Beneficial Complexity: A Field Experiment in Technology, Institutions, and Institutional Change in the Electric Power Industry

Lynne Kiesling[1] and David Chassin[2]

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Abstract: This paper presents and analyzes the results of a recent field experiment in which residential electricity customers in Washington State with price-responsive in-home devices could use those devices to change their electricity consumption autonomously. Doing so also required an important institutional change: the regulatory institutions had to change to allow dynamic pricing. Customers could choose a retail pricing contract from a portfolio of contracts, instead of the fixed, regulated retail rate. Here we focus on the results of the real-time contract, under which homeowners participate in a double auction with a market clearing occurring every five minutes. These customers saved money, and their peak demand (and pressure on infrastructure at peak capacity) fell by 15 percent. Moreover, this combination of technology and institutional design enabled decentralized coordination, and we use complexity science to interpret results that show that the real-time market outcomes were those of a self-organizing and scalable complex adaptive system. We also draw policy implications from these results.

I. Introduction

For the past century, both the economic and the physical regulation of the electric power industry have been premised on the need for centralized control – economic regulation based on natural monopoly theory is a centralized institution, as is physical grid management through control room operators turning off entire substations to maintain system balance. This focus on centralized control has been a function of technological necessity, due to the nature of alternating current electric power flow and the way that integrated generation and distribution technologies historically led to vertically-integrated firms. Regulatory institutions, with their origins in the technological and social context of the early 20th century, consequently incorporated this focus on centralized control, leading to government-granted exclusive service territories, cost-recovery-based price determination, and strict regulatory control over retail prices and product offerings.

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[1] Corresponding author: Department of Economics and Kellogg School of Management, Northwestern University, and Pacific Northwest National Laboratory (lkiesling@northwestern.edu).

[2] Pacific Northwest National Laboratory.

Over the ensuing century, though, many technological and social changes have transformed other aspects of our environment. Despite these dramatic changes, the technology used in the electric power industry, and the regulatory institutions that govern the transactions and decisions in the industry, are substantially unchanged from their forms a century ago.[3] Most of the physical assets in the electric power network remain electro-mechanical, although the costs of digital communications technology are falling and their benefits are large (including remote fault sensing and repair, automated substation and distribution management, and advanced metering that provides more information to consumers and enables retail product extension and differentiation). Similarly, the regulatory institutions remain focused on controlling retail prices to consumers (especially residential customers) by controlling the investments that utilities make. The dominant regulatory objective of the past century was to keep retail electricity prices as low and stable as possible while ensuring a reasonable rate of return for the utility; the means of achieving this objective have traditionally included rate-of-return regulation based on historic cost recovery, imposition of an obligation to serve on utility in return for the government-granted monopoly, and regulatory prudence review of utility investment proposals. This drive to control retail prices by limiting utility costs is becoming increasingly problematic as fuel costs rise and concerns mount about the environmental implications of fossil fuel use; a regulatory policy that keeps prices low and stable induces more electricity use, and is thus in tension with growing environmental concerns and other related policy objectives.

This paper presents a field experiment that confronts these issues from a technological and institutional design perspective, and shows how technological change and institutional design can lead to decentralized coordination in a complex adaptive system. In particular, this experiment with a set of households in Washington State tested a combination of digital end-use technology and institutional design. In the GridWise^{TM} Olympic Peninsula Testbed project, each household had a price-responsive thermostat and price-responsive water heater that could be programmed to respond autonomously to changes in electricity prices over the course of the day. The institutional design feature of the experiment was enabling prices to change (dynamic pricing) instead of being fixed and averaged; households could choose a retail contract from a

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[3] The one meaningful exception to this claim is the combined-cycle gas turbine generator, which led to the opening of wholesale power markets in the U.S. and elsewhere.

portfolio of contracts. Did this combination of distributed end-use automation technology and retail dynamic pricing make consumers better off while maintaining system reliability, preventing outages, and providing other supply-side and infrastructure benefits? The short answer is yes, and the body of the paper explains how those beneficial results were achieved.

