installation industries to some degree. The entry pool variable is equal to the number of HVAC and roofing contractors in the market, meant to proxy the number of related-service contractors that could potentially enter the PV installation industry (Dunne et al., 2013).[4] The results suggest that markets with more potential entrants are associated with more installers and lower national-scale installer market shares. Put another way, markets with more local service contractors tend to have larger local PV installation industries.

5.2 Robustness Check: Unstable Policies

These results are not necessarily stable over time for at least two reasons. First, policies have evolved over time, particularly in the case of the steady decline of subsidies. Second, the installation industry has evolved. In particular, the installation industry has

[4] Note that HVAC and roofing contractors were chosen rather than more related services, such as electrical and construction, to ensure the exogeneity of the entry pool variable. Because electrical and construction contractors are licensed to install PV in states like California, statistics on the numbers of these contractors may include PV installers.

accumulated experience over time which has contributed to installed PV price reductions. To explore the possibility of time-varying effects, a time-varying coefficients model was implemented using the plm package in R (Croissant & Millo, 2008). The time-varying models suggest that 1) the effects of bill savings on the number of installers and HHI have been relatively stable over time but unstable in the case of effects on national-scale installer market share, 2) the effects of subsidies and ongoing incentives have fluctuated over time as the levels of these incentives have varied; and 3) the effects of leasing have been relatively stable, particularly in terms of impacts on national-scale installer market share. Indeed, the time-varying models suggest that the impact of leasing on national-scale installer market shares has increased over time. The growing impact of leasing on national-scale installer market shares may reflect the impacts of experience (i.e., learning) accumulating in those large-scale firms. See Tables S2.1-S2.3 for numerical results.

5.3 Robustness Check: Endogenous Policy

At least two aspects of the PV industry could cause the financial incentives (bill savings, subsidies, ongoing incentives) to be endogenous. First, policymakers provide subsidies to promote PV adoption and, possibly, to support the development of local PV industries. For instance, policymakers in areas with few competing installers may use subsidies to spur market entry, in which case the causal direction reverses in Equation (1) and subsidies become endogenous. Second, PV installation is among the fastest growing industries in the United States, employing more than 100,000 people nationwide (The Solar Foundation, 2018). The industry wields increasing political power through multiple national-level associations. Strong local PV industries may be able to lobby for more favorable policies, providing another way that the causal direction could reverse in Equation (1). National-level changes in the PV industry's political power are controlled for through the time fixed effects. However sub-national variation in PV installer political power could be problematic for the results.

Restricting data to a corridor around geographic discontinuities is one way to address potentially endogenous policies. This method ensures exogenous identification, provided that any non-policy differences are irrelevant on either side of the discontinuity (Keele & Titiunik, 2015). In-state electric utility borders generally meet this criterion. Given that installers are licensed at the state level, installers can freely conduct business on either side of an in-state utility border. Further, the choice of utility plays an insignificant, if any, role in where people decide to live. Therefore relevant supply- and demand-side factors should be constant across in-state utility borders and remaining non-policy factors should be irrelevant. Consistent with previous studies (Bollinger & Gillingham, 2012; Hughes & Podolefsky, 2015), the border between Pacific

Gas & Electric (PG&E) and Southern California Edison (SCE) in California is used as a geographic discontinuity in this study. The PG&E/SCE border provides an ideal discontinuity because the border was determined in the early 1900s, long before PV markets could influence the position of the border (Hughes & Podolefsky, 2015).

A balanced panel dataset was created using 38 zip codes in a 20-mile corridor around the border (Figure 4, right pane), consistent with Hughes and Podolefsky (2015). Markets are defined at the zip code level. Subsidy levels varied over time on either side of the border based on a declining rebate schedule set for each major utility in California (Figure 4, left pane). Rate structures also vary on either side of the border based on variations in volumetric rates. Both utilities offered full retail rate net metering. The state-level investment tax credit is excluded from the calculation of the subsidy level. Ongoing incentives were unavailable for residential customers in California during the study period and are excluded from the model.

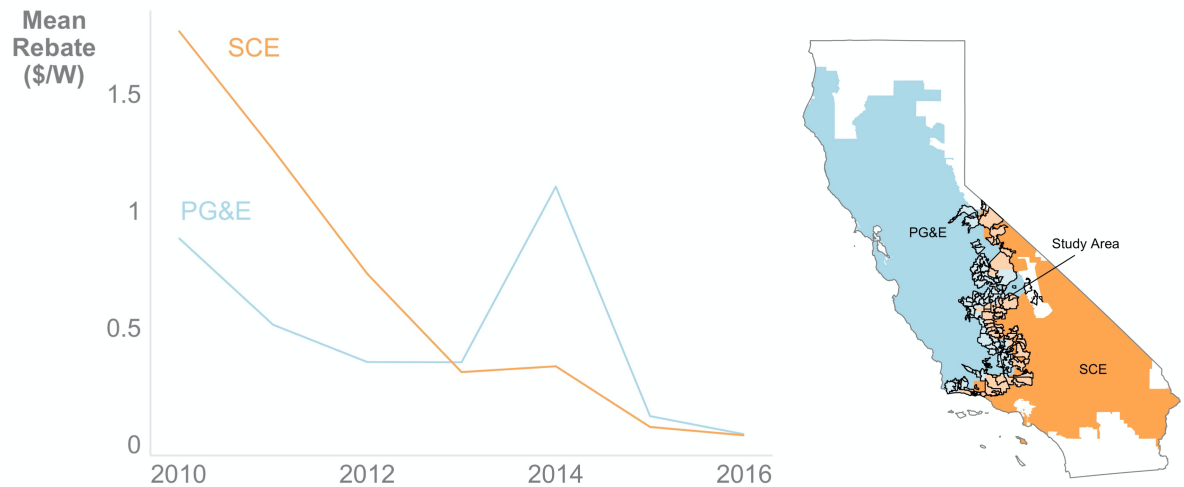

Figure 4. Mean Rebates (Left Pane) in PG&E and SCE Over Time, Study Area for Geographic Discontinuity (Right Pane)

The data in this case are nested at the zip code and utility levels. Table 4 presents the results of the geographic corridor regression for the policy variables (see Table S3 in the Supplementary Information for full model results). The coefficient signs for all of the key results from the base model are preserved in the geographic corridor regression. Although endogenous policy may bias the results in Table 3, the results of the geographic corridor regression suggest that the signs on the effects are valid. Specifically, (1) the number of installers increases in bill savings and declines in subsidies; (2) HHI declines in bill savings and increases in subsidies; and (3) the market share of national-scale installers declines in subsidies.

Table 4. Regression results limited to corridor around PG&E/SCE border

Note: Base model results in parentheses

	(1) Y=# installers	(2) Y=HHI	(3) %national
Bill savings ($/W)	2.68[b] (9.39)	-0.19*[a] (-0.07)	-13.00[b] (-8.25)
Subsidies ($/W)	-3.86*[a] (-3.36)	0.17*[a] (0.03)	-4.51[b] (-1.41)
N	266	266	266

Notes: * *Statistically significant at p<0.05*

[a] *Robust: Significant and consistent sign with significant base model result*

[b] *Semi-robust: Insignificant but consistent sign with significant base model result*

Limited external validity is one potential limitation of the geographic discontinuity approach. Further, the results of the base model may be dominated by trends in California, given that California accounts for about 63 percent of systems in the dataset. As an additional robustness check to assess the validity of the results outside of California, Table 5 presents regression results for the policy variables while excluding systems installed in California (see Table S4 in the Supplementary Information for full model results). The effects of the financial incentives are again largely robust, though the effects of bill savings and subsidies on the number of installers become insignificant.

Table 5. Regression results limited to systems installed outside of California

Note: Base model results in parentheses

	(1) Y=# installers	(2) Y=HHI	(3) Y=%national
Bill savings	1.23[b] (9.39)	-0.07*[a] (-0.07)	2.93 (-8.25)
Subsidies	-0.20[b] (-3.36)	-0.004 (0.03)	-2.95*[a] (-1.41)
Ongoing incentives	1.33 (-2.24)	-0.02 (-0.03)	-7.59*[b] (-10.07)
Leasing	2.70* (1.56)	-0.09*[a] (-0.11)	16.14*[a] (13.14)

*Notes: * Statistically significant at p<0.05*

[a] Robust: p<0.05 and consistent sign with significant base model result

[b] Semi-robust: Insignificant but consistent sign with significant base model result

6. Conclusion and Policy Implications

This study uses a data-driven approach to study the effects of state and local policies on local PV installation industries. The analysis shows that more installers tend to compete in markets where customers earn greater bill savings from PV adoption. This result accords with economic theory that markets with stronger demand will attract more market entrants and allow more firms to compete. The results also show that fewer installers compete in markets with higher subsidies. This result may indicate installers implement different strategies in subsidized markets, focusing on increasing market shares rather than profit margins. Alternatively, this result may suggest that subsidies favor larger installers, such as through installer eligibility criteria that restrict subsidy distribution to smaller, less experienced installers. Further, the results indicate that national-scale installers hold less market share in subsidized markets. This outcome may suggest that subsidy programs and ongoing incentives favor local and regional firms—possibly by policy design, such as subsidy platforms that channel customers to local firms. Finally, the results confirm expectations that policies to enable PV leasing yield markets where national-scale installers hold more market share.

Several of the results could extend to other emerging industries with similar characteristics. Specifically:

- Stable policies that increase the value of adoption for an emerging technology induce more companies to enter the emerging industry and yield markets with more suppliers of the emerging product.
- Short-term subsidies for emerging technologies may, possibly by design, allow certain companies to scale more effectively, yielding markets with fewer but larger companies.
- Local incentives for emerging technologies may, also possibly by design, favor local companies in ways that allow these local companies to scale before other national-level companies enter the local product market.
- Policies that allow companies to offer an emerging technology as a financial service (e.g., leasing) may favor larger companies.

At a minimum, the results of this study indicate that policy analysts should be cognizant of the effects of policies on emerging industries. As shown in Markusen et al. (1993), failure to account for policy impacts on industry can result in misleading policy analysis. More broadly, it may be possible for policy analysts and policymakers to use these results to inform industrial policy, i.e., policy measures implemented to intentionally influence market structure. Various policy measures in emerging industries can help raise an "infant" industry to maturity, thus generating long-term social benefits (Pack & Saggi, 2006). Optimal industrial policies could comprise a mix of direct financial incentives (e.g., rebates), measures to increase the end-user value of the product (e.g., bill savings), measures to reduce technical and administrative hurdles to adoption (e.g., interconnection requirements), and measures to support customer financing (e.g., leasing).

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