From Airbnb to Solar: Toward A Transaction Cost Model of a Retail Electricity Distribution Platform

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Abstract: Digital technologies have reduced transaction costs and led to platform business models and the sharing economy. Platform business models are increasingly part of policy debates in electricity distribution and retail due to the proliferation of digital and distributed energy resource (DER) technologies, such as residential rooftop solar. What are the implications of falling transaction costs and platform business models in electricity distribution and retail, and in the burgeoning markets for DERs? Our core insight is that excess capacity is variable, and varies inversely with transaction costs. Digital platform business models enable asset owners to rent out this excess capacity. Here we propose a two-stage transaction cost model to represent the effects of transaction cost-reducing innovation on two aspects of such transactions: gains from trade in sharing, and the margin that divides renters from owners. We analyze the equilibrium comparative statics of the model to derive observable predictions, and find that the rental market option makes the opportunity cost of excess capacity salient. As peer-to-peer transactions in energy capacity become more feasible, our results suggest that ownership of DER capacity will be driven less by one's expected intensity of use and more by relative price concerns and subjective preferences for energy self-sufficiency or environmental attributes.

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1 Introduction

Digitization has transformed the 21st century economy. One manifestation of this transformation has been the emergence of the platform economy, seen in online commerce from Amazon to Zillow. The 15 largest publicly-traded platform firms globally already have $2.6 billion in market capitalization (Accenture, 2016), and the fastest-growing firms globally have platform business models (Parker *et al.* (2016), p. 3). Continued improvements in cloud computing, the Internet of Things, and mobile devices enable the extension of platforms into increasing numbers of markets and the creation of new markets.

A subset of the platform economy, the sharing economy, involves consumers giving each other access to the underutilized assets that they own, often in exchange for payment (Horton & Zeckhauser (2016), Frenken & Schor (2017), Frenken *et al.* (2015)). Ride sharing (Lyft, Uber) and accommodation sharing (AirBnB) exemplify this platform business model, which involves using digital technology-enabled market platforms to rent out excess capacity in durable assets. Figure 1 shows the number of individuals in the United States ages 18 and over who have used a community-based online service that coordinates peer-to-peer paid access to property, goods and services, in total and as a percentage of the U.S. population.

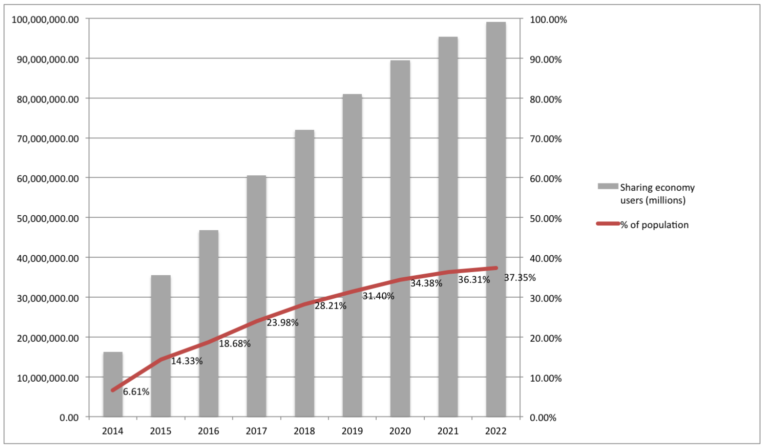

Figure 1: Size and Growth of the Sharing Economy (Source: eMarketer)

Digitization enables these platform business models to emerge because digital technologies reduce transaction costs.

In his 1937 *Economica* paper, R.H. Coase famously asked a difficult question: if markets and prices are so effective for value creation, why do firms exist? His answer was "transaction costs," meaning that using the price system and contracts was expensive. Firms organize production lines as small, self-contained "command economies"; each firm expands or shrinks as variations in transaction costs move the margin at which the last transaction organized internally costs as much as the next transaction organized through markets and prices , or it can buy the input or service in the market, sometimes quite quickly, as innovations in informing, transacting, and enforcing agreements emerge (Williamson (1981), Klein (2005), Poppo & Zenger (1998), Alston & Gillespie (1989)).

The platform economy operates on a nearly identical logic, but on a different margin. Instead of "make or buy", the relevant choice is "rent or own". Many durable assets, ranging from clothing to kitchen equipment, and from lawn mowers to electricity generation facilities, sit idle for some portion of their useful lives. Digital platform markets make excess capacity economically relevant by increasing the opportunity cost of idleness. Each unused minute involves both storage costs and the opportunity cost rate of return that the durable asset's owner could be earning on excess capacity.

There has been surprisingly little price-theoretic analysis of the value proposition that has engendered such growth for Uber and other platform companies: the effective opportunity cost of excess capacity varies inversely with the transactions costs of sharing that capacity.[1] One does not think of the cost of unused capacity of idle durables unless there is some way of selling or renting out that unused capacity. Consequently, in this paper we present an explicitly transaction costs-based model of the platform economy. Digital technologies can be platforms for transaction cost reduction, enabling transactions that

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[1] The paper that most resembles ours, Horton & Zeckhauser (2016), is a notable exception.

produce only a small surplus to be negotiated and executed.

Digital platforms and peer-to-peer rental markets now abound in the economy, and in the electricity industry these technological and organizational changes are coinciding with another important technological change – the development of distributed energy resource (DER) technologies. DERs are small-scale assets that can generate or store electricity; they can be used by their owners for self-consumption, can be aggregated into a self-contained network called a microgrid, and can be used in aggregate to provide distribution grid stability and other grid services. In the presence of an open retail market, they can also be used to sell energy to others in the distribution network in which they are interconnected. This last use is the subject of current policy discussions (in, for example, the Illinois Commerce Commission's NextGrid "utility of the future" study), and is an example of the application of digital platforms and peer-to-peer rental markets for excess capacity in durable assets. Our analysis focuses on this application.

Examples of DERs that a residential consumer might own are rooftop solar photovoltaic (PV) panels, an electric vehicle or plug-in hybrid vehicle, and a battery connected to the solar array to store energy generated beyond current consumption. Technological change, coupled with polices aimed at increasing the share of renewable energy in the fuel portfolio (e.g., Abdmouleh *et al.* (2015)) have contributed to residential DER growth over the past decade, particularly in solar, and particularly in states with high solar insolation. DERs may also satisfy a range of other dimensions of consumer preferences other than price — preferences for energy consumption that is renewable (Dagher *et al.* , 2017), that is local, or that enriches bonds within a community.[2] That fact, combined with the dramatic decentralizing forces of digitization and the ability to provide services at smaller scales, makes economies of scale and scope less of a factor in determining firm structure and industry structure than they were a century ago.

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[2] One example of a community-focused transactive energy microgrid that prioritizes user engagement is the Brooklyn microgrid project; see Mengelkamp *et al.* (2018) and Meeuw *et al.* (2018).

Between 2010 and 2014 US solar capacity increased by more than 430 percent, including strong growth in residential rooftop solar. In 2016 residential solar generated almost 20 percent of the solar energy generated in the US, with California, New Jersey, Arizona, and New York as the largest residential generating states (EIA, 2017). Electric vehicles, which provide both transportation and energy storage, had sales growth of 37 percent in 2016 and have grown at a 32 percent average annual rate since 2011 (Rapier, 2017). Digital home energy management systems are developing as DER adoption and consumer awareness grow and tech companies learn what consumers want (Fehrenbacher, 2017). These end-use technologies, combined with digital automation within the distribution grid, now make transactive energy feasible – using markets and automation to coordinate energy generation and use in a decentralized system.

Digital technologies reduce transaction costs in a DER-rich environment in many ways: facilitating interconnection and automation of devices, including distributed solar, into the existing distribution grid; making it possible to have a more modular network architecture, which has implications for firm structure and industry structure; and making more decentralized exchange possible, which creates the possibility of and the value propositions in digital energy market platforms. These phenomena lead to the two research questions in this paper: how do falling transaction costs and available digital platform markets affect asset ownership and rental of excess capacity, and what do these effects imply in the case of residential DERs?