In particular, this paper focuses on a set of results from the project participants who were on the real-time price contract. The results from this group are the most groundbreaking in several dimensions. First, the design of the real-time market was innovative; this was the first time that residential customers have ever participated in a real-time double auction. Second, although common wisdom in this industry suggests that residential customers avoid price volatility and do not prefer a real-time contract, in this case most of the participants preferred it both *ex ante* and *ex post*, because they knew they had the enabling technology to make their responses and participation autonomous. Finally, and most important from a theoretical and methodological perspective, the network of distributed price-responsive technology changed the network and the control environment. No longer was this a centralized control environment in which the only way to manage the grid was through centralized decisions to shut substations down; the distributed technology accessed the intelligence, the diffuse private knowledge at the edge of the network, in the preferences of the residential customers themselves. Thus the distributed technology changed the network to a distributed, complex adaptive system by making the network transactive. Such complex adaptive systems are capable of self-organization, and in this paper we discuss evidence from the experiment that suggests that the real-time market in the Olympic Peninsula project did form such a self-organized system. In other words, the combination of distributed technology and institutional design that allowed dynamic pricing enabled decentralized coordination to occur in the system instead of centralized control being imposed.

In Section II we describe the project, its technology, and its institutional design. Section III reports the results and our analyses of the results from a complexity science perspective. Section IV concludes with policy recommendations.

II. The Field Experiment: The GridWise Olympic Peninsula Testbed Project

The GridWise Olympic Peninsula Testbed project was a demonstration project, led by the Pacific Northwest National Laboratory (PNNL), testing a mixed residential, commercial, and industrial power distribution utility network with highly distributed intelligence and market-based dynamic pricing.[4] Washington's Olympic Peninsula is an area of great scenic beauty, with population centers concentrated on the northern edge. The peninsula's radial electricity distribution network is connected to the rest of the network through a single distribution substation. While the peninsula is experiencing economic growth and associated growth in electricity demand, the natural beauty of the area and other environmental concerns mean that the residents wanted to explore options other than building generation capacity on the peninsula or building additional transmission capacity.

Consequently, Bonneville Power Administation (BPA) initiated an effort to address the transmission constraint through a so-called non-wires solution, among others. Siting a test bed where a real need for alternative supply solutions is already apparent increases the likelihood that any demonstrated benefits may be clearly recognized and rapidly adopted. These considerations provided a strong incentive for selecting the Olympic Peninsula's distribution system as a prime project site where GridWise technologies could address a present need and be demonstrated unambiguously.

Thus this project tested the combination of enabling technologies and market-based dynamic pricing to investigate the effects of dynamic pricing and enabling technology on utilization of existing capacity, deferral of capital investment, and the ability of distributed demand-side and supply-side resources to create system reliability. Two questions were of primary interest in this project: (1) what dynamic pricing contracts are attractive to consumers, and how does enabling technology affect that choice? (2) to what extent will consumers choose to automate energy use decisions?

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[4] For more information on the project, see Hammerstrom et. al. (2007).

116 broadband-enabled households with electric heat-pump heating participated in the project, which lasted for the year April 2006-March 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. Households also received dryers equipped with a GridFriendly™ appliance (GFA) controller chip developed at PNNL that enables the appliance to receive price signals and be programmed to respond automatically to those price signals. Consumers could control the sensitivity of the appliance through the PCT settings.

These households also participated in a market field experiment involving dynamic pricing. While they continued to purchase energy from their local utility at a fixed price, they also received a cash account with a pre-determined balance that was replenished quarterly based on their historical energy consumption. The energy use decisions they made would determine how much was deducted from their cash account, and they were able to keep any difference as profit. The worst a household could do was a zero balance, so they were no worse off than if they had not participated in the experiment. At any time customers could log in to a secure web site to see their current balance and how effective their energy use strategies were.

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 is the first instance in which a double auction retail market design has been tested in electric power, and the use of a retail double auction with residential customers in the market is one of the unique features of this market design.

