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

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Abstract: The growth of digital platform business models – with Uber and Airbnb standing out as obvious examples – has attracted both popular and scholarly attention, and platform business models are increasingly part of policy debates in electricity distribution and retail due to the proliferation of smart grid and distributed energy resource technologies. But there has been little price-theoretic analysis of the underlying economic forces driving these dramatic changes, including the extent to which digital technologies reduce transaction costs. Our core insight is that excess capacity is variable, and varies inversely with transaction costs. Digital platform business models enable asset owners to rent excess capacity. In this paper 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. Our model highlights three dimensions that determine the extent to which a platform business model will develop: (1) transaction costs and how reducible they are, (2) the level of (potentially) valuable excess capacity, and (3) the regulatory institutions that structure the permission environment. We use our model to propose and analyze designs for transactive retail electricity platforms that enable owners of distributed energy resources to rent excess capacity to others, in the form of selling excess energy generated by rooftop solar photovoltaic systems.

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1 Introduction

In his 1937 *Economica* paper, R.H. Coase famously asked a difficult question: if markets and prices are so great, 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. This margin is also known as the "make or buy" decision: a firm can acquire or build the capacity to make an additional input or service, or it can buy the input or service in the market (Klein 2005). Changes in transaction costs drive changes in contracting and thus in optimal firm size, sometimes quite quickly, as innovations in informing, transacting, and enforcing agreements emerge.

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. Idleness has two obvious costs: the durable asset or equipment must be housed, safe from theft, the elements, and so on, and the value of the capital tied up in the durable asset foregoes its opportunity cost rate of return in alternate uses during that idle time.

Given the transactions costs of contracting over the use of excess capacity, these costs may often simply be borne. A homely but obvious example is the toothbrush: even an assiduous brusher of teeth likely uses her tooth brush no more than 10 minutes per day. That leave 23 hours and 50 minutes of unused capacity. But it would be prohibitively expensive to find anyone willing to pay to use this asset, and the costs of sharing will prevent sharing from taking place. When you think about a toothbrush and how you use it, perhaps that's just as well.

That is not always the case, however. A car's owner typically uses it for 40 minutes to an hour per day, 5 or 6 days per week. Otherwise, it is stored in the garage or a parking space that could be used for car traffic or bicycles or just for a little more elbow room in crowded cities. That time amounts to 160 hours per week when the car is sitting unused. Taken together, the cost of parking and the cost of foregone returns on the $30,000 or more tied up in owning the car are substantial. But these costs do not become relevant to the decision calculus of owners, or potential renters, until transaction costs are low enough to make that opportunity cost discernable.

The unifying theme of digital platform business models, whether focused on excess capacity (e.g., Airbnb) or renting very short-term services (e.g., TaskRabbit), is the ability to lease excess capacity using highly mobile devices (generally smartphones) with third-party designed software (apps) linked over data network or wifi Internet connections. Digital platforms that implement business models of "sharing" – with Uber and Airbnb as prime examples – make excess capacity 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.

Digital technologies make these platforms possible by reducing transaction costs. The Internet's open architecture (open communication protocols and interoperability) makes creating new devices and applications layered on top of the Internet easy and inexpensive. Internet pioneer Vint Cerf credits this value creation to the Internet's role as a platform for permissionless innovation (Cerf 2012). Airbnb and other digital platforms are an example of such permissionless innovation, and this innovation is a primary driver of transaction cost reduction (McKinsey Global Institute 2015, p. 8).

Digital innovations have reduced transaction costs in most markets and industries, transforming our economy as a result. Such welfare-enhancing creativity is now possible in electricity distribution as well, as seen in residential solar, microgrids, electric vehicles, and applications and devices for autonomous and mobile home energy management. Digital smart grid technologies and distributed energy resources (DERs) have proliferated over the past decade. Between 2010 and 2014 US solar capacity increased by more than 430 percent, including strong growth in residential rooftop solar. Residential solar capacity is expected to grow by 9 percent in 2017, and non-residential by 11 percent (GTM 2017) 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 distribution automation, now make transactive energy feasible – using markets and automation to coordinate energy generation and use in a decentralized system.

Consider a scenario with homeowners, some owning rooftop solar photovoltaic systems, participating in a retail electricity market.[1] The solar PV owners use a digital inverter as their home energy management gateway, and they can set prices at which they are willing to sell energy and

[1]Think of this market as a retail market in which homeowners purchase energy management services from retail energy service providers, and those services include facilitating and managing their participation in this market.

prices at which they are willing to buy energy from the market when their PV is not generating enough to power their uses in the home. The inverter submits those bids and offers to the market, autonomously changing the settings on the household's devices in response to the market price in that period. At times when the PV 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 from the PV. 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.

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. 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 transactions costs-based model of the platform economy, and use it to develop an institutional framework for a retail electricity platform. Digital technologies can be platforms for transactions cost reduction, enabling transactions that produce only a small surplus to be negotiated and executed.

Here we propose a transaction costs 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

Consider a well-known example: Airbnb. The usual answer to the problem "where to stay in a strange city" has been "hotels," often coupled with a transaction-cost-reducing mechanism called brand names. Brand names solve all three of transaction costs problems. Hotels are expensive, both because they may have locational market power and because they have to cover their average costs: all their value is in the business of selling rooms by the night.

That average cost pricing constraint is not true of apartments or homes where people live, because those other expenses are being paid already. A homeowner can charge a price that covers marginal cost and still be glad to have access to the transaction. That low price will be better for the buyer also, of course, as long as the three categories of transactions costs can be reliably reduced to the point where exchange is possible. Airbnb figured this out, realizing that, unlike hotels, one need not rent out space at all. Instead, Airbnb uses a digital platform business model to sell (1) information about location and quality, (2) reliable transaction clearing, and (3) distributed trust, or dependable access to vetted market participants. Trustworthy buyers find trustworthy sellers, and the inconveniences of search, price negotiation, and payment can all be substantially done seamlessly using the platform. The rest is up to the people who have excess capacity (in this case, space) and the people who want to rent that excess capacity (in this case, an accommodation in a place where they do not know anyone but want to sleep safely).

Airbnb was originally an idea for making money by renting out rooms, beds, or couches in hotel-poor Silicon Valley (Parker, Van Alstyne, & Choudary 2016, pp. 1-3). The founders, Brian Chesky, and Joe Gebbia apparently had the idea when they could not pay their own rent, but noticed that when there were conferences or other gatherings people had to pay very high prices or drive very long distances. The name is obvious, in a way: instead of actual beds (these were

20-something programmers!) they leased access to an air mattress. Air mattresses, sometimes two or more to a room, and a home-cooked breakfast, and voila: Air Bed and Breakfast! They made enough profit to avoid losing their apartment after their 2008 launch.

In 2009 they shortened the name of the venture to AirBnB, and they met with Paul Graham of Y-Combinator, the start-up incubator. Graham suggested that instead of working on the programs and web site the founders (who by now had reconnected with former roommate and "brilliant" programmer Nathan Blecharczyk) go to New York and develop a portfolio of actual properties. Graham saw that they needed to demonstrate that the concept could actually work intensely and consistently, after which the product would begin to sell itself.

Reducing transactions costs makes existing excess capacity more expensive from the owner's perspective, in terms of opportunity cost. Whether a couch or an empty room most of the time, or an entire empty apartment when the occupant(s) leave for a longer period of time, the transactions cost reduction from the digital platform turns that excess capacity into an idle asset that the owner could monetize.

The function of the Airbnb platform is to reduce the three core transaction costs and allow willing sellers of a apartment/nights to rent to willing buyers. The transaction is between the owner of the apartment and the person who wants to stay in the apartment; Airbnb as a platform operator earns its service fee by helping them find each other, make the payment, and trust each other.

The reduction in transaction costs converts what was simply a temporarily unused apartment into excess physical capacity that can be rented via a market process. Before Airbnb a transactible commodity did not exist. In fact, as recently as 2011 an article in the New York Times noted:

> In a large swath of the East Side bounded by Fifth and Park Avenues and East 49th and 70th Streets, about 30 percent of the more than 5,000 apartments are routinely vacant more than 10 months a year because their owners or renters have permanent homes elsewhere ... (Roberts, 2011)

Once Airbnb had begun to develop a portfolio of properties and renters with established reputations through the platform for being reliable transaction partners, the number of dark, empty windows began to decline and capacity utilization increased. The key factor to recognize, as this example illustrates, is that excess capacity is variable and is a function of the transaction costs of finding someone who can use it, effecting payment, and preserving the safety of buyer and seller while the transaction is being consummated. By 2016, Airbnb had more than 2 million listings in 200 countries. If Airbnb were a hotel company, it would be the third largest in the U.S., after only

Hilton and Marriott.

In this paper 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. 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.

Our model does not have any features preventing this new market from emerging. Airbnb's digital platform business emerged around the edge of a network born from permissionless innovation. Is such innovation feasible or desirable in a regulated industry like electricity distribution? Adam Thierer calls such an industry "born in captivity" (Thierer 2016). Here we apply our transaction cost model to articulate an electricity distribution platform business model and the economic logic underlying its possible effects.

As digital and DER technologies become more efficient and economical, how do these changes affect market structure in retail electricity markets and the business model of the regulated distribution utility? What are the implications of these changes for the regulatory institutions that provide the institutional framework in which firms and homeowners make decisions about DER ownership and energy use? The proliferation of sophisticated digital metering technology enables retail markets for DER energy sales and payments for grid services, because it reduces the transaction costs of measuring excess generation and makes more of the grid services offered both transparent and transactive.

The model we develop here provides a framework for an electricity distribution platform business model. 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.

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. Our model explores 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.

To incorporate these consequences we model a retail electricity platform as a multi-sided market platform with three related markets: energy, reactive power/voltage control, and reserves (Tabors et. al. 2017). The energy and reactive power markets can operate as real-time double auctions, with device owners using algorithms to determine how their devices will respond to price signals and changing their settings accordingly. A market platform company connects parties for mutual benefit and receives a fee for service. The reserves market is likely to be a procurement market, with the grid services company as the monopsonist in that market.

Completion of the transaction between the decentralized parties requires connection through two sets of centralized infrastructure – the communication infrastructure of the Internet, and the physical wires network to distribute energy from one party to another. The unique nature of alternating-current electricity means that, unlike sharing data or car rides or apartments, neither party in the transaction can specify the contract path or can have full property rights in a particular physical path. For that reason a distribution platform must have some degree of centralized control over physical dispatch to maintain the physical balance of the distribution grid, given the existing architecture of the distribution grid. Thus the second set of functions in a transactive retail electricity distribution platform is the grid services that the grid operator provides: interconnection, delivery, and balancing. Re-imagining the distribution utility as a grid services company uses transactions cost economics to identify new firm boundaries in light of falling transactions costs.

Technology-induced transactions cost reduction implies not only changes in market structure and the nature of the firm, but also changes in the regulatory framework to enable other beneficial changes while also facilitating policy objectives. Historically, policy objectives in electricity were relatively straightforward: least-cost provision of a well-defined commodity product at affordable prices that allow universal access with high service reliability. The theoretical underpinnings of these objectives concentrate on static efficiency in a system without real-time pricing that requires real-time balancing. Those policy objectives were predicated on a system of electro-mechanical technologies and a system architecture constructed with uni-directional current flow based on those technological capabilities.

In much the same way that system architecture and system technologies are endogenous, regulatory institutions and system technologies are also endogenous. The set of policy objectives has evolved and increased in the past 40 years, incorporating environmental policy objectives alongside affordability and service quality. The static efficiency metric now becomes capacity utilization because digital devices and automation make it easier and cheaper to build transactive energy systems that use price signals in ways not before possible. Innovation's benefits also suggest a policy objective of dynamic efficiency and enabling innovation to occur. Rather than the focus on reliability, resilience is becoming the measure of system and service quality. Affordability and access remain important policy objectives. Digital and DER technologies change how policy objectives can be achieved, increasing the extent to which they can be achieved through market processes rather than centralized control (although the nature of alternating current electricity means that some centralized dispatch will be valuable for the forseeable future.

We begin our analysis by relating our model to literature on the sharing economy, 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 use this model as a framework for a design of a distribution grid services platform company.

2 Relation to the Literature: The Sharing Economy, Transactions Costs, Platforms

2.1 The sharing economy

With the recent growth of "sharing platforms" such as Airbnb and Uber, there has been obvious recent interest in understanding the economics of these novel market structures. The paper most similar in theoretical approach to our own is Horton and Zeckhauser (2016) (henceforth HZ). HZ directly model the choice of whether to rent or to own an asset, and model the market for asset ownership and asset rental as two different markets both shaped by preferences, technology, and transactions costs. 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.

2.2 Transaction cost economics

Digitally-enabled DER ownership, and coordinating transactions among owners and renters of DER assets, raises the subject of governance. In the context of an historically regulated vertically integrated industry such as electricity distribution, governance means not just the organizational and managerial questions, but also the regulatory institutions.

Since the origins of the electricity industry in the 1880s, firms have been vertically integrated. Innovation in generation technology in the 1980s led to the unbundling of generation from vertically-integrated utilities in states that restructured their regulation to allow competitive wholesale markets. Today, digital consumer device and smart grid technologies reduce transaction costs so dramatically at the distribution edge that another wave of unbundling may occur, this time of retail from distribution.

In a standard neoclassical competitive model, with full information, no incentive alignment problems, and zero transaction costs, the existence of firms is entirely an artifact of the cost functions in the industry, of such associated issues as economies of scale and scope, and of the size of the relevant (well-defined) market. Vertically-integrated firms are primarily a response to market power or a strategic move to enhance market power in an upstream or downstream market (Joskow 2005). This approach also undergirds natural monopoly theory and the definition of subadditivity of costs that is the hallmark of electricity regulation.

Work in transaction cost economics and organization theory demonstrates that this standard approach overlooks the incentive and governance reasons for having some transactions occur within firms and some occur in markets. As Coase (1937) and others have shown, the desire and ability to decrease transaction costs shapes vertical integration and contracting in a variety of industries (see, for example, Klein, Crawford, and Alchian 1978; Baker, Gibbons, and Murphy 2002; Bajari and Tadelis 2001; Bresnahan and Levin 2012). Vertical integration can also emerge due to contractual difficulties in cases with asset specificity (e.g., Joskow 1988; Masten, Meehan, & Crocker 1989), or in cases in which transactions costs lead to incomplete contracting (e.g., Grossman & Hart 1986). Rather than model the firm as a set of cost functions, Williamson (1985) argues that organizational structure is a consequence of the act of economizing on transaction costs. We employ this framework to draw institutional implications from our model to inform our platform design in Section 4.

Principal-agent problems, the difficulty of writing complete contracts, and other transaction costs in our triangulation-transfer-trust taxonomy determine the transactional boundary of the firm. When transaction costs change, the profit-maximizing firms boundary should change to incorporate the new tradeoffs if the firm is free to evolve its business model to economize on transaction costs and reflect the expected effects of these new relative margins. The form and magnitude of the change in the firms boundary is a function of the expected benefit and cost of rearranging how the transaction is realized, and also of the cost of bringing about the change.

Transaction costs, the transactional boundary of the firm, and the feasibility of creating new markets forms the framework for understanding the potential for unbundling energy retail transactions from electricity distribution, a potential that smart grid technologies catalyze. Innovation, including but not exclusively technological innovation, changes the efficient transactional boundary of the firm because it affects the transactions costs, economies of scale, and economies of scope that make vertical integration a profitable organizational structure. These technological changes have created the opportunity to change transaction costs in the industry, thereby creating opportunities to do two dynamic things: change the boundary of the firm in accordance with the change in transaction costs, and create new markets where they previously failed to exist because of transaction costs.

This general transaction cost model applies specifically to situations in which technological change reduces transaction costs, such as the digital and DER innovations in electricity and around the distribution edge. The transaction cost model suggests that when transaction costs fall along any of the three margins we describe – triangulation, transfer, or trust – due to innovation, the incentives for the firm to expand through vertical integration are sharply attenuated. In fact, the firm may vertically disintegrate or unbundle, specializing in a pure brokerage activity, bringing together sellers who have a newly-commodified excess capacity and buyers who are willing to transact peer-to-peer rather than insisting on purchasing from a centralized entity such as a utility.

On the other hand, there may be important implications for economies of scale and economies of scope in this new transactions cost analysis. Having a large sample of potential sellers may facilitate triangulation, if transmissions costs rise sharply with distance, for example. Likewise, having many observations on trustworthiness may reduce the implicit risk premium, though innovations such as blockchain contracting may ultimately obviate the need for outsourcing of trust in the first place. Still, at the margin the transactions cost analysis indicates a likely substitution away from a need for vertical integration and focus on generation and transmission and toward brokerage and fulfillment functions to facilitate local peer-to-peer energy markets.

2.3 Platform Economics

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 and Woodard 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 (2009, p. 19), and Parker, Van Alstyne, and Choudary 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" (2016, p. 3). As a business model, a platform architecture creates value by facilitating exchange.[2]

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

- *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).
- *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.