Our analysis creates a model of a scenario with residential consumers, some owning rooftop solar photovoltaic systems, participating in a retail electricity market once transaction costs are low enough for that market to emerge.[3] The DER owners can set prices at which they are willing to sell energy and prices at which they are willing to buy energy from the market when their DER is not generating enough to power their uses in

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[3] Rather than imagining the consumer doing all of the search and information gathering and maintenance, think of this market as a retail market in which consumers purchase energy management services from retail energy service providers, and those services include facilitating and managing their market participation – an example of how falling transaction costs lead to emergence of new markets, products, and services.

the home. Their home energy management system submits those bids and offers to the market, autonomously changing the settings on the household's devices in response to the market-clearing price in that period. At times when the DER generates more energy than the owner is consuming, there is excess capacity that can be rented to others, in the form of selling them the excess generation. If this market operates as a platform it connects DER owners wishing to sell energy with others who wish to buy. A retail electric platform can use digital technology to decrease transaction costs and enable DER owners to rent their excess capacity. Availability of this opportunity to monetize excess capacity may induce more homeowners to buy DERs, or to install more capacity, yielding both lower greenhouse gases and a more resilient distribution system.

Importantly, this value proposition is precisely the same as that seen in other platform companies. Ride sharing platforms, for example, give vehicle owners an opportunity to monetize excess capacity in an underutilized asset they own – seat space in their cars – while giving others an opportunity to get rides. Ride sharing platforms change the vehicle purchase calculus, at the margin affecting the decision of when to buy a new car, how nice a new car to buy, and how many hours to spend on the platform and available to give rides.

Here we propose a transaction cost model that categorizes the transactions cost impediments to otherwise mutually beneficial sharing of excess capacity into three dimensions:

1. *Triangulation:* information about identity and location, and agreeing on terms, including price;
2. *Transfer:* a way of transferring payment and the good that is immediate and as invisible as possible;
3. *Trust:* a way of outsourcing assurance of honesty, and performance of the terms of the contract.

Table 1 presents a taxonomy of transaction costs and the value of an asset's excess capacity that identifies the types of assets that are amenable to contracting and exchange using a digital platform. This taxonomy captures some of the different "shareability" properties of goods like toothbrushes (neither desirable nor feasible to rent), laundry machines (desirable and easy to rent commercially), and rooms (potentially desirable and feasible).

	Low TC	High reducible TC	High fixed TC
Low value	Consumed non-durable	Consumed non-durable	Not a commodity
Moderate value	Already availble	Marginally profitable	Not a commodity
High value	Already available	**Best value proposition**	Personal items

Table 1. Transaction cost (TC) and value of excess capacity platform potential (Source: Munger (2018))

Reductions in transaction costs can have unexpected results. One of the most important innovations of the Chicago Mercantile Exchange, for example, was to break the link between a particular farmer or shipper and the lot of wheat or hog bellies being transacted. Once the products on the Exchange became "commodities," they could transact independently of who owned them. Commodification simplifies the transaction, allowing the storage of huge homogenous bins of grain or meat, so long as quality can be distinguished by grading (Cronon, 1992). The Exchange bought the commodities, and then sold the commodities, as a broker rather than requiring that individual buyers find individual sellers.

The platforms in the new economy play a similar role, but with some important differences. The product being commodified, as Table 1 illustrates, is excess capacity. A car, a tool, storage space, or an apartment, if unused, has excess capacity. But it is not possible to commodify that excess capacity unless the transaction cost of doing so can be reduced. The platform acts as a broker, connecting individual buyers and individual sellers. It's not quite like grain, of course, since the platform does not take possession of the newly commodified product or service. Nonetheless, the analogy is very close, as the success of one of the Silicon Valley "unicorns" demonstrates – AirBnB.

If I have an apartment on the Lower East Side in Manhattan, and you are visitor to the city who needs a place to stay, we might pass each other at the airport. The founders of AirBnB recognized that there was a mutually beneficial transaction that could take place, if the transaction costs could be reduced. From the buyer's perspective, the "commodity" is a place to stay. Each particular apartment in New York, or Paris, or for that matter Springfield, Missouri, has unique features. How can these idiosyncratic places to stay be commodified? The answer is grading, just as it was for wheat or hog bellies. Hog bellies can be US#1, US#2, US#3, Medium, or Cull grades.

Apartments on AirBnb are "graded" also, with 1 through 5 stars, and written descriptions. There are no health or meat inspectors employed by the platform, as in the case of the Merc. Rather, AirBnb uses peer-to-peer grading, asking ranking of its customers by the customers who have dealt with them. The result is that AirBnb is by far the largest provider of room/nights for travelers, much bigger than any other single hotel chain, without owning any real estate.[4] Once the platform commodifies the product or service, transactions can take place between strangers, who yet can trust that the transaction is reliable and safe.

AirBnB's commodification of such a complicated, idiosyncratically variable "product" as physical space has an obvious extension to energy markets. Like wheat or hog bellies, all that is necessary is a reliable metric for measuring quantities, a mechanism for ensuring trust among strangers, and a physical delivery system (although unlike other commodities, in the case of electricity the emphasis on maintaining network reliability and resilience is higher due to the real-time balancing nature of the network). An individual who has temporary excess capacity can sell to another individual, who happens in that time period to be a net user of electricity, even though the buyer and seller have not met and in fact do not know each others' identities. Further, and perhaps most surprisingly, their identities are not fixed: the morning's buyer might be the afternoon's seller, as conditions and needs change over the course of a day. For this reason DERs belong in the "best value proposi-

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[4] Horton & Zeckhauser (2016) summarize the literature on the use of reputation mechanisms in online platforms.

tion" category in Table 1.

Platforms that reduce the transaction costs of such market participants enable peer-to-peer exchanges that are immediate and dynamic. Until now, we have had no means of pricing the foregone use of excess capacity. But the platform economy simultaneously prices the opportunity cost and provides an outlet by which even very temporary excess capacity can be bought and sold with very little friction.

In this paper we propose a two-stage model to represent the effects of transaction cost-reducing innovation on two aspects of such transactions: gains from trade in sharing, and the margin that divides renters from owners. In our model the digitally-induced reduction in transaction costs enables a rental market for excess capacity to emerge, generating gains from trade. The ability to monetize excess capacity may also induce some renters to become owners of the asset.

We begin our analysis by relating our model to literatures on the economics of residential solar, transaction cost economics, and platforms. We then present a model of individual agents in a market for an asset and derive the results of a reduction in transaction costs for (1) creation of a new rental market and (2) how the reduction in transaction costs affects ownership choice in the asset market. We conclude by discussing how this model serves as a framework for establishing some market design principles for a distribution grid services platform company.

2 Relation to the Literature

In this paper we address two specific research questions:

- What are the effects on asset ownership when transaction cost reductions make a decentralized rental market possible?
- How do these general effects manifest themselves in the case of residential digital home energy management and distributed energy resources (DERs)?

The analysis in this paper draws on, and contributes to, three literatures: empirical residential solar energy economics, transaction cost economics, and the economics of platforms and the sharing economy.

2.1 The Economics of Residential Solar Adoption

In 2017 distributed solar accounted for 49 percent of new installed generation capacity in the U.S. (SEIA, 2017). The National Renewable Energy Laboratory estimates that the cost per watt of installed residential solar has fallen 61 percent since 2010 (Fu *et al.* (2017), p. vi).

The growth of digitally-interconnected small-scale DERs is a developing empirical pattern with both policy relevance and important underlying economic theory to understand the pattern. Digital technologies facilitate interconnection of distributed residential solar into the existing distribution grid, in addition to their other effects. The literature analyzing solar power informs our understanding of why DER innovations are expanding the way they are, and the roles of digital technologies and market platforms in future expansion.

Our analysis contributes to the large and growing literature on residential solar energy by exploring the role that digital market platforms play in inducing homeowner purchases of solar energy assets (in other words, in inducing residential solar adoption). Residential solar adoption decisions occur within a public policy context focused on decarbonization (Geels *et al.* , 2017). This policy takes the form of net metering regulations, enabling a residential solar owner to supply excess generation to the distribution utility.[5] That quantity offsets some or all of their grid-supplied consumption, usually at the regulated retail rate. While this policy is intended to induce solar adoption, it contains additional indirect subsidies because the solar owner does not pay the distribution wires charge despite using the distribution grid to "sell back" excess generation. Distribution utilities criticize this implicit subsidy, as do those who argue that net metering subsidizes wealthy homeowners

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[5] Net metering regulations have existed for several decades, since before digital meters existed. When implemented, the only technological way to "pay" solar owners for their excess generation was to "spin the meter backward".

and thus has negative distributional consequences. The digital retail market platform we model here provides an alternative to net metering.

Four categories comprise much of the empirical residential solar energy economics literature: effects of regulated retail rates, net metering, and tax credits on solar adoption, the distributional effects of policies to induce solar adoption, economic analyses of the potential for self-consumption, and behavioral analyses of residential solar adoption. Surveys of the literature on the factors affecting residential solar adoption and diffusion include Timilsina *et al.* (2012) and Lang *et al.* (2015). Kwan (2012) examined the factors influencing the spatial distribution of residential solar adoption at the U.S. zip code level, including environmental, social, economic, and political factors. Kwan's results suggest that the principal factors influencing residential solar adoption are solar insolation, the price of grid-provided electricity, and the financial incentives available to homeowners. These factors map into the broad categories in the literature, and into the opportunity cost and price parameters in our model.

Regulated electric rates and net metering subsidies affect the consumer's opportunity cost when considering solar adoption. Eid *et al.* (2014) summarize the economic issues in net metering and identify the implicit subsidies embedded in them and the potential distributional impacts across residential customers with different incomes. They recommend a regulated tariff that more explicitly targets incentives for solar adoption as an alternative to regulatory net metering. Comello & Reichelstein (2017) construct a model of net metering's pricing effects and implicit subsidies, and use that model to analyze net metering data from California, Nevada, and Hawaii. They find that the estimated levelized cost of electricity (LCOE) acts as a benchmark tipping point, and that net metering payments below the LCOE are associated with sharp reductions in solar investment and adoption.[6]

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[6] The levelized cost of electricity is the net present value of the per-unit lifetime cost of electricity generated using a particular generating asset and technology. It is an economic-engineering estimate that approximates the average price the generating asset must receive in a market to break even over its lifetime. By providing a cost estimate on a per-unit of output basis, it allows comparison across different generating technologies with different lifespans and average utilization rates.

The economic viability of self-consumption is another aspect of a consumer's opportunity cost. Hagerman *et al.* (2016) explore "socket parity", the cost at which solar self-supply is equivalent to the retail electricity rate. They provide a spatial analysis at the U.S. county level, and construct estimates of the break-even electricity price for solar adoption; they find that financing and installation costs are the largest determinants of socket parity (controlling for solar insolation). Their estimates suggest that as of 2016 in the U.S., only Hawaii had achieved subsidy-free socket parity, while six other states achieve socket parity with their existing subsidy programs (but not taking into account the welfare losses associated with funding the subsidy).

Mitscher & Rüther (2012) analyze financial performance of residential solar installations in five Brazilian cities using three different interest rate scenarios. At the time, only the subsidized scenario yielded costs that were economically competitive with existing grid-supplied electricity prices, controlling for solar insolation. As Hagerman *et al.* (2016) found, Mitscher and Ruther found high capital costs a barrier to residential solar adoption. Lang *et al.* (2016) examine residential solar self-consumption across four different building types in Germany, Switzerland, and Austria, where the primary economic drivers of solar adoption were grid-supplied electricity prices and the share of the building's demand that could be met with self-generation. Camilo *et al.* (2017) analyze data on solar adoption, self-consumption, and storage in Portugal, finding that self-consumption is economically competitive even without storage, but that storage is still too expensive despite recent cost reductions.

Borenstein (2017) analyzes residential data from California with three findings relevant to our work. He examines the role of regulated tariff rates, net metering, and incentive policies in solar investment and consumption. First, the structure of the regulated residential monthly tariff induced solar investment because of its steep tiers — as monthly consumption increases, the per-unit energy portion of the rate increases steeply. Second, he finds that indirect subsidies to solar are embedded in net metering regulations, and that they do play a role in inducing consumers to invest in solar assets. Finally, homeowners are eligible for a 30 percent federal tax credit on solar investments, and the financial incentives that homeowners acted on arose from both the tiered tariff and the tax credit in almost equal amounts. In terms of our model, Borenstein's results suggest that the pricing and other financial implications of the outside option facing the consumers affects their decisions.[7]

2.2 Transaction Cost Economics: Firms, Industries, Markets

Transaction cost economics (TCE) analyzes how transaction costs affect the institutional structure of the economy. In the case of DERs and digital market platforms, transaction cost changes manifest themselves in several ways. Digital interfaces enable interconnection of DERs to the existing distribution grid and automation of their physical and economic participation in networks and markets. Open (i.e., non-proprietary) technology interoperability standards that enable this interconnection and automation create a transactive energy system.[8]

We use TCE to understand these implications at three levels — firm structure, industry structure, and market structure, and ultimately the nature of the firm (Kiesling, 2016). The traditional transaction cost economics literature has examined changes in production and supply chain decisions, and has explored how long-term contracts can enable transactions between firms as alternatives to vertical integration. This work tends to focus on vertical integration and on supply-side questions. Vertical integration is a form of organizational structure in which multiple steps in a production supply chain occur under common ownership, and the decision-making rights over those steps are integrated. In contrast, a market transaction occurs through arm's-length contracts in which the parties have separate decision-making rights. Lafontaine & Slade (2007) provide a valuable survey of the

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[7] Borenstein also finds that the income distribution of solar owners was heavily skewed toward wealthier homeowners, with that skew decreasing over time. These income effects are beyond the scope of our current analysis and are the focus of ongoing research.

[8] The GridWise Olympic Peninsula Testbed Demonstration Project was the first field experiment testing the price-response and automation aspects of transactive energy; see Chassin & Kiesling (2008) and Hammerstrom *et al.* (2008).

TCE literature on vertical integration, as does Joskow (2005).[9]

The "make or buy" literature examines the role of transaction costs in influencing a firm's decision of whether to contract with an outside party to purchase an input into its production or to produce it within the firm (Klein, 2005). A strong empirical finding in TCE is that the make or buy decision is more likely to lead to vertical integration when the assets used in the supply chain are more relationship-specific (Lafontaine & Slade (2007), p. 648). For example, if an ice cream shop uses a specific type of cone that no other ice cream shop uses, and producing that cone requires a specific type of machine, those two transactions (making cones to sell to the retailer, and selling ice cream cones to customers) are more likely to be vertically integrated into a single firm rather than the shop procuring cones from an independent manufacturer through a market contract. Asset specificity can create hold-up problems or other *ex post* opportunistic behavior in contracting, which gives the parties an incentive to integrate, to economize on transaction costs and mitigate hold-up. As Lafontaine and Slade observe, "In sum, when the problems that are associated with transaction costs are important, transaction cost models suggest that firms will choose governance structures — including vertical integration or separation — to reduce the likelihood and cost of haggling and exploitation." (pp. 649-650) Consider the asset specificity in the electricity supply chain, which has traditionally had highly specific assets that must be combined in particular ways to generate, transport, deliver, and sell electricity to consumers. This specificity provides one economic justification for its historic vertical integration, and as technologies change, that specificity is also likely to change.