The households ranked their contracts, and were then divided fairly evenly among the three types and a control group that received the enabling technologies and would have their energy use monitored, but did not participate in the dynamic pricing market experiment. All but 11% of the households not placed in the control group received either their first or second choice (49% and 16% respectively); interestingly, nearly 90% of the households ranked RTP as their first or second choice. This result counters the received wisdom that residential customers want only reliable service at low, stable prices, but may be enhanced by an early-adopter effect.

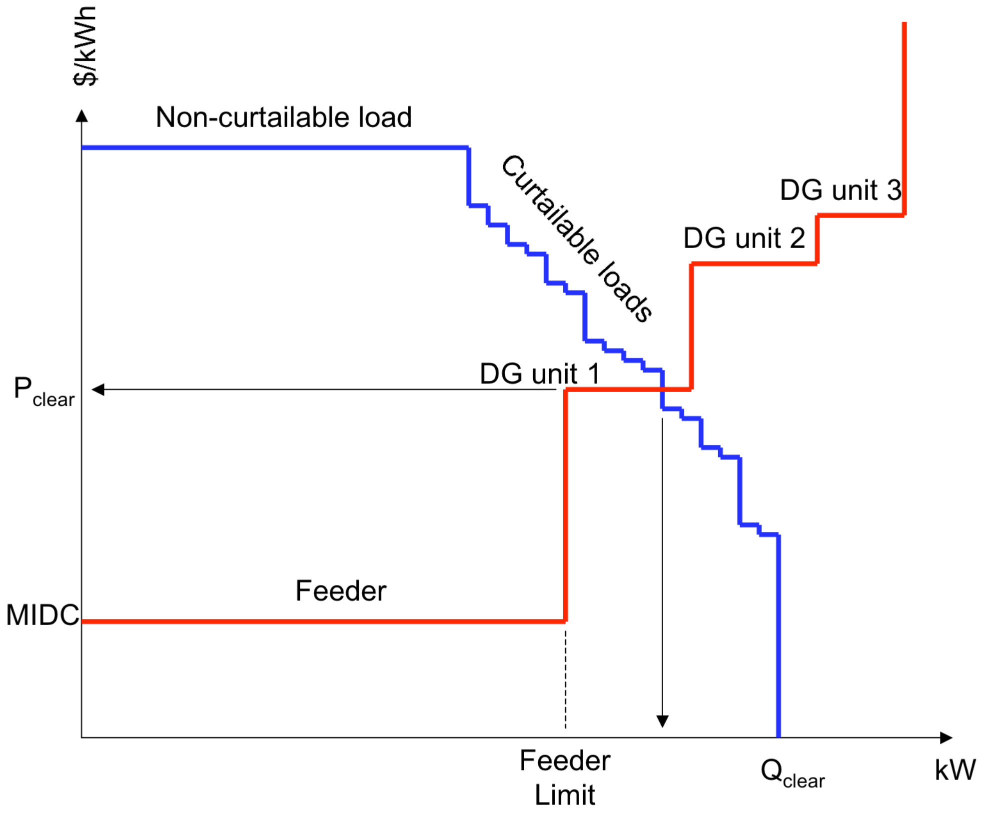
Of the 116 households, 30 were in the fixed price contract, 30 were in the RTP contract, 31 were in the TOU contract, and 25 were in the control group that received the digital technology but did not participate in the market experiment.

The control group participants were not charged for their energy consumption. Fixed price group participants were charged 8.1¢/kilowatt hour (kWh). The TOU participants were charged under two different rate structures depending on the season. During the fall, winter and spring seasons (1 Oct – 24 Jul), the off-peak (9:00 AM – 5:59 PM and 9:00 PM – 5:59 AM) price was 4.119¢/kwH, and the on-peak (6:00 AM – 8:59 AM and 6:00 PM – 8:59 PM) price was 12.15¢/kWh. During the summer period (25 Jul – 30 Sep), the off-peak (9:00 PM – 2:59 PM) price was 5.0¢/kWh, and the on-peak (3:00 PM to 8:59 PM) price was 13.5¢/kWh. A single CPP event was called Nov 1 from 2:00 AM to 6:00 AM, with a price of 35.0¢/kWh. The RTP participants were charged the price of energy as cleared every five (5) minutes by a retