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The geography of solar energy in the United States: Market definition, industry structure, and choice in solar PV adoption

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ABSTRACT

The solar photovoltaic (PV) installation industry comprises thousands of firms around the world who collectively installed nearly 200 million panels in 2015. Spatial analysis of the emerging industry has received considerable attention from the literature, especially on the demand side concerning peer effects and adopter clustering. However this research area does not include similarly sophisticated spatial analysis on the supply side of the installation industry. The lack of understanding of the spatial structure of the PV installation industry leaves PV market research to rely on jurisdictional lines, such as counties, to define geographic PV markets. We develop an approach that uses the spatial distribution of installers' activity to define geographic boundaries for PV markets. Our method is useful for PV market research and applicable in the contexts of other industries. We use our approach to demonstrate that the PV industry in the United States is spatially heterogeneous. Despite the emergence of some national-scale PV installers, installers are largely local and installer communities are unique from one region to the next. The social implications of the spatial heterogeneity of the emerging PV industry involve improving understanding of issues such as market power, industry consolidation, and how much choice potential adopters have.

1. Introduction

The job title of solar photovoltaic (PV) installer only emerged near the end of the 20th century. However today, thousands of PV installation companies with hundreds of thousands of employees install more than 180 million PV panels per year worldwide [1,2]. Spatial analysis of demand in the emerging PV industry has received considerable attention, especially concerning peer effects and adopter clustering [3–7]. However similarly sophisticated supply-side spatial analysis of the PV installation industry is unavailable. Improved supply-side spatial analysis, and more specifically geographic market definition, would provide insights into spatial PV market structure. In the absence of an alternative PV market definition, several studies have used jurisdictional lines by default to analyze spatial market structure [8–10]. These studies have generally used county lines to calculate market structure metrics such as installer density and concentration. However, defining markets based on jurisdictional lines rather than economic forces limits market research on the effects of competitive conditions on firm behavior [11–14].

In this paper, we develop a method to define PV markets based on the spatial distribution of installers. We apply the method to a dataset of the U.S. PV installations. The method is meant to be practical for future applied research. However the results of the method applied to the U.S. data are also illustrative per se. Using our market definition, we show that the U.S. PV installation industry is spatially heterogeneous. An installer community in one city typically only weakly resembles installer communities in other nearby cities, in the sense that one city contains a group of localized installers that operate exclusively in that city. The resemblance between installer communities diminishes with distance. We show that the spatial heterogeneity of the PV industry may be one driver of the spatial patterns of installed prices. At the same time, the ubiquity of a few national-scale installers ensures some spatial homogeneity even over large distances. An improved understanding of the spatial distribution of PV installers will inform future research on spatial market structures.

Our market definition is broadly applicable in the context of other industries (e.g., distributed energy storage) and has applications for a variety of social science questions. For example, social scientists could use our approach to study how spatially heterogeneous installation industries affect local economies. The local economic impacts of highly

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localized and spatially heterogeneous installer communities could be compared with the economic impacts of a more spatially homogenous PV installation industry. Such analysis could inform policymaking to maximize the environmental and social benefits of the emerging PV industry.

The paper proceeds as follows. In Section 2, we provide a review of the market definition literature. In Section 3 we develop our methodology. In Section 4 we apply the method to a dataset of U.S. PV installers. In Section 5, we discuss the outcome of the method's application. In Section 6, we conclude by providing some guidance on the future application of the method.

2. Market definition literature review

A market may be broadly defined as the area within which supply and demand determine prices [12]. However, there is no consensus on how to define this area in space [13–19]. A body of literature provides a variety of approaches and some guiding principles for geographic market definition.

The task of market definition is to use economic forces, rather than political or geological features, to delineate geographic boundaries [11]. Early market definition models attempted the task using transportation costs [11], trading areas [20,21], and shipments data [22]. Subsequently, the theoretical focus has shifted toward price interdependence [12,16,23–25,14]. Stigler and Sherwin [12] cite price dependence (independence) between two areas as evidence of market integration (segregation). Price interdependence implies the temporal correlation of prices – rather than price equality – between two areas [12,16,14,24]. That is, price *levels* may vary within a market due to local factors, but all levels will correlate in time due to shared economic forces. Several studies have developed econometric models to establish price interdependence for market definition [23,15,16,26,24].

Price interdependence within a market follows from the interaction of firms with their rivals and their customers. Within a market, a firm's price behavior is necessarily constrained by the actions of rivals in the same market. The degree to which firms constrain their rivals' behavior in geographic space may therefore provide evidence of price interdependence and market integration [12,27]. Brooks [13] defines an "enacted" market as the set of rivals that demands the strategic attention of a given firm. In other words, the enacted market is the geographic area that contains the rivals that constrain the prices of a given firm. Kay [28] and Geroski [18] propose an alternative view of the "strategic" market as the smallest geographic area over which a firm can profitably compete. The authors argue that firms may choose to compete in larger markets, but the relevant market for price formation is the smallest viable niche. For instance, in an industry with both local-scale and national-scale firms, the strategic market is defined from the perspective of the local, but profitable, firms. The national-scale firms compete in multiple strategic markets. A national-scale firm's prices in one strategic market are not necessarily constrained by the actions of rivals in a separate strategic market.

The U.S. Department of Justice developed a market definition for antitrust cases in the United States. The US DOJ hypothetical monopolist test (HMT) defines a market as the smallest geographic area over which a hypothetical monopolist could impose a small but significant and non-transitory increase in price (SSNIP). To implement the HMT, some candidate market area is first chosen. The potential for the hypothetical monopolist to exercise the SSNIP is then tested. If the SSNIP is not possible, the candidate market area is expanded and the process repeats until the area is large enough to accommodate the SSNIP [29,14].

If any market definition rule exists, it is that the appropriate approach ultimately depends on the task at hand [18,14]. Ultimately, the goal of market definition is not to identify an objective reality based on the "right" approach but rather to define markets so as to be able to usefully explain economic phenomena [18].

3. Methodology

We develop a PV market definition approach based on the spatial distribution of installers. Our approach is closest in spirit to the enactment and strategic market definitions [28,13,18], but novel in its application of spatial firm activity data to infer price interdependence. Our primary assumptions are that installer prices are interdependent within some geographic area and that the spatial distribution of installers provides evidence of this price interdependence. We first justify these assumptions.

3.1. Spatial distribution as evidence of price interdependence

The PV transaction process can be modeled as a competitive bidding process where one or more installers submit bids to a prospective customer. Assuming that installers bid strategically, bid prices are constrained by rival bid behavior [30–36]. For any given customer, installers do not know which or how many rivals will also submit bids. Installer bid behavior is therefore constrained by *potential* rather than actual rivals. Our point of departure is that PV installers observe some set of potential rivals within a geographic area and base bids on this group of potential rivals.

Let $\beta(\cdot)$ denote an optimal bidding strategy [37]. For a customer in area i, a strategic bidder's optimal price can be modeled:

$$p_i^* = c + \beta(\aleph_i, v_i, d_i) \tag{1}$$

where c denotes an installation cost, $\aleph_i$ denotes the set of potential rivals in area i, v_i denotes the value of solar in area i (defined further in the following paragraph), and d_i denotes idiosyncratic customer preferences in area i. The variable $\aleph_i$ captures all elements of the price constraints that installers in area i exert on one another, including any disproportionate market power held by any given installer.

The value of solar refers to the financial benefits that customers derive from solar adoption, including utility bill savings and the sum of all incentives received. Higher values of solar generally reduce customer demand elasticity, possibly allowing installers to bid up prices through Eq. (1) [8,9]. The value of solar tends to be spatially auto-correlated due to electricity rates and incentives set at the utility or state level. In other words, the influence of v_i in an area i tends to be close to the influence of v_j in an area j that is geographically close to i.

The idiosyncratic customer demand variable (d_i) allows for variation in customer valuation that may or may not be spatially auto-correlated. For instance, customers in one area i may exhibit similar environmental preferences on average as customers in a geographically proximate area j, even if individual preferences within these areas vary.

Consider two geographically proximate areas j and k where $v_j \approx v_k$ and $d_j \approx d_k$ due to their geographic proximity. If the sets of active installers are similar in both j and k, it follows from (1) that prices in the two areas are interdependent (temporally correlated):

$$\aleph_j \approx \aleph_k \rightarrow p_j^* \propto p_k^* \tag{2}$$

However if the sets of installers in j and k are dissimilar, it follows that prices in the two areas are independent (uncorrelated):

$$\aleph_j \not\approx \aleph_k \rightarrow p_j^* \perp p_k^* \tag{3}$$

Eq. (2) establishes that a shared installer set is a sufficient condition for price interdependence (correlation) between two geographically proximate areas with correlated value of solar and customer characteristics. A shared installer set is a necessary condition for price interdependence when the assumptions on v_i and d_i are relaxed such that these values may vary between geographically proximate areas. For instance, two adjacent areas at a state border may have significantly different values of solar depending on state-level incentives, despite their geographic proximity. In this case, price *levels* may vary between two geographically proximate areas due to underlying differences in