The economics of the make or buy decision relates directly to our main question in this paper, although the context differs. Here we model people as having utility functions over primary consumption goods (which we do not model explicitly), and electricity consumption is an important input into the primary goods and services an individual consumes.

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[9] The extensive literature following Klein *et al.* (1978) examines how firms use long-term market contracts as an organizational alternative to vertical integration, rather than the binary distinction between markets and hierarchy. Our model suppresses opportunities for long-term contracts and focuses solely on how falling transaction costs enables markets to emerge, so we abstract from this point.

This framework underlies our model's specification, in which each agent has a bliss point for electricity consumption.

Digital technologies reduce transaction costs, making it more economical to engage in transactions through contracts and markets that used to occur within vertically-integrated firms. In electricity, the generation, transport, and retail sale of electricity used to be vertically integrated into a single firm; transaction cost-reducing digital technologies can shift the retail transactional boundary of firms so that vertical integration is no longer the economical way to organize retail transactions.[10] Both TCE theory and empirical analysis in other industries predict that digitization and DER penetration should lead to unbundling of retail transactions from previously vertically-integrated firms.

The effects of transaction costs on industry structure follow naturally. Determined by regulation over a century ago, the industry structure of electric utilities has been vertically-integrated monopoly due to large economies of scale and scope that created a natural monopoly cost structure. As digital technologies reduce transaction costs and make market exchange more economical, the availability of DER-generated energy and the unbundling of retail transactions can enable new markets to emerge and can make the retail electricity industry more rivalrous and competitive, while the distribution utility still owns and operates the wires network (which retains an economies of scale cost structure) as a regulated monopoly.

Modularity is another way that digital technologies can affect firm structure and industry structure (Langlois (2002), Langlois *et al.* (1992)). Russell (2012) calls modularity an "ordering concept" for organizing and using information, and defines a modular system as "... smaller parts (modules) that fit together within a predefined system architecture." (p. 257) Modular technology design means that standardized elements fit together, and when combined they form a larger system. Modularity in technology design implements

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[10] This transactional boundary shift occurred in the liberalization of wholesale energy markets in the early 1990s, brought on by innovation in natural gas generation technologies that reduced economies of scale in generation.

the Simon (1965) argument that "decomposable" systems and standardization can attenuate some aspects of complexity by removing some dimensions of interdependency. From a TCE perspective, modular design provides a way to reduce transaction costs by enabling standard interfaces, interconnections, and interactions.

Modularity entails breaking up an otherwise complex system (in the technical sense of possessing complex interdependencies) into discrete components, and having the components interact in an additively separable fashion. The function that most users would associate with modularity is plug-and-play functionality: the user can unplug one printer or other peripheral and plug in another, with no other changes to the system, but the system immediately adapts to the new peripheral. Modularity increases the ease of interconnection within the system.

Digital and DER technologies create a different pattern of asset specificity than the traditional one in the vertically-integrated electricity industry (Joskow, 1988), asset specificity involved using fairly homogeneous generation, wires, transformers, and meters in a very specific combination to produce a very specific product and deliver it in a very specific way to consumers.

Digital and DER technologies not only reduce transaction costs – by making a retail electricity platform model feasible and potentially economical, they also change the nature of asset specificity in the industry. Residential DER owners can use their assets for self-consumption and/or can sell from it in a retail market if one exists. Distributed asset integration and interconnection using open, interoperable technology standards mean that that resulting network is modular in a way the traditional supply chain was not. Modularity is a change in asset specificity. Asset specificity is about bilateral dependency and it makes sense that new distribution technology, as an increase in modularity (in Langlois's sense), reduces this dependency as it lowers transaction costs. In general, more modular technologies have less relationship specificity.

In addition to modularity and changing asset specificity, this combination of digital and DER innovations is also having a more profound effect on industry structure than the production-focused analyses of the make or buy and vertical integration literatures explore. The make or buy literature focuses on production, and on how changes in transaction costs affect patterns of production by changing firm structure and industry structure. The changes brought about by digital/DER energy are different in nature because they enable consumers to produce, both for self-consumption and, if transaction costs are low enough that markets emerge, for sales to others. These changes in transaction costs are crossing the producer/consumer distinction, thus creating a new category of "prosumers". This broader phenomenon in the entire digital economy (blogs, YouTube videos, podcasts) manifests in electricity as individual consumers being able to self-consume and also sell energy to others from their DER assets.

Residential DERs differ substantively from the traditional make or buy production literature in that the economic actors in the model are consumers, not producers, and that technological change enables them to change their roles in the market. Technological change in DERs enables them to become prosumers, and digital innovations make market platforms possible that reduce transaction costs and enable them to trade with each other. The availability of residential DERs creates a make or buy choice for consumers between self-consumption and grid-supplied consumption, and transaction costs will affect that choice. Rather than modeling that decision explicitly, though, our analysis focuses on how the ability to buy and sell the energy generated from residential solar affects the choice between self-consumption and grid-purchased consumption.

TCE also yields insights on how transaction costs influence market structure. Digital technologies that reduce transaction costs make exchange more economical, and if parties can benefit from those exchanges, they will create new markets. This insight connects directly to the digital platform literature, discussed below.

One aspect of market structure specific to retail electricity is that delivery of energy from one person to another (i.e., contract fulfillment) requires physical delivery via the distribution grid. The distribution grid's architecture was designed over a century ago for one-way current flow and delivery from centralized generators to distributed consumers. Now that more distributed resources will increasingly characterize the network, and some actors in the network will be prosumers rather than just producers or consumers, the grid architecture has to change to enable two-way current flow and the physical delivery to fulfill the contracts and market transactions in which these prosumers will engage. These investments in the distribution grid are transaction costs, but if the potential value creation from enabling decentralized exchange exceeds those investments then they are net benefits.

2.3 Platform Economics and the Sharing Economy

Digital technologies create the potential for firms in a variety of industries to operate as a platform, analogous to a stand-alone "app" for use by consumers and producers. Baldwin *et al.* (2009) define a platform as a set of stable components that supports variety and evolvability in a system by constraining the linkages among the other components (p. 19), and Parker *et al.* (2016) model platforms as "a new business model that uses technology to connect people, organizations, and resources in an interactive ecosystem in which amazing amounts of value can be created and exchanged" (p. 3). As a business model, a platform architecture creates value by facilitating exchange.[11]

Following Gawer (2014), we synthesize three complementary definitions of a platform in the distribution platform model:

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[11] For a more thorough discussion and analysis of platforms in general, see Parker *et al.* (2016) and Munger (2018). Kiesling (2018) examines the epistemological implications of platforms, arguing that the modular and decentralized nature of digital platform markets makes them epistemic frameworks for decentralized coordination. Prices and markets make more coordination possible than would happen in their absence, and platforms make more and different types of markets possible, deepening and broadening the scope of human activity over which we can achieve decentralized coordination and inducing experimentation and innovation.

- *Technological*: A technology platform is a common core of technologies within a modular architecture, with variable technology elements around the periphery that interoperate with the core technologies and architectures.
- *Economic*: An economic platform is a means for facilitating and coordinating mutually-beneficial exchange or transactions in a two-sided or multi-sided market (Rochet & Tirole (2003), Parker & Van Alstyne (2005), Rysman (2009)).
- *Organizational*: A platform can provide institutions that enable the coordination of the actions and plans of agents (be they individuals or firms) within a technology platform for mutual economic benefit, and it can have different organizational form in different industries and contexts (Gawer & Henderson, 2007).

Other theoretical papers to address the platform economics of the sharing economy include Benjaafar et al. (2015) and Einav et al. (2016), with Fradkin and Farronato (2016) focusing on Airbnb specifically. Hagiu & Wright (2015) model the choice between a multi-sided platform and vertical integration and apply their results to study the organizational choice of professional service firms.

Much of the literature on peer-to-peer markets focuses on matching, building on previous work in online markets (see, e.g., research discussed in Azevedo & Weyl (2016)). One relevant insight from this literature is that in situations with many-to-many matching, the combination of algorithms and price signals leads to higher capacity utilization and better use of resources.

The paper most similar in approach to our own, and from which we borrow much of our theoretical structure, is Horton & Zeckhauser (2016). Horton and Zeckhauser are interested in modeling consequences of introducing a novel market in peer-to-peer asset rental explicitly and rigorously. They model the choice of whether to rent or to own an asset, and they consider the market for asset ownership and asset rental as separate but interdependent markets both shaped by preferences, technology, and transactions costs. Their paper uses a model of preferences in which each consumer has an ideal usage level of a given asset, and must choose whether or not to purchase this asset based upon their own projected future usage levels. The authors are interested in the question of how ownership and usage patterns change from this status quo given an added opportunity to rent out one's own asset to other potential users, and they present comparative statics results on how lowering the costs of renting out an asset in this market influences the decisions of prospective buyers in the ownership market.

Our theoretical model differs from theirs in introducing an explicit outside option in the form of grid-purchased electricity. We also explicitly model an additional source of heterogeneity among consumers, namely the degree of substitutability between self-consumed and grid-purchased electricity. During our discussion of our own results, we will highlight similarities and differences from the results derived by Horton and Zeckhauser in their paper, and discuss the drivers of these similarities and differences.

Our motivation is understanding the implication of digital technologies, distributed energy resources, and platform business models in the retail electricity industry. The model we develop here suggests a framework for an electricity distribution platform business model, although we do not construct that model here. Open, competitive retail markets with low entry barriers to producers and consumers (and "prosumers") at a range of scales create opportunities for DERs to generate electricity and provide other services outside of a regulated model, and for other customers to benefit economically and environmentally from such innovation. The resulting distribution platform business model thus has the distribution utility as a grid services company, with competing retailers operating around the distribution edge as well as "prosumers" with transactive distributed generation that enables them to buy and sell in retail markets.

Parag & Sovacool (2016) provide a survey of the market design issues in "the prosumer era" in electricity. Kalathil *et al.* (2016) model three categories of sharing in electric systems: sharing excess energy generated from rooftop solar PV installations, sharing of demand flexibility through dispatchable reductions in demand, and sharing energy storage capacity. Our model complements theirs by focusing on sharing in this same sense, exploring the choice of whether or not to buy an asset when that asset will have excess capacity and how a rental market for that asset affects the ownership decision. In that sense our model most directly relates to the sharing of excess capacity in a rooftop solar PV installation, but it also applies to demand flexibility and energy storage to the extent that we can think of those categories as involving an asset purchase, a degree of excess capacity in the asset, and the availability of a rental market for the asset arising from transactions-cost reducing digital innovation. Tabors *et al.* (2017) also propose a digital platform market design taking into account locational pricing to account for the spatial characteristics and effects of DERs in distribution networks. Morstyn *et al.* (2018) propose a peer-to-peer market design in which prosumers self-organize into "federated" virtual power plants.

Small-scale DERs are becoming more economical, and digital technologies are reducing transaction costs in ways that change modularity (technological and organizational) and asset specificity. These changes can lead to changes in firm structure and industry structure. By making digital market platforms possible, they may also change market structure and enable DER-owning prosumers to rent out their excess asset capacity by exchanging energy on decentralized market platforms.

3 A Simple Model of Transactions Costs, Rental, and Ownership

Using these frameworks and focusing on the application to residential DERs (particularly solar), we construct a formal model to capture the key drivers of trade in excess asset capacity. Although the model is a transaction cost model of a generic platform, our application is a distributed energy asset such as residential rooftop solar power, so we refer to DER assets throughout.

3.1 Asset Ownership and Use Without a Rental Market

In a world with sufficiently high transaction costs, no market for excess capacity rental exists. Consider an economy of n agents and a DER asset with a use capacity normalized to 1. This asset, if purchased at a price p_a, enables an agent to generate energy up to the asset's capacity limit of 1; otherwise the agent's outside option is to purchase energy from a grid-based retail supplier (hereafter called grid consumption). Each agent has a choice of how much capacity to use, given their outside option. x represents the choice of how much capacity to use, and y represents grid consumption at a price p_g; $x + y$ thus represents total electricity usage.

The model's simplified structure means that p_g is not simply price per kilowatt hour, and thus requires some interpretation. The asset's capacity is normalized to 1, so p_g is the price of an amount of grid-sourced electricity equivalent to the per-period production of the asset. Thus p_g represents the price of a solar panel's worth of electricity, but purchased from grid providers. We focus on consumption and trade, so this is not an investment model; therefore we suppress the durable, intertemporal nature of the asset to focus on how a market platform affects ownership and exchange.

Agent i derives utility u_i from an amount of own-electricity usage x, conditional on asset ownership, and an amount y of grid-purchased energy:

$$u_i(x, y) = 2\alpha_i(x + \lambda_i y) - (x + \lambda_i y)^2$$

The functional form of the utility function follows Horton & Zeckhauser's model of peer-to peer asset sharing, modified slightly to allow for an outside option, the purchase of substitute services (y). As in HZ, α is an individualized parameter representing an agent's "ideal" or "bliss point" level of effective electricity use (i.e., the amount of electricity this agent would consume given a zero price). We interpret α in this context as the share of total capacity that the agent would prefer to use; given the quadratic term in the functional form, that share will be less than 1, so every agent, even the one with the most intense use (highest α), will have excess capacity.

We also introduce another individualized preference parameter, λ_i, representing substitutability between x and y, between self-consumed and grid-purchased energy. Individual preferences over such substitution are subjective, varying from person to person, indicating an individual's idiosyncratic tastes for independence from the grid, "greener" consumption, or local/community commerce. The $x + \lambda_i y$ term conveys the amount of effective electricity use from a given combination of self-consumed electricity x and grid-purchased electricity y. Individual agents are characterized by the pair of parameters α_i, λ_i. Our version of the model thus extends HZ by incorporating an outside option and substitutability preferences.

Each agent i faces two stages of decision-making, one in each of two sequential markets: buy the asset at price p_a or not, and then conditional on the first stage decision, how much electricity to use, and how much to buy from a grid provider at price p_g and / or self-consume using the asset. Figure 2 represents the agent's decision of whether to purchase the asset or not, and the four possible outcomes – without the asset the agent consumes grid-purchased energy, and with asset ownership the agent chooses among self-consumption, grid-purchased energy, and a combination of the two.

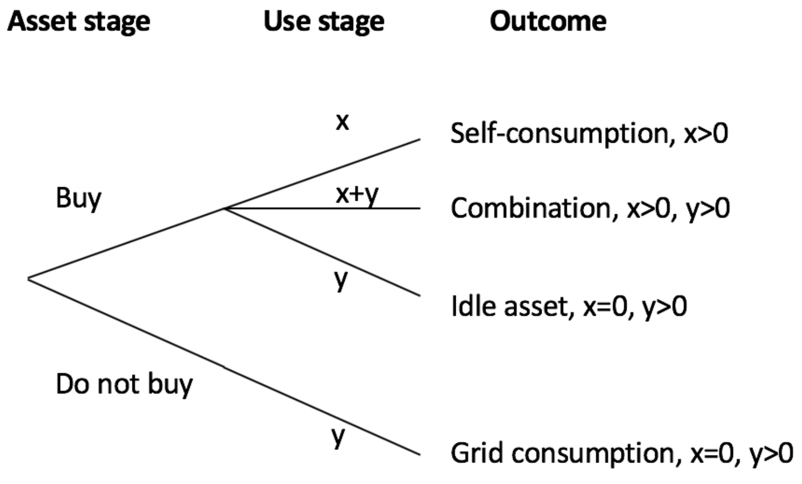

Figure 2: Model's Decision Structure

We solve the model for the two categories of agent choices – asset purchase and no asset purchase – using backwards induction. The no-purchase category is straightforward because the agent does not have the option of self-consumed energy. Given a choice not to buy the asset in the first stage, an agent will always face a binding constraint of $x = 0$; the only available source of energy is grid-purchased energy y.

$$\max_{x,y} u_i(x, y) - p_g y \quad s.t. \quad x = 0$$

or

$$\max_{x,y} 2\alpha_i(x + \lambda_i y) - (x + \lambda_i y)^2 - p_g y \quad s.t. \quad x = 0$$

Thus in equilibrium without asset ownership,

$$x^* = 0 \qquad y^* = \alpha_i - \frac{p_g}{2\lambda_i} \tag{1}$$

Solving for the case where an agent has chosen to purchase the asset reflects their optimization over x and y, given α_i and λ_i. The formulation of the asset owner's problem is:

$$\max_{x,y} u_i(x, y) - p_g y \quad s.t. \quad 0 \leq x \leq 1$$

$$\max_{x,y} 2\alpha_i(x + \lambda_i y) - (x + \lambda_i y)^2 - p_g y \quad s.t. \quad 0 \leq x \leq 1$$

Thus the equilibrium for an asset owner is:

$$x^* = \alpha_i \qquad y^* = 0 \tag{2}$$

If the agent chooses to buy the asset, as long as $\alpha < 1$ an agent can be self-sufficient and meet all of their energy needs through self-consumption. In equilibrium $y^* = 0$ and $x^* = \alpha$. Note that in this case, absent a rental market, an asset owner's optimal consumption level is independent of λ_i, of the subjective substitutability between self-supply and grid-purchased energy. Consumption in this case is entirely a function of the degree to which the agent uses the asset capacity, indicated by higher levels of α.

The next step in solving the model involves using the equilibrium levels of x and y in both categories to establish the determinants of asset ownership. By inserting these optimal choices back into the agent's utility function, we can compare the utility attainable from ownership and from non-ownership in the second stage, and derive the following necessary and sufficient condition for asset purchase in the first stage:

$$\alpha_i \geq \frac{\lambda_i p_a}{p_g} + \frac{p_g}{4\lambda_i} \tag{3}$$

Notice two things about this ownership condition. First, given this framework, both α *and* λ matter jointly for the ownership decision. Moreover, the effect of λ_i on this break-even point is ambiguous – one might expect that, given an α_i, a decrease in λ_i would always increase an agent's willingness to purchase their own electricity-generation capacity, but this is not necessarily true. Second, notice that if $\lambda_i = 1$, for all agents, it has to be the case that for any ownership to happen in equilibrium, $p_a/p_g < 1$ is a necessary condition. In other words, it must be that the price of purchasing the asset is less than the price of an equivalent amount of potential usage (normalized to 1, in this model) from the grid.[12]

3.2 Asset Ownership and Use With a Rental Market

Now, suppose technology-driven transaction cost reductions enable a decentralized rental market to emerge for use of the asset. In the application to residential solar this market enables one agent to sell electricity from his/her solar panels to other agents. This new market introduces the possibility for a non-owner to purchase an amount of energy r from grid-connected asset owners, and for an owner in turn to sell r units of electricity usage, at

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[12] Notice that this normalization to 1 essentially collapses a time dimension; the price p_g should be seen as the price of buying the same amount of energy from the grid as the asset would generate over the course of its entire lifetime of use, turning the energy consumption into a fundamentally static problem. While abstracting from an important aspect of reality, this modeling choice allows us to focus on the decision of whether to buy or own at a single point in time, and then to employ comparative statics for analyzing changes over time in later sections.

a market-determined price p_r.

As in the model without a rental market, we solve via backwards induction, starting from the second-stage problem of how much to purchase *or sell* on the market. Again we start with the non-owner's problem, which now includes the option of buying energy from an asset owner in addition to the grid purchase option. That problem, defined over x, y, and r, in the second stage, is given by

$$\max_{x,y} 2\alpha_i(x + \lambda_i(y + r)) - (x + \lambda_i(y + r))^2 - p_g y - p_r r \quad s.t. \quad x = 0$$

As before, the non-owner agent is constrained to set $x = 0$. Furthermore, for a non-owner we model y and r as perfect substitutes – a non-asset owner doesn't care whether the electricity they are buying is from a firm or from a solar panel owner. In equilibrium, therefore, p_r is precisely equal to p_g. Thus the non-owner's equilibrium choice of grid-purchased electricity $(y + r)$ is exactly the same as before:

$$p_r = p_g, x^* = 0 \qquad (y + r)^* = \alpha_i - \frac{p_g}{2\lambda_i} \tag{4}$$

Because of this indifference between y and r, in equilibrium the decomposition of grid-purchased electricity into y and r is entirely determined by the supply of r in the retail market relative to the total quantity of grid-purchased electricity demanded.

Given this result for non-owners, we now turn to the problem faced by an asset owner in the second stage. Assume that the asset owner is able to sell directly to renters at the price p_r, suppressing for now the questions of energy delivery and grid services. The owner then faces the following problem:[13]

$$\max_{x,y} 2\alpha_i x - x^2 + p_r r \quad s.t. \quad 0 \leq x + r \leq 1$$

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[13] Two notes on notation: we suppress y from the problem since an owner will never choose a positive value of y, given $\alpha > 0$, and we also use r to denote energy sold/solar capacity rented, with a slight abuse of notation

As before, y and r are delineated in units of a solar installation's production of energy because of the normalization of asset capacity to 1. Solving this problem gives us:

$$x^* = \alpha_i - \frac{p_r}{2} \qquad r^* = 1 - \alpha_i + \frac{p_r}{2} \tag{5}$$

Observe that now, the asset owner behaves as if s/he were a renter with a $\lambda_i = 1$. This result reflects one of the main insights from the model: the owner now faces an explicit opportunity cost of energy consumption that was previously suppressed by the lack of an explicit market in excess capacity. The existence of a rental market now induces the owner to take into account the alternative uses of their solar capacity when making consumption decisions.

Again we can compare the maximum utility attainable in the second stage from ownership and non-ownership to derive the following necessary and sufficient conditions for asset purchase:

$$\lambda_i < \frac{p_g}{p_a} \tag{6}$$

This condition has several notable implications. First, notice that α_i drops out entirely from the decision to purchase or not; in other words, how much one plans on using electricity, as a heavy or low intensity user, does not affect one's ownership choice, given the option of renting out one's excess capacity. This relates to the change in behavior noted above: owners now reduce their own usage, and behave *as if* they are facing a rental price. Because of this change in the salience of opportunity cost, intensity of use in and of itself does not matter for asset ownership decisions as it did in the no-rental case. This result is identical to the HZ result on long-run asset ownership – high intensity users are no more or less likely to purchase than low-intensity users (p.16). Unlike HZ, however, our model allows some potential users strictly to prefer purchasing the asset, because we allow for an additional dimension of heterogeneity, namely λ_i.

In contrast to the scenario without a rental market option, the effect of λ on ownership is now unambiguous - a higher λ, meaning a greater substitutability between self-consumed and grid-purchased energy, makes one more likely to purchase the asset. Furthermore, this heterogeneity in λ is the *only* factor driving heterogeneity in asset ownership across potential users. This result yields a particularly concrete prediction of our model: as peer-to-peer transactions in energy capacity become more feasible, we expect ownership of solar capacity to be driven less by one's expected intensity of use and more by relative price concerns and subjective preferences for energy self-sufficiency or environmental attributes.

As an interesting baseline case, consider the case in which λ is uniform across the entire population. In that case, we have a particularly stark, knife edge equilibrium: the only situation in which we have any sharing of excess capacity is when $\frac{p_r}{p_a} = \lambda$. Any price ratio other than this would lead to either no ownership at all or to everyone opting to own at once. In the next subsection, we break down how changes in both prices and preferences change the equilibrium pattern of ownership.

3.3 Comparative Statics Analysis

The key parameters in our model are the two subjective preference parameters, α and λ, as well as the prices faced by consumers in the market for grid-purchased electricity (p_g) and in the market for energy-producing assets (p_a). The key predictions of the model come from the reaction of consumers to two changes: 1) reductions in transactions costs and the corresponding opening of opportunities to trade their own excess capacity, and 2) changes in prices. Consumers' responses to these changes, in turn, take two forms: their choices in the market for energy-generation *assets* and their choices in energy *usage* in the energy market. In terms of the model's structure, consumers' responses are expressed in the asset market and the energy market.

As derived above, the equilibrium conditions for asset ownership in the two scenarios imply different comparative statics for asset ownership. Without a rental market, Equation 3 provides the necessary and sufficient condition for asset ownership:

$$\alpha_i \geq \frac{\lambda_i p_a}{p_g} + \frac{p_g}{4\lambda_i}$$

Defining $\bar{\alpha}$ as the threshold $\alpha \in [0, 1]$ at which consumers are precisely indifferent between owning and not owning, we can directly derive the marginal effects of changes in λ on this threshold:

$$\frac{d\bar{\alpha}}{d\lambda} = \frac{p_a}{p_g} - \frac{p_g}{4\lambda^2}$$

$$\frac{d^2\bar{\alpha}}{d^2\lambda} = \frac{p_g}{2\lambda^3} > 0$$

As the second derivative shows, $\bar{\alpha}$ is convex in λ, indicating the aforementioned ambiguous effect of λ on consumer decision-making in the asset market in the absence of a rental market. For low values of λ, $\bar{\alpha}$ is a decreasing function of λ, while for high λ, $\bar{\alpha}$ is increasing in λ. This nonlinearity gives $\bar{\alpha}$ a parabolic shape. The intuition behind this shape comes from the two terms in the above asset-purchase condition: the first term represents a relative-price effect of lambda on the purchase decision (because λ determines the price of a certain effective amount of energy), while in the second term λ enters in the denominator, as a higher λ dampens the effect of a reduced p_g on consumers' willingness to purchase from the grid in the case where they do not own their own assets. As λ shrinks, the second term comes to dominate the first, producing a nonlinear effect of λ on $\bar{\alpha}$ when no rental market exists.

In the contrasting scenario with a rental market, the necessary and sufficient condition for asset ownership from Equation 6 is

$$\lambda_i \leq \frac{p_g}{p_a}$$

As noted above, the α_i preference parameter drops out in this condition, so the relevant comparative statics are how λ_i varies in response to changes in the price parameters. Defining $\bar{\lambda}$ analogously to $\bar{\alpha}$ as the λ such that a consumer is precisely indifferent between purchasing and not purchasing an asset, we then have:

$$\frac{d\bar{\lambda}}{dp_g} = \frac{1}{p_a}$$

$$\frac{d\bar{\lambda}}{dp_a} = -\frac{p_g}{p_a^2}$$

The interpretation of this effect is clear; λ represents the marginal rate of substitution between self-consumed and grid-purchased electricity. This marginal rate of substitution must be sufficiently high relative to the price ratio between the two to make the purchase of energy-generating assets sufficiently reasonable for consumers. An increase in p_a therefore lowers $\bar{\lambda}$ (and thereby increases the scope of asset ownership), while an increase in p_g increases $\bar{\lambda}$ (decreasing the scope of asset ownership).

3.4 Illustrative Parameter Heat Maps

The comparative statics described above are illustrated in Figure 3, which depicts the range of asset ownership with and without a rental market for two different price pairs ($p_a = 0.2$, $p_g = 0.2$) and ($p_a = 0.6$,$p_g = 0.4$). Each consumer can be represented as a pair α, λ. The blue areas indicate the α, λ pairs that correspond to asset ownership *without* a rental market. Without a rental market and with a low relative grid-supplied energy price, lots of grid buyers and very few owners (above parabola). Reflecting our previous mathematical discussion of the comparative statics of λ on $\bar{\alpha}$, notice that the dark blue boundary of this set ($\bar{\alpha}$) has a parabolic shape, with both extremely high and low λ corresponding to non-ownership.

The white area indicates the pairs of α, λ such that consumers would be willing to buy the asset *with* a rental option, but not without. Finally, the yellow area indicates the pairs of α, λ such that consumers would *never* be willing to purchase the asset in question. The boundary between these latter two regions is governed by the red line, representing $\bar{\lambda} = \frac{p_g}{p_a}$.

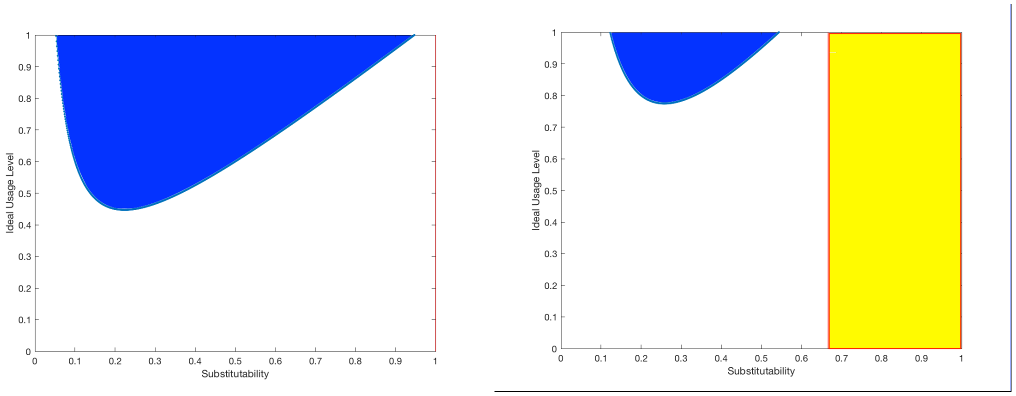

Figure 3: (α, λ) space; for $p_a = 0.2, p_g = 0.2$ and $p_a = 0.6, p_g = 0.4$, respectively. Regions with ownership in the absence of a rental market in blue, regions without ownership with a rental market in yellow.

Comparing the two panels in the above figure illustrates the effects of a price change in our model. In the left panel of Figure 1, we have a case where the price ratio $\frac{p_g}{p_a} = 1$. In this case, notice that we have a particularly large set of owners in both the case with and without a rental market. Consumers with preferences in the blue area (with a sufficiently high α) would consume their own energy in the absence of a rental market. With the introduction of a rental market, we have an even starker prediction: every agent with $\lambda_i < 1$ will choose to purchase the asset. Because the introduction of a rental price now introduces a new opportunity to sell out one's energy generation, potential energy users now view owning and selling an asset's energy output and purchasing energy directly from the grid as direct substitutes for one another; since the choice now becomes purely one of choosing between generating all of one's energy for oneself and selling off the remaining capacity and getting the same amount of energy from the grid, any slight preference for producing one's own energy will push consumers to purchase their own asset.

In the right panel of Figure 3, on the other hand, the relative price of grid-supplied energy is $\frac{p_g}{p_a} = \frac{0.4}{0.6} = 0.66$, making grid purchases cheaper than self-consumption. In this case, ownership in the asset market in the absence of a rental option is concentrated among a relatively small number of high-α_i users. In the presence of a rental option, the number of users who own their own energy-generation capacity increases, but rather than encompassing the entire market, we now have a case where users falling to the left-hand side of the red line (representing $\bar{\lambda}$) own assets, and then sell their energy output to users falling on the right-hand side of $\bar{\lambda}$, with energy purchased from the grid making up any difference between quantity supplied and quantity demanded in this market.

Comparing these two figures allows us to illustrate clearly the effects of a price change on consumer behavior in the asset market. Notice that as p_g falls relative to p_a, the region in blue shrinks, while the region in yellow expands. This result is intuitive; as the relative cost of meeting one's energy demand via grid purchases relative to one's own generation falls, one's willingness to purchase an energy-generating asset for one's own use falls, regardless of one's ability to resell one's own generated electricity. If buying grid-supplied energy is relatively cheaper, *ceteris paribus*, energy asset purchases and self-consumption are lower.