Technological platforms

These aspects of a platform emphasize its technology elements and the architecture that shapes the system that these elements create. A platform generally has several technically connected elements, typically with a stable, common core and a variable, heterogeneous periphery (Gawer 2014, p. 1242). Bresnahan and Greenstein use this technological framework, defining a platform as a "a reconfigurable base of compatible components on which users build applications" (1999, p. 3). Video game platforms – Playstation or Xbox, for example – are a canonical example: the core technology is a set of proprietary elements that work in conjunction with other, possibly quite diverse, elements to enable game playing. These other elements include games (software written

[2] For a more thorough discussion and analysis of platforms, see Parker, Van Alstyne, and Choudary (2106) and Kiesling (2018).

to play on the platform) and peripheral devices such as controllers or joysticks that complement the core system.

A core of common components allows for economies of scope in production to develop around the edge of the platform. Because the platform shares certain features across all applications and peripherals, substantial portions of software can simply be copied, rather than having to be reproduced from scratch for each new use. These economies of scope – declining costs for producing several different products on the same platform – are some of the main drivers of innovation around technological platforms. Such cost efficiencies can be realized both within firms and across firms; the transactions cost economics implications for the extent of vertical integration and the expansion of a single firm to make a variety of different products are quite complex. Our extension of transactions costs into the three different categories – triangulation, transfer, and trust – allows us to consider the problem of optimal firm size and scope far more precisely than more granular conceptions of transactions costs for previous analyses.

Economic platforms

An economic analysis of platforms views such applications as transaction facilitators and intermediaries. By using technologies that reduce transaction costs, economic platforms create value by enabling parties to connect for mutual benefit, typically in the form of a transaction or exchange. Platform providers create markets, connecting producers and consumers (Rochet & Tirole 2003, Parker & Van Alstyne 2005, Armstrong 2006, Rysman 2009). Such a framework views agents as having specific roles (buyer, seller, platform provider) and exchanging a specific good or service. In the video game platform example, the platform provider creates value by providing a technology (the game console and its operating system) that acts as a focal point (Schelling 1960) for a game seller and game buyer to transact; the exchange yields mutual benefit, and the existence of the platform provides incentives to the seller to develop games for the platform and the buyer to purchase the games. Thus an economic analysis of platforms views the platform as a two-sided market or multi-sided market, where the platform provider coordinates agents through transactions and price signals. But describing the function of economic platforms in such simple language misses the key aspect of being able to sell reductions in transactions costs: platforms can create markets, both in practical terms and in the minds of participants, where no market previously existed. The items or services being transacted may not have previously been "commodified," because some combination of triangulation, transfer, or trust meant that owners and potential other users never considered buying or selling these items or activities.

Platforms as institutional-organizational elements

Platforms arise and evolve in different organizational contexts, so an organizational lens is a worthwhile complement to the technological and economic platform analyses. Gawer's integrated theoretical framework for analyzing platforms starts from the observation that in order to create value, platforms rely crucially on economies of scope in supply and innovation (for the engineering design view), and economies of scope in demand (for the economics view) (2014, p. 1244). Agents who constitute the platform ecosystem may take on multiple roles; they may be individuals, households, firms, or some other organizational form that is endogenous to the system.

Agents can be individuals or firms, and can play a variety of roles; those roles can change over time, as environment changes, as interactions in a complex system yield new patterns and outcomes. Both the technological analysis and the economic analysis abstract from how the roles of platform owners and platform complementors can evolve between complementarity and competition. They also abstract from the ability of an agent to have different roles in the ecosystem at different times, but this heterogeneity is a novel feature that digital technology enables, and that can have significant institutional and organizational implications.

The technology literature models agents as having fixed roles as collaborative innovators around the platform, while the economics literature models agents as having fixed roles as producers and consumers in multi-sided markets. Empirically, agents can and often do play different roles, and those roles can change as transaction costs and opportunity costs change (Gawer 2014, p. 1243). In the application to DER asset owners who were consumers in the traditional distribution model but are now "prosumers", this institutional-organizational framework for analyzing platforms enables us to reflect this change of role and use transaction costs economics to analyze and design the institutional framework compatible with such technological dynamism. Modeling the platform as an institutional-organizational element thus provides a useful context for our transactions cost analysis.

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

Using these frameworks and focusing on the case of residential rooftop solar, we construct a formal model to capture the key drivers of trade in excess asset capacity. In particular, transaction costs affect the heterogeneity of both valuations of the asset's services and in a given user's prospective usage. After defining the general framework and the cost structure, we present three iterations of the model: a basic two-person model that identifies gains from trade in excess asset capacity and the role of transactions cost reduction in facilitating such trades, a two-stage three-person model that illustrates an individual switching from renter to owner, and a two-stage continuous model to represent the effect of the transaction cost reduction on the degree of sharing, and at the margin how large the shift from renter to owner can be. 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.

3.1 The General Framework

Consider a potential market in which there is an asset A with finite usage capacity normalized to 1, and n individual agents who may choose to purchase A. Each agent i has a different, inelastically demanded level of usage of the asset, indexed by u_i, between 0 and 1, representing the share of time that the agent utilizes the asset s/he owns if purchased. When $u_i < 1$ excess capacity in A_i exists in some technical, but perhaps not actionable, sense. Each agent values each unit of time spent using the asset at v_i, meaning that i's overall willingness to pay to own the asset is $v_i u_i$. This formulation captures the idea that heterogeneity among agents is present for both valuation and usage.

Asset A may be purchased in a competitive market, and can be produced at constant marginal cost MC.[3] Each agent will then buy the asset and become an owner only if $v_i u_i > P_A = MC$. Agents who either do not value the asset in question or who do not expect to use it enough will not purchase the asset. Thus agents with a sufficiently high combination of value and utilization will choose to become owners.

After purchasing the asset, owners find themselves in possession of excess capacity (for owner i, this would be $1 - u_i$). A potential market demand, consisting of agents with low levels of $v_i u_i$, exists for rental of this capacity. We denote the realized quantity of capacity traded as Q_r[4].

As noted in Table 1, however, transactions costs make renting this excess capacity difficult. Such transaction costs may stem from institutional or regulatory constraints, or they may be due to irreducible physical considerations (as is relevant in the electricity application). Therefore, some of these potential gains from trade will be blocked by the presence of these costs. With sufficiently high transaction costs a rental market does not emerge, and asset use and ownership are directly connected. Only with the emergence of a rental market can use and ownership be unrelated.

[3] As long as we are analyzing from the perspective of asset users only, this can be viewed as reflecting that the users in question are a small part of a larger, competitive market for the asset.

[4] When considering the interpretation of this model in the electricity case, it is important to take into account *timing of use* in addition to capacity utilization at a given point in time, a crucial dynamic dimension that we are, for the moment, bracketing.

We represent these diverse transactions costs with a variable t, which is a normalized per-unit cost of discovering and engaging in mutually beneficial exchange of asset capacity. In this model t changes the realized transactions in excess capacity, so that only transactions occur for which differences in valuation are greater than t; Q_r therefore depends directly on t, and should be written as $Q_r(t)$. *Ceteris paribus*, $\frac{dQ_r}{dt} < 0$, so when transactions costs fall for a given level and ownership pattern of assets, rental of excess capacity increases. Conversely, for sufficiently high t, $Q_r(t) = 0$

3.2 A Two-Person Model of Gains From Trade in Excess Capacity

This simple model can help illustrate how gains from trade arise from an innovation that reduces transactions costs. Consider an example with two agents, High (H) and Low (L), with values $v_H > v_L$, and with u_H, u_L such that H is willing to buy the asset and L is not (that is, $v_H u_H > MC = P_A > v_L u_L$). Suppose, moreover, that initially transaction costs are at a level $t_0 > v_L$, meaning that exchange in the rental market is prohibitively expensive ($Q_r^* = 0$). H is the only owner and the only user, so total use is u_H and total welfare is $v_H u_H - MC$.

Now suppose that a new technology platform reduces transaction costs from t_0 to $t_1 < v_L$ and makes renting feasible, because now H and L can discover each other, establish trust, and exchange excess capacity. For simplicity suppose they can trade at a price P_r which apportions the gains from trade in such a way that both sides are mutually advantaged, with transactions costs covered in some way.[5] For a given asset capacity and pattern of asset ownership, equilibrium p_r^* clears the rental market such that offered excess capacity equals the quantity demanded of excess capacity, with the equilibrium amount exchanged being $Q_r^* = \min\{u_L, 1 - u_H\} > 0$ (depending on whether the excess capacity available from H is sufficient to satisfy all of L's demand). L can now use the asset without being an owner.

The asset's capacity utilization increases to $u_H + \min\{u_L, 1 - u_H\}$, reducing idleness to $\min\{1 - (u_H + u_L), 0\}$. Welfare unambiguously increases by $(v_L - t)(\min\{u_L, (1 - u_H)\}) > 0$. The distribution of these gains in welfare depends on the mechanism for price determination.