This analysis also allows us to illustrate a clear dimension along which our model differs from Horton and Zeckhauser's very similar model. In HZ, the prediction regarding consumers' ownership response to the opening up of a rental market is ambiguous; depending upon the other parameters of the model, the effect could be positive or negative. In contrast, the reaction of consumers to the emergence of a rental market in our model is unambiguous. Opening up opportunities to sell output from their DER assets always induces more consumers to purchase their own assets and become sellers in the energy market.

This unambiguous effect is due to the fact that in our model, grid prices are treated as an *exogenous* institutional parameter facing consumers, while in HZ the price at which owners can rent out their assets is endogenous in the long-run, and determined by market clearing in the rental market, with the final equilibrium condition being that the price of purchasing the asset must equal the price of renting an equivalent amount of usage. They therefore find that depending upon the parameters of the model, these corresponding price shifts might induce either more or less ownership following the introduction of a rental market.

In our model, by contrast, p_g is modeled as an exogenously given price for an outside option supplied over the grid. Given this, we do not model p_g as changing in response to the introduction of the rental market, removing the key source of ambiguity in their predictions; since p_g never falls in response to the introduction of this rental market, there is an unambiguous increase in the incentive to own. If p_g *did* fall sufficiently, there would then be a diminished incentive to become an owner, as the option of simply purchasing from the grid becomes more attractive.

In part, the presence of an outside option (grid purchased electricity) with an exogenously fixed price in our model reflects the traditional institutional structure of electricity pricing, with prices administered either by regulators or by a monopolistic grid utility, but with the move towards energy market deregulation in recent decades, p_g is becoming more determined by market forces than by centralized decision-makers. Alternatively, even in a market setting, a fixed p_g embodies an assumption that DERs form a relatively small part of the market and therefore have a little to no effect upon price. The validity of this price-taking assumption depends upon the penetration of solar assets, as well as the distribution of consumer preferences (ie., α and λ) in the market in question. As the number of potential DERs gets very large, the price-taking assumption becomes untenable. In cases such as these, the stark effects on ownership from the presence of a rental market predicted by our model will likely be dampened by the effects of unmodeled price changes that have so far been left to the side.

As consumer-generated solar energy becomes a larger market relative to the overall market for electricity, neither p_a nor p_g is likely to remain constant in the long run. In some extreme cases with exceptionally high elasticity, such as that in Figure 4 below, these relative price effects might entirely reverse our predictions. In cases such as these, we have the “ownership region” switching from the blue region on the left panel (with $p_a = p_g = 0.5$) to the blue region of the right panel (with $p_g = 0.1$, and $p_a = 0.9$), due to an increase in

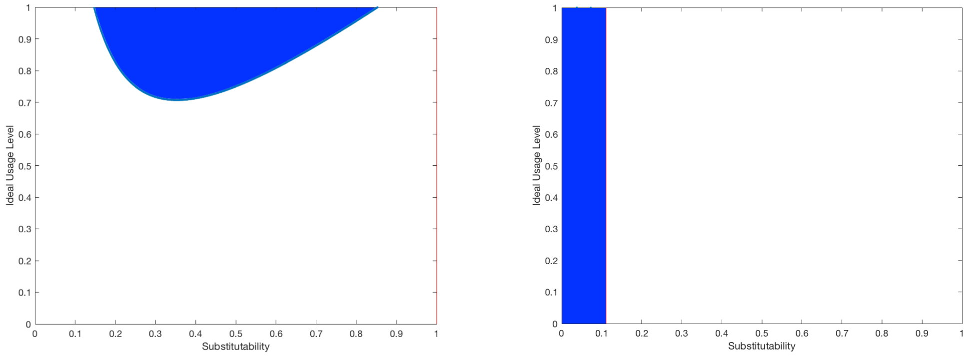

Figure 4: (α, λ) space; for $p_a = p_g = 0.5$ and $p_a = 0.9, p_g = 0.1$, respectively. Regions with ownership in the absence of a rental market in blue.

p_a as a result of increased demand and a decrease in p_g as a result of increased supply and price competition on the generation side of the grid, leading to *less* ownership after the introduction of a rental market. While such effects are extreme, they suggest that our original model's predictions are much more extreme in their implications for ownership of assets than is likely to be observed in applications.

3.5 Endogenizing the Price of Grid Energy: Institutional, Physical, and Market Design Implications

A richer model of how retail pricing interacts with the opening of a rental market would be necessary to bring these effects fully into the scope of our formal analysis. Such an extension would require an explicit model of generation on the supply side, as well as an explicit model of distributions over α and λ in the population on the demand side of the grid, thereby endogenizing p_g and reintroducing market clearing as an important force in our analysis. Finally, the institutional design of peer-to-peer energy transactions is a necessary framework for modeling how all of these dimensions of demand and supply result in the emergence of the price p_g facing consumers.

Addressing an endogenous p_g requires the model to take into account the physical reality of energy delivery. In particular, it becomes necessary to break apart p_g into the respective components $p_e + p_w$, where p_e represents the price of energy generated, while p_w represents the price of transporting energy over the physical infrastructure of electrical wires. Put differently, p_w represents a physical, inescapable cost due to the need for physical delivery.

One immediate institutional question arises from these considerations: given the need to cover this cost, who do we believe will end up paying p_w, buyers or sellers? Here, the logic of tax incidence analysis provides some insight. Legal incidence is irrelevant to economic incidence; what matters is relative elasticity. Due to our quadratic model, demand and supply are both linear in price. Furthermore, slope of supply is $\frac{1}{2}$, while the slope of demand is $\frac{1}{2\lambda}$. Therefore, with $\lambda < 1$, demand is more responsive than supply, and one should then expect owners to bear more of the incidence of p_w under any institutional assignment of the responsibility for paying p_w. This result provides yet another empirical prediction of our model.

4 Conclusion

Our results suggest that the availability of a rental market option makes the opportunity cost of excess capacity salient. Furthermore, as peer-to-peer transactions in energy capacity become more feasible, ownership of DER capacity will be driven less by one's expected intensity of use and more by relative price concerns and subjective preferences for energy self-sufficiency or environmental attributes.

Platforms that reduce transaction costs transform market processes by commodifying excess capacity. In some cases, this can mean that products or activities that have never been conceived as connected directly to markets can now be (partly) production decisions, rather than consumption decisions by residents connected to a grid system.

The potential to sell excess energy from a DER increases the probability that consumers would be willing to buy the asset, knowing that they can monetize some of the value of the asset. Similarly, in making that decision consumers may decide to purchase larger-capacity DERs. These opportunities create the potential for the homeowner to be both consumer and producer. The DER purchase calculus then becomes one of evaluating the discounted present value of the revenue stream that is likely from the asset, in addition to the consumption value that the owner will derive from consuming the energy and/or transportation services of the asset.

The classic transactions costs story for the theory of the firm has to do with the "make v. buy" choice, where the marginal of additional transactions organized within the firm exactly matches the marginal costs of purchasing inputs or organizing sales of outputs through market transactions. This Coasean analysis has illuminated both the levels, and the comparative statics, of a wide variety of firm size, product scope, vertical integration, and contracting forms.

In this paper, we have investigated a different margin, using an analogous transaction cost approach. At the risk of over-simplifying, we might name this the "rent v. own" choice, and note that the margin where owners are able to rent out excess capacity in durable assets, and where buyers are able to rent rather than purchase assets, is likewise determined by the level of transaction costs. Recognizing that technological, economic, and organizational platforms – often but not necessarily apps shared over networks by a variety of users – are a means of renting excess capacity in assets has the potential to unseat many of our settled notions of the nature of buying and selling.

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