This simple exchange model illustrates the gains from trade when a platform technology enables owners and non-owners to discover each other and transact over valuable excess capacity. As transactions costs fall, realized rentals and total welfare increases. Aggregate (technical) excess

[5] In a more fully-elaborated model of double-sided exchange the technology would include equilibrium price determination through a market platform such as a double-sided auction; see the multi-sided platform literature cited in Section 2.

capacity is also unambiguously reduced.

3.3 A Three-Person Model of Ownership Switching

In the above example, a reduction in transactions costs affects aggregate welfare solely through its effects on the excess capacity rental market. As our next example illustrates, technology-induced reductions in transactions costs may also have dynamic effects. Lower transactions costs can induce non-owners of the asset to become owners because they can now monetize their excess capacity, shifting the distribution of people who own the asset. The following three-person model presents a simple illustration of this principle.[6]

Consider a simple model with three agents, High (H), Medium (M), and Low (L), in which $v_H > v_M > v_L$. For simplicity, suppose that $u_L = 1 > 2 - (u_H + u_M)$, that is, that L is willing/able to use the asset at full capacity, but does not value this usage highly. Suppose also that $v_H u_H > P_A = MC > v_M u_M > v_L$, but that $v_M u_M + v_L(1 - u_M) > P_A$. In this case, the supply and demand situation in the market for asset A can be illustrated by Figure 1.

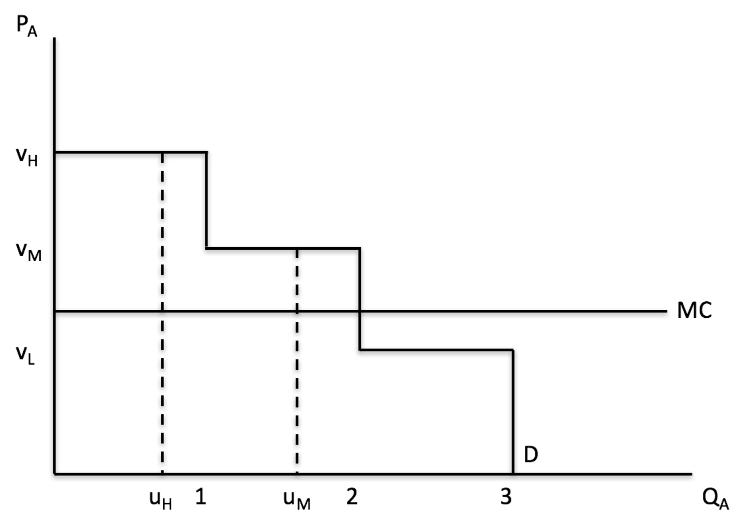

Figure 1. The three-person market for asset A

In the absence of any rental market (i.e., in the case of $t > v_M$), only H will choose to buy. In this case H is the only owner and the only user, so total use is u_H and total welfare is $v_H u_H - P_A$.

[6] HZ present an example of increases in ownership resulting from a two-person model, as they allow overall usage rates of the asset to be endogenously determined. In this model, where u_i is taken as an exogenous parameter for each individual, a three-person model is necessary to illustrate this effect.

In the absence of any other changes, the realized Q_r^* in equilibrium is 0, meaning no renting/sharing occurs.

Let us examine what occurs as we reduce t in this example. For simplicity suppose that trade occurs at a market-clearing price P_r in the rental market, and that all transactions costs fall on the seller in a given transaction. Suppose $v_M > t_0 > v_L$. L is too low-value for H to transact with, while it is profitable for some trade to occur between H and M. We then have realized rentals of $Q_r^* = \min\{u_M, 1 - u_H\}$, and another unambiguous increase in welfare, just as in the two-person model (indeed, in this case, L is irrelevant to the outcome and we are simply repeating our two-person analysis from above).

Matters become more interesting as we consider a further reduction in transactions costs to $t_1 < v_L$. There are, in particular, two cases to consider.

In Case 1, $t_1 > v_L - \frac{P_A - v_M u_M}{1 - u_M}$. In this case, in equilibrium H is willing to rent excess capacity to both L and M, leading to a $Q_r^* = 1 - u_H$ (this may or may not be strictly greater than Q_r^* with t_0, depending on u_H relative to u_M). The asset's total utilization is 1, meaning idleness must be 0. Welfare strictly increases both mechanically due to the fall in t, and possibly due to an increase in realized utilization. This case again mirrors the two-person model.

More interesting, however, is Case 2, in which $t_1 < v_L - \frac{P_A - v_M u_M}{1 - u_M}$. In this case, the supply and demand situation in the rental market (in equilibrium) is illustrated in Figure 2. H continues to rent excess capacity, but now the reduction in transactions costs is such that, in equilibrium, M is willing to purchase asset A and subsequently rent out his/her excess capacity.

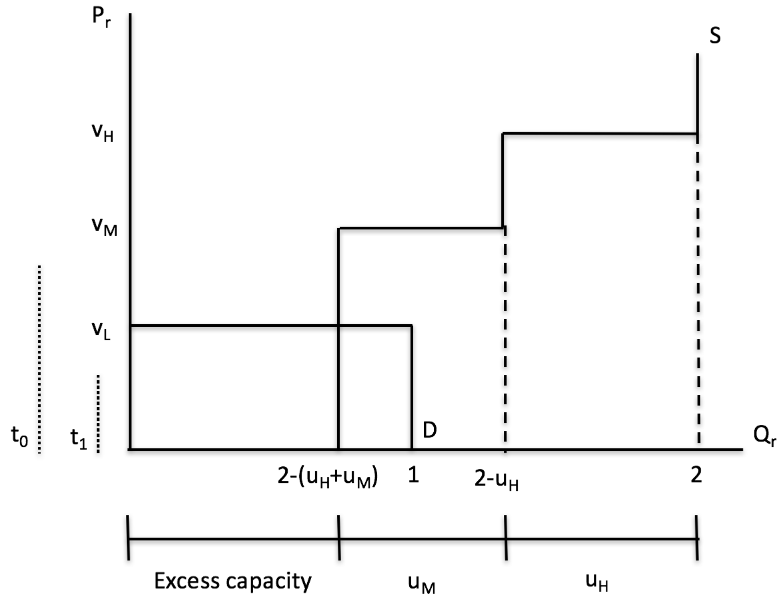

Figure 2. The rental market for asset A in Case 2

Because M expects a surplus (net of transactions costs) of $(v_L - t)(1 - u_h)$ in the rental market, it is now profitable for M to buy the asset, which was previously not a profitable investment due to M's insufficient valuation/usage of the asset. This leads to an unambiguous increase in realized rentals to $Q_r^* = 2-(u_H+u_M)$, an unambiguous increase in overall usage to 2, and an unambiguous increase in welfare.

This particular example relies on the existence of a population of low-value, high-volume renters such as L, which may be seen as a restrictive assumption (although, in our particular examples, it can be very easy to think of consumer types that fit that description). At the same time, this three-person model illustrates that a fall in transaction costs, facilitated by sharing platforms, can have structural effects on the market in question beyond merely increasing utilization of existing capacity; the expansion of rental markets can actually induce a *more* decentralized pattern of ownership than previously existed.

3.4 A Continuous Model

The two-person and three-person models suggest that digital platform-based reductions in transactions costs enhance welfare through enabling asset owners to rent their excess capacity, and if the demand for excess capacity is sufficiently high, enhance welfare through inducing renters to become owners and supply more excess capacity. These two motivations combine to increase the size of the rental market for excess capacity.

As a natural extension, here we sketch a model with a continuum of agent types for a given asset. In this section we lay out the logic of such a model; the formal analysis is work in progress.

Consider a model with n agents. For simplicity assume that the agents are distributed according to a gamma distribution ($\alpha = 5, \beta = 1$) along the continuum $[v_0, v_1]$, with v_1 representing highest-value usage of the asset and v_0 representing the lowest-value usage of the asset.[7] In between those extremes agents are arrayed according to their value of asset ownership, and there will be some threshold value (call this $\underline{v}$) below which agents do not find it cost-effective to own the asset because they simply will not use it enough and are aware of the opportunity cost of their excess capacity. In equilibrium, agents with value higher than the threshold value $v_i > \underline{v}$ own the asset (become owners) and agents with lower value $v_j < \underline{v}$ do not own the asset.

As before, suppose excess capacity exists, meaning that owners can only use a fraction u of the asset's capacity; for now, we abstract from heterogeneity in capacity utilization to focus on heterogeneity in valuation.

Suppose that for this asset t is high enough that trade in excess capacity is prohibitive. In this case owners are the only users. In the absence of any other changes, the realized Q_r^* in equilibrium is 0, meaning no sharing occurs.

Now suppose that a new matching technology reduces transaction costs and makes renting feasible, because now agents $v_j < \underline{v}$ can discover owners $v_i > \underline{v}$ and trade excess capacity with each other. As before, suppose they simply trade at a price P_r. Just as in our three-person model above, these changes to the rental market will also have implications for the market for ownership. In this model, there are two effects of a fall in transactions costs from t_0 to t_1.

The first effect is a pure expansion of the market for existing capacity; existing owners rent excess capacity to existing non-owners, increasing capacity utilization and total welfare as described above. Potential users who previously fell below a threshold value (call it $r^*(t_0)$) for renting (due to high transactions costs) can now be profitably sold to. This changes the realized sharing in the rental market, depicted above in the move from $Q_r^*(t_0)$ to $Q_r^*(t_1)$ in Figure 3. This expansion of the market, however, also causes $\underline{v}$ to shift to the left, from $\underline{v}(t_0)$ to $\underline{v}(t_1)$. In others words, some

[7]The gamma distribution is a general category of two-parameter probability distributions. α is a shape parameter and β is a rate or inverse scale parameter. The exponential distribution and chi-square distribution are special cases of the gamma distribution. This functional form, in combination with the linear function form of v, will yield convexity in Q_r^*.

renters nearby the old cutoff $\underline{v}(t_0)$ will switch to becoming owners.

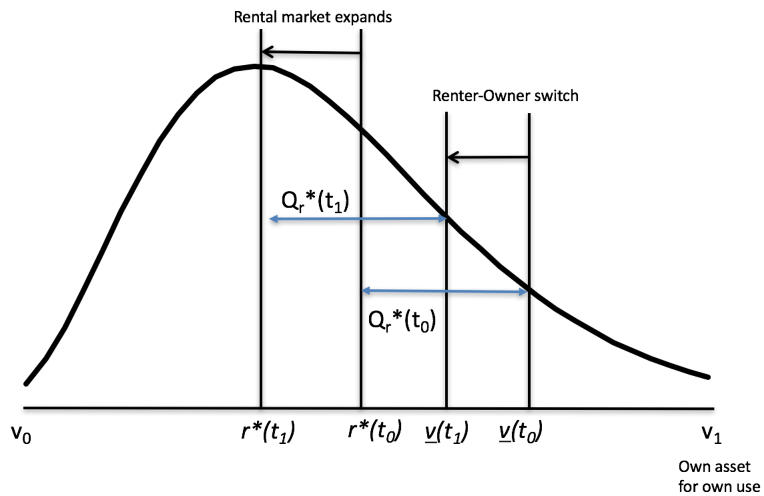

Figure 3. A fall in t in the continuous model

These comparative statics obtain due to the presence of a population of relatively low-value renters that value the asset but not enough to own (analogous to L in the three-person model); opening the market to these users by reducing transaction costs now presents a profit opportunity to higher-value users (M in the three-person model), who are now induced to make the switch to becoming owners and who can make up some of the costs from purchasing excess capacity by renting to these newly-accessible users.

In general, when digital technologies enable people to find each other and agree on contractual terms (triangulation), reduce the cost of finding a mutual means of payment (transfer), and inexpensively provide credible reputation mechanisms (trust), people will be able to create gains from trade. Asset owners will now find the opportunity cost of idle capacity salient to a new degree, and if the rental market for excess capacity is sufficiently robust, some new owners will purchase capacity and some existing ones will expand capacity.

3.5 Excess Capacity and Economies of Scope

Given this foundation, what are the possibilities for beneficial exchange between owners and non-owners? At what prices might these exchanges occur? How can individuals with their own cars and apartments compete against firms specialized in the transportation and hotel professions?

For example, an apartment owner is willing to accept a considerably lower price than nightly hotel rates on a per-square-foot basis. Specialization and productivity suggest that hotels should be able to underprice these amateurs, *ceteris paribus*; on the contrary, apartment owners appear to price nightly stays ower than hotels in corresponding locations. Some hypotheses include:

- Quality differentials between hotel rooms and apartments
- Hotels pay hospitality taxes and Airbnb owners do not, while both pay property taxes
- Market platforms enable individuals to exploit economies of scope that they could not exploit before due to transaction costs

Conditional on individual already owning asset A as defined above, the individual is more able to price the shared good closer to marginal cost because the investment is sunk and the revenue from the shared good contributes to paying the debt service for A. In other words, the consumer has already made the $MB > MC$ choice to purchase A.

The firm, on the other hand, prices at average cost in equilibrium to recoup fixed costs and as a consequence of rivalry with other providers (note that this competitive market structure does not apply to the taxi industry). The difference is that the individual is simultaneously both a consumer and a producer, changing the economic calculation associated with the decision of how to use the asset and what to do with its excess capacity.

Individual consumers purchase asset A_i to enable them to consume a flow of units of the good u_i. The consumer's cost associated with consumption is

$$C(u_i) = A_i + \int C'(u_i) \tag{1}$$

For example, if User 1 owns an apartment, A_1 is the cost associated with the mortgage and the marginal cost reflects the per-day variable costs like electricity and water.

Now suppose that User 1 has underutilized capacity in A_1, and a market platform exists that enables the consumer to sell use of the excess capacity to User 2, who does not own A. Denote those units available for sale as u_2.

Consumer 1 is now incurring the cost for both the own-consumed units u_1 and the sold units u_2, and has the cost function

$$C(u_1, u_2) = A_1 + \int C'(u_1, u_2) \tag{2}$$

This concept is an extension of the analysis of joint production to the case where a consumer produces units for own consumption and produces units for sale. Thus we can apply multi-product firm models, implying that the consumer's production of u_2 has economies of scope. With economies of scope, joint production of two goods is less costly than producing the two goods separately (Teece 1980, 1982; Panzar & Willig 1981; Alston & Gillespie 1989).

If the consumer's production of u_2 is characterized by economies of scope, then we can apply the stand-alone test:

$$C(u_1, u_2) < C(u_1) + C(u_2) \tag{3}$$

and therefore

$$AC(u_1, u_2) < AC(u_1) + AC(u_2) \tag{4}$$

For example, apartment sharing may exhibit economies of scope if the cost of establishing and maintaining an apartment as a residence makes it cheaper on a per-night basis to produce hospitality for others. If that's the case, then at the margin the consumer will be willing to price even below $AC(u_1, u_2)$ because what the consumer is selling is underutilized capacity. The incremental effect of digital platforms has been to enable people to exploit their economies of scope who could not before.

This analysis thus has a further dynamic implication consistent with the model outlined above. The availability of a digital market platform, by enabling more people to exploit economies of scope, may induce investment in additional capacity compared to investment in the absence of a market platform. Not only can asset non-owners switch to owners, but owners can invest in larger or higher quality apartments. In the application to electricity distribution, this implication is profound – it indicates the economic logic underlying a consumer's choice to invest in, for example, a rooftop solar installation larger than required for his/her own use if a decentralized market platform exists.

4 A Transactive Distribution Platform for Distributed Energy: Markets, Firms, and Regulation

Our model describes an asset and whether or not to purchase an asset knowing that you can lease or rent excess capacity. One implication of our model is that institutions matter – the rules matter in terms of market design and in terms of regulation for whether or not technologies that reduce transaction costs will get translated into value creation by asset owners being able to rent out excess capacity and trade energy with each other.

Using our model alongside Gawer's framework, we conceptualize electricity distribution platforms as " evolving organizations or meta-organizations that (1) federate and coordinate constitutive agents who can innovate and compete; (2) create value by generating and harnessing economies of scope in supply and/or demand; and (3) entail a modular technological architecture composed of a core and a periphery." (2014, p. 1240) Applying these models to electricity distribution suggests some clear functions and scope for a distribution platform – a retail market platform and a grid services platform – while still leaving some design details open for analysis. Potential gains from trade in distributed energy and gains from DER ownership can now exist, because a retail market platform can make the opportunity cost of idle capacity salient to owners and enable them to rent it to others.

The institutional implication of technology-induced reductions in transactions costs as seen in our model is a transactive distribution and market platform rather than a traditional vertically-integrated utility. Distribution platform functions fall into two categories: market functions and grid operation functions. Some proposals for distribution system operators (DSOs) combine these two into a single firm (e.g., Apostolopoulou et. al. 2016), athough some analysts argue that the integrated DSO model with the incumbent utility as DSO would lack transparency and accountability (Van Nostrand 2017). In this section we start by defining and analyzing these functions separately, and we end our discussion with an analysis of the implications of organizing them into a single firm.

The platform economy transaction modeled here involves residential ownership of DERs. When a DER owner is generating more energy than s/he is using, a market platform would enable a transaction with another agent who may want to purchase energy, creating gains from trade as in our two-person model. The availability of a market platform may also induce more investment in DER assets, as in our three-person and continuous models. In all cases, transactions cost reductions enable decentralized markets, which increases capacity utilization in the system because of the ability to trade.

The institutional design has three parts – market, organizational/business model, and regulatory – and the three parts are endogenous. Starting with market design makes sense because those rules shape incentives, but of course those incentives will also be shaped by the regulatory framework that creates the institutions that will shape both the organizational structure and the transactions that are and are not allowed to happen in markets.

4.1 Historical Background

Since the beginning of commercial electric power in the 1880s, vertically integrated firms have sold electricity as a bundled good to consumers for a fixed volumetric price that compensates them both for the fixed costs of wires and capital equipment and the variable costs of generation.[8] Separate real-time monitoring of electric current was technologically feasible by the 1950s, but bundling and vertical integration remained the status quo for the electric utility business and regulatory environment, until technological change in generation precipitated the regulatory and organizational changes that brought about competitive wholesale markets in the early 1990s. Before then, monopoly utilities only traded with one another to meet emergency needs, which meant that few high-voltage interconnections existed among service territories. In the United States, meaningful institutional change at the federal level occurred with the Energy Policy Act of 1992, creating the potential for wholesale electricity markets by reducing legal entry barriers to exchange, and allowing third-party generation and sales of electricity to distribution companies. A wave of unbundling of generation assets into separate companies ensued. As a result, today 75 percent of the US population lives in one of the 16 jurisdictions with a competitive wholesale power market.[9]

The history of liberalizing wholesale power markets in the US illustrates how technological change can reduce transactions costs and lead to organizational change. Innovation changed the transactional boundary of the firm, reduced the benefits of vertical integration, and made generation unbundling possible. In this regulated industry, though, organizational structure is a function of both technology and regulatory institutions. Firm boundaries are a function of both technology-induced and policy-induced transactions costs. New technologies also made possible both centralized and decentralized generation, diversifying the means of energy generation and in turn providing further support for the regulatory unbundling of energy from wires. Yet the regulation of energy and wires as a bundled good sold through vertically-integrated monopolists persists in many regions to this day.

Digital and DER technological change has created a second wave of innovation in electricity, this time at the distribution and retail level. As digital and DER technologies around the distribution edge have become more feasible and heterogeneous in nature and scale, they enable organizational unbundling of the vertically integrated distribution utility, self-generation at smaller scales for smaller customers, and organization of self-contained microgrid systems around the distribution edge. Furthermore, in retail markets when consumers can self-generate with electric vehicles or other forms of distributed energy, the existence of a retail market platform would enable such a

[8] For a more in-depth discussion of the historical background of regulation and innovation, see Kiesling (2015).

[9] In Canada, Alberta and Ontario also have liberalized their wholesale power markets, and Mexico is in the process of liberalizing its electricity industry and unbundling the government monopoly utility.

consumer to be a consumer in some conditions and a producer in other conditions, a phenomenon captured in our model.

4.2 Market Design: A Retail Market Platform Model

For a market like retail electricity, triangulation, transfer, and trust are essential dimensions of the environment. The magnitude of these transactions costs has been a principal element in the continuing economic regulation of retail and distribution. Physical location determines service location, and historically regulation has constrained prices, so regulation enforced triangulation. The means of transferring payment are the traditional monthly bills. And the heavy hand of the regulator is intended as the intermediary to assure trust between producer and consumer. This institutional framework has helped overcome these transactional impediments, but at a high infrastructure cost with undesirable environmental consequences and substantial excess capacity at some times (and congestion and insufficient capacity at others). As these transactions costs have fallen with the growth of smart grid technology, coordinating decentralized demand and supply with a market platform has become feasible.

The defining feature of a platform firm is that it acts as an intermediary connecting two or more agents for mutual benefit, and the most common economic role of a platform firm is intermediation in transactions by providing a market platform that brings together potential buyers and sellers and makes it easier for them to find each other. Consider the analogy to financial market exchanges, such as stock exchanges or futures exchanges, which provide trading platforms. By being attentive to the interests of both buyers and sellers, they define standard products and rules by which exchanges will occur, and provide timely information and a way for buyers to bid and sellers to offer, opening or closing new markets as the interests of buyers and sellers wax and wane. Our model suggests that the transactions cost reduction arising from digital and DER innovations can be used to monetize existing excess capacity and enable the industry to evolve in a lower-emission direction by providing a market platform that enables decentralized exchange and a transactive energy system.

A market design must specify certain rules for market participation, market operation, market clearing, and communicating the results to the interconnected devices and grid operators: who can buy and sell, how buyers submit bids, how sellers submit offers, the duration of the market period, market clearing rules, the price(s) buyers will pay and sellers will receive, and the actions that market participants and grid operators must take upon completion of market clearing in that period. Consider a retail market platform with markets for three goods: energy, reactive power or voltage control, and reserves (Tabors et. al. 2017). This combination of markets would provide a platform for coordinating the consumption, production, and ancillary services required for balance and resilience in the distribution network. The market platform company operates these markets, implements these rules, and charges a transaction fee to market participants.

Prices in this set of distribution level retail markets have to reflect not only the opportunity cost of energy from the resources that the assets provide, but also system conditions, such as congestion or scarcity on the distribution network. In electricity, such prices must communicate the heterogeneous spatial characteristics of the bidder, the supply resource, and grid conditions such as congestion. A market design with distribution locational marginal prices (DLMP) would satisfy these characteristics: "We argue that understanding of and ability to calculate DLMPs is the critical step in the power system and also provides the signals necessary for efficient physical operation of the system in much the same manner as LMPs provide those signals at the wholesale level." (Tabors et. al. 2017, pp. 2995-2996)

Owners of distributed energy resources will evaluate the prices in those markets at any given time and look at the opportunity cost to them of selling energy into each of those markets, and compare it with their own opportunity cost of using that capacity. This process maps into the rental choice in our model. In the sense having a website of retail energy markets and a platform around which to interconnect distributed energy resources will optimize not in the sense that is traditionally electricity, but in a more holistic economic sense that induces individual consumers to evaluate the value they attach to the distributed energy assets that they own and the opportunity cost to them of using those assets or selling the use of the assets into the retail energy markets. Retail energy markets are analogous to the rental market in our model because retail energy markets are essentially a means through which DER asset owners lease out or rent out the use of excess capacity to other people.

Demand-side market participants in the energy market will be end use consumers and retail demand aggregators (such as microgrids needing to purchase additional energy). Energy supply comes from retailers that purchase energy in the wholesale market and sell to their customers, retail aggregators (demand response and microgrids selling energy), and end users selling energy from their DERs (prosumers). In the markets for reactive power and reserves, supply-side participants are the same entities as in the energy market, reflecting the opportunity costs facing the owners of those assets – both the capacity of an asset and the consumption value that individuals attach to using their DER capacity contribute to those opportunity costs and can be reflected in all three markets through the offers that those potential suppliers submit in each market. The demand side in the reactive power and reserves markets will be a monopsonist: the grid services company/grid operator, which requires those ancillary services to maintain physical balance and network resilience in an efficient manner.

Auction design – the rules governing the submission of bids and offers, market time period, and market clearing – is an essential aspect of market design. Two types of auction design are relevant to electricity markets: single-sided and double-sided markets. Single-sided market design is used in procurement, in monopsony situations with a single buyer that states a quantity demanded and solicits offers. Suppose potential sellers have asset capacities less than that quantity, so multiple suppliers combine to meet the quantity demanded. Arranging offers from lowest to highest generates a supply curve, the intersection of which with the quantity demanded yields the market-clearing price and determines which producers will be called on. If the auction is a uniform-price auction those sellers all receive the market-clearing price; if it is a discriminatory auction each seller receives its bid. This market design (single-sided uniform-price auction) is common in wholesale power markets, where the demand curve comprises quantity bids from load-serving entities (typically distribution utilities) based on their load forecasts for that market period. One challenging problem with single-sided market design is inelastic demand, which can lead to higher prices than if the buyers had some price responsiveness.

A double-sided market design involves both buyers and sellers actively making (price,quantity) bids and offers. Unlike a single-sided market, buyer's bids include marginal willingness to pay for particular quantities, so a single buyer can submit different bids for each unit of the good to reflect varying values and diminishing marginal utility. When aggregated into a market demand, this bid variation makes the market demand curve more elastic. Double-sided market designs and double auctions are more information-rich, tend to converge to the market-clearing price more quickly, and less prone to market power, thus yielding high welfare (Smith 1962, Friedman 1984).[10]

In 2006 the GridWise Olympic Peninsula Testbed Demonstration Project was the first project to test a double-sided retail real-time market design in electricity (Hammerstrom et. al. 2007, Chassin & Kiesling 2008). The Olympic Peninsula project originated the field of transactive energy. This demonstration project, led by the Pacific Northwest National Laboratory (PNNL), tested a mixed residential, commercial, and industrial power distribution utility network with highly distributed intelligence and market-based dynamic pricing. 116 broadband-enabled households with electric heat-pump heating participated in the project, which lasted for the year April 2006-March

[10] Vernon Smith's pioneering double auction experiments in the 1950s were the origins of experimental economics. Other experimental economics research demonstrating the effects of double-sided auctions include Cason & Friedman (1996) and Gode & Sunder (1993), which analyzes the effects of having automated 'zero-intelligence' agents as double-sided market participants For a more recent analysis apply a double auction design to electricity markets, see Zou (2009).

2007. Of these, 112 remained in the project for the duration of the study. Each household received a two-way programmable communicating thermostat (PCT) with a visual user interface that allowed the consumer to program the thermostat for the home, and specifically to program it to respond to price signals if desired. Upon signing up for the project the households received extensive information and education about the technologies available to them and the kinds of energy use strategies made possible by these technologies. They were then asked to choose a retail pricing contract from three options: a fixed-price contract (with an embedded price risk premium), a time-of-use (TOU) contract with a variable critical-peak pricing (CPP) component that could be called in periods of tight capacity, or a real-time price (RTP) contract that would reflect a retail-level market-clearing price in 5-minute intervals. The RTP was determined using a uniform price double auction, in which buyers (residential, commercial, and industrial) submit bids and sellers (wholesale and retail-level distributed generation) submit offers simultaneously. The digital technology in the household enabled residential customers to participate actively in such frequent markets because they could automate the bidding of their demand functions into the market. This project was the first instance in which a double auction retail market design was tested in electric power, demonstrating the ability to achieve decentralized coordination in a distribution network through edge intelligence, algorithms, and automation in a retail market.

What are the implications of this market design theory and practice for a transactive digital retail market platform? The retail energy market can be a double auction with active demand and supply participation, enabling DER owners to submit offers to supply energy (i.e., renting their excess capacity in the terms of our model) and/or bids to buy energy as market conditions and their heterogeneous values and opportunity costs interact. In the reactive power and reserves markets, with the grid services company as the sole buyer, a single-sided market is traditional. However, these markets can be double-sided if the grid services company can calculate the marginal value of each additional kilowatt-hour of reactive power and reserves. The marginal and spatial nature of DLMPs, and the low-cost computation that algorithms and automation provide, makes a double-sided design feasible in these markets and thus may counter some of the negative welfare effects associated with monopsony power. Automation also enables DER owners to program their opportunity costs into their devices (solar PV, electric vehicle, home energy management system) to transact in all three of these markets. Automation and algorithms also accelerate and simplify the process of communicating the market period results to the DER devices and the grid operator, enabling a decentralized market process to generate real-time balancing.

4.3 Organizational Design: A Grid Services Platform Model

The technology-induced transactions cost reductions reflected in our model also imply changes in organizational design and changes in the business model of the utility. If the transaction cost reduction reveals value to consumers who own DERs being able to trade with each other, then the distribution utility can create value with its grid infrastructure as a grid services platform. Exchanging energy in a retail market is not as simple as trading other physical commodities. The unique nature of alternating current means that the contract path will never be fully specified and individuals on the network will never have fully specified property rights, even if transactions cost fall to zero. For this reason, there will be a role for centralized dispatch in the distribution network for the foreseeable future. In a decentralized market utilities will be required to provide centralized dispatch, real-time balancing, and other grid services that make it technically possible for individuals who own distributed energy resources to interconnect them on the grid and to be able to buy and sell energy and exchange with each other. Thus one implication of the transaction cost reductions arising from digital technology is that the regulated utility could evolve into a grid services platform physically connecting consumers and consumers who own production assets for mutual benefit.

The distribution wires network has always had economic value, but the nature of that value is changing as technology changes, and the distribution utility's business model can, and should, change to continue creating value from this central backbone. In the early decades of the industry, the distribution network helped local electric companies increase their generation capacity utilization and reduce their average cost by supplying electricity for lighting to residences in the evening and for transportation and industrial motors during the day. The distribution network made large-scale remote generation possible, enabling electric companies to create and exploit economies of scale and scope to reduce average cost even further. For most of the 20th century, the benefits of centralized generation and the relatively low cost of maintaining the distribution grid meant that it continued to have value.

But even in a decentralized, meshed network rather than the traditional linear network, the distribution network as a central backbone still has the potential to provide value to being interconnected. The two main value categories are insurance and exchange. A distributed energy installation that disconnects completely from the distribution network is independent and likely to be reliable and/or resilient, but in the case of system maintenance or an unexpected system failure, that system's owner/user(s) bear all of the cost incurred in the outage. A reasonable range of risk aversion is consistent with wanting some insurance, some backup for the times when such an outage will occur. An insurance contract for such backup would be valuable, depending on the relative risk aversion of the distributed resource owner. Backup entails some form of external distribution of energy to that system, and thus entails use of the distribution network. The distribution platform company would have to factor that probability and capacity into its investment plans for maintenance and expansion. One form this transaction could take in a platform model would be for the distributed system owner to contract with a retailer for energy backup, a transaction that would require wires backup, so the insurance charge would be an energy price and a wires charge. There are lots of different ways to price this contract – an annual fixed fee split between energy and wires (with the wires charge being part of an open-access tariff, along with the other standard distribution wires charges), and a pre-negotiated per-kWh energy price and wires price that would be incurred in the case of having to use the backup. Given how contentious the fights have been over the past two decades over standby charges and fixed fees charged to distributed system owners, the details of this insurance transaction are likely to be fraught and difficult to work out, but this form of insurance is one of the main benefits of a distribution network as a central backbone in a decentralized system.

A core function of a grid services platform will thus continue to be operating the distribution wires network. Given existing technology, and given initial conditions of existing physical distribution wires network, a central backbone distribution network is likely to continue to have economic value into the foreseeable future. To the extent that economies of scale and scope still exist in electricity distribution, a grid that is a central backbone will have value. Implementing a transactive system and retail markets through a market platform amplify this value, enabling decentralized value creation by connecting DER owners and others in exchange. Grid services that the utility has provided and a grid services company will provide include: interconnection, dispatch, energy delivery, network management, voltage and VAR control (VVC), frequency control (FC), and black start arrangements in case of a widespread outage.

The grid services platform will have the operational and regulatory requirement to deliver electricity services to end users. Accompanying that role are a resilience requirement, with some administrative definition of what constitutes resilience, and the physical real-time network balancing function. As a regulated monopolist the grid services platform earns a normal rate of return and the revenue to maintain and modernize infrastructure through a wires charge to retail customers, in combination with the transaction fees paid to the market platform.

The ability to separate and specify the grid services that the utility provides when it connects others it in the network as a platform, rather than being the provider of the energy commodity itself. Digital technology enables monitoring and transmission of data such as prices so that markets can exist. Measurement of the types of activities and information required to define and contract over energy, reactive power, and reserves become possible. In the analog electricity industry, all of these functions and transactions were subsumed into the vertically integrated, regulated utility. The return to the utility for performing those functions was captured in the rate of return that it earned on the assets and its rate base. In a platform business model, however, a grid services company can specify various services that it provides to the different parties to whom it provides them, and can charge service fees commensurate with the value of those services. In this sense even if the grid services company continues to be regulated utility, its accounting can and should change as the focus shifts from cost recovery and least cost provision of service to value creation. In this way the grid services company monetizes the value of the distribution grid assets that it owns: the wires, the transformers, the substations, and the control rooms.

4.4 Regulatory Design: An Institutional Framework for Transactive Platforms

INTERCONNECTION RULES

Regulatory institutions will play an important role in how this transition occurs and how this evolution plays out. Regulatory institutions shape the incentives facing utilities, consumers, and other parties participating in the retail network, and provide a framework for market exchange and other interactions or contracts that may emerge. Traditionally regulation is a process of rate determination based on cost recovery, using the utilities estimates of their costs of production and the estimates of their expected future investment in assets required to maintain reliable service. With competitive retail markets connecting DER owners, however, the nature of the regulatory function can and should shift away from rate determination and toward a more competition policy oriented approach. This approach entails a shift towards looking at risk characteristics of current of contractual retailers, and engaging in consumer protection by prosecuting fraud and providing information.

An electricity distribution platform ecosystem will involve heterogeneous agents in many scopes and roles – an electric vehicle owner can be both a consumer and producer where she was previously just a consumer; a private microgrid operator can aggregate demand and supply transactively within the microgrid and contract with the distribution wires company to provide ancillary grid services (e.g., voltage support, frequency support, black start service). As traditionally constituted, the utility would see these agents as substitutors, while in a platform ecosystem they are possible complementors if the wires company operates a market platform and earns a service fee for facilitating a multi- sided market. Regulators play a role in this ecosystem to the extent that the distribution wires network continues to exhibit the economies of scale and scope associated with a natural monopoly cost structure, in which case the wires will continue to be a regulated network with competitive markets on either side of the supply chain (wholesale and retail). Today utilities operate based on regulatory cost recovery, and any move toward a platform business model would have to meet the approval of the regulatory commission (or, as in the case of New York, be initiated through a Commission regulatory proceeding).

Given existing technology, fulfilling the core distribution role in the foreseeable future is likely to be a regulated function, retaining legal entry barriers. With this core role, the primary performance objective will be a measure of resilience and how well the distribution platform delivers reliable service. The role of the regulator will be to define, monitor, and evaluate performance metrics, and to evaluate the distribution platforms estimate of its infrastructure costs to maintain and invest in the assets to enable it to perform these functions satisfactorily. The introduction of a retail market platform suggests a role for the regulator in information provision, market monitoring, and consumer protection through information requirements and fraud reporting procedures.

One important focus of regulatory policy over the past century has been service reliability. Reliability has very strict technical definitions and is the primary focus of any determination of whether investments in assets or changes in allowed rates are deemed prudent. With digital technology and distributed energy resources, though, the traditional definition of reliability is becoming obsolete. Consumers now have more decentralized control through devices and through automation of their energy choices, both for production and consumption, and the traditional reliability definition of the power always being on and "I flip the switch and the light goes on" is not as relevant as it has been for the past century. Now consumers can use automation to control their response to information such as price signals, which makes retail energy markets transactive, and they could now choose whether or not they want a particular energy use or room in their house to be turned on or off at some different level of reliability then the uniform regulatorily-defined reliability standard that we have seen for the past century.

For this and other reasons, the concept of reliability is evolving into a broader concept of resilience. Define resilience as the ability of a system to rebound from some change in its status. For example, in an electricity system, how quickly does the system rebound from a storm or other natural disaster, or a terrorist attack? Resilience measures how quickly the system returns to some base state after a disruptive and unexpected event. Resilience is thus a more dynamic concept and a more dynamic measure of service quality than the traditional concept of reliability.

Distributed energy resources are themselves capable of providing resources that contribute to this resilience. They can, however, also disrupt the balance in the distribution network, especially if the resources are intermittent like wind and solar, and they put energy into the grid in ways that are difficult to control and in large amounts at any particular time. For these reasons, the shift to resilience as the regulatory objective and focus is reasonable and it enables regulators and power systems engineers who are designing the centralized dispatch capability to determine what rules and what technologies are useful to facilitate the balance and operation of the grid with so many heterogeneous, diverse, and decentralized resources all interconnected in the network.

In a transactive retail electric platform industry, the role of the regulator evolves toward consumer protection and toward enforcing a resilience standard.

4.5 Details and Open Questions

This set of designs – market design, organizational design, and regulatory design – does not give a full definitive account of the institutional details. Some important open questions still exist when thinking about the details of such a market design for a market platform and a grid services platform. The most prominent and important open question rests with the design of the market platform company and the grid services platform company. Should the same firm provide both of those platforms? And should that firm be the incumbent regulated utility?

Given the transactive distribution platform institutional design described above, some open question are:

- DSO vertically-integrated market and grid services platforms can create conflicts of interest and perverse incentives in market bids and physical dispatch;
- Incumbent as one/other/both creates the opportunity for incumbent vertical market power if regulations do not quarantine the monopoly (Kiesling 2014);
- Preferential incumbent DSO dispatch of resources owned by self or by related entities;
- Network architecture and how to pay for grid upgrades to enable two-way flow; and
- Distribution system planning.

DISCUSSION OF EACH OF THE FIVE TO COME

If we think of the grid services company and consider that company as the distribution system operator or DSO, one question about having that firm also be the market platform company is the question of conflicts of interest and market power. The grid services company will be the buyer in the reactive power market and would be the buyer in the reserves market. If this firm also operates the market platform, a difficulty arises because then the firm that's operating the market platform is also a market participant in at least some of the transactions that occur on the platform. This conflict of interest and set of incentives that may not be aligned with efficiency or consumer surplus maybe a problem. If the incumbent is the market platform operator, then the market power problem arises again in the reactive power in reserve markets because then you have the incumbent as the buyer and this raises the potential for incumbent vertical market power in this market, where the incumbent would be a monopolists a nest. Another potential conflict of interest question arises when the grid services company-distribution system operator is responsible for the dispatch order it when the markets clear some resources will be dispatched to generate and sell and others will not. If the incumbent operates the distribution system operator and the great services company, and also operates the market platform, if that incumbent has an affiliated relationship with any owner of any of the resources participating in the market, they may have an incentive to choose the order of dispatch of resources that favors their affiliated companies.

As the end users become more heterogeneous and can possess more diverse technologies, the distribution company would create additional value by facilitating the interconnection of those agents and their technologies to the distribution network and the connection of agents, most likely in transactions. In that sense a distribution platform would layer market platforms on top of the physical distribution network. The existence of these retail market platforms would generate incentives and opportunities for entrepreneurs to develop devices that can operate on that platform (e.g., vehicles, home energy management) and applications that connect the owners of those devices to other agents via the platform. For this market facilitation the distribution platform would earn a service fee (details about per transaction or per kWh remain an open question).

Note that the availability of these potential decentralized transactions may also serve the insurance role, because an interconnected DER owner could transact with another DER owner in the case of an individual system problem. In that case exchange enables DER owners to insure each other mutually, and the beneficial role of the distribution platform is facilitating the data and current connection, for which the distribution company earns a (per kWh) wires charge.

Unlike a traditional wires-only business model, a platform model emphasizes the role of the firm as an intermediary facilitating the interactions of agents in the network. A platform model does imply some technological differences in the distribution network compared to the traditional distribution grid architecture. The architecture of the distribution grid is designed for one-way current flow, from generator to end user. In a technological context with few large-scale generators and many users, one-way flow was a cost-effective architecture choice. But smart grid and distributed resource technologies have the potential to enable smaller-scale generation and distribution throughout the network, and to enable small-scale transactions between distributed agents, which would require a network capable of two-way current flow. Digital sensors and other distribution automation technologies allow for more transparent monitoring and balancing of two-way flows in a distribution network, but the distribution grid as currently built, configured, and operated cannot provide the central backbone for a platform utility; thus moving to a platform model would take advantage of the widespread transaction cost reductions, enable innovation around the distribution edge, and create a business model for investing in innovation within the network.

5 Conclusion

Deciding to buy a rooftop solar system or an electric vehicle provide examples of how a transactive system, with a market platform and a distribution grid services platform, can influence DER ownership choice. The potential to sell excess energy from a solar system, or to sell stored energy from a car battery, increases the probability that a consumer would be willing to buy the asset, knowing that s/he can monetize some of the value of the asset. Similarly, in making that decision the consumer may decide to purchase a larger-capacity solar system. 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.

Smart grid technologies and the increasingly decentralized capabilities of a physical and digital smart grid network change the nature of the types of actions, interactions, relationships, and organizations that are possible in the electric system. Types of generation technologies become more heterogeneous, both in fuel type and in scale, and can be situated differently in the network. Types of consumption can also become more heterogeneous. Agents in the network are no longer only generators, consumers, or transporters (i.e. wires owners) specifically; agents can now be both generators and consumers due to electric vehicles. Economic agents can take on multiple roles where before each had only one role. By changing what role agents could take, the scales at which they can operate, and the knowledge that is now accessible at the edge of the network, digital technologies change the role that the distribution utility can play in the system. It thus changes both the possible utility business models and regulatory institutions. These changes arise from digitally-induced reductions in transaction costs.

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 Coasian 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.

The reason that people own assets is to secure, at low transaction costs, the stream of services associated with that asset. But if it were cheaper and more convenient to rent, or to secure the services in some hybrid manner that doesnt exactly fit our current notions of "ownership," we can anticipate that such changes might rapidly dominate some markets. These markets are likely to have the feature that there is high notional excess capacity as well as high, but cheaply reducible, transaction costs for gaining access to this excess capacity. The nature of the transaction costs themselves can usefully be divided into categories: triangulation, or gaining information and finding locations; transfer, or effecting the actual exchange and making payment; and trust, or enabling confidence that buyers and sellers can rely on the terms of the negotiated deal to be implemented with (much) cost or hold-up problems.

The potential benefits arising from exchange that our model identified are the biggest reason for the distribution business model to be a platform. The mission of the firm evolves from providing reliable commodity electric service to all end users in geographical territory to facilitating their mutually-beneficial connections as a grid services company.

Consequently, the regulatory and business model conclusion of this analysis is that falling transaction costs should lead to lowering legal entry barriers to retail markets and unbundling retail service from the vertically-integrated distribution utility. The result is a distribution wires company and multiple rival retail service providers. This regulatory move would set up the legal conditions under which the distribution wires company could operate as a wires and market platform, earning wires fees for its distribution services and service fees for its market facilitation. This regulatory framework and business model would be conducive to innovation around the distribution edge, and would also enable innovation within the distribution network to facilitate the two-way flow of energy and the beneficial economic and environmental outcomes associated with it.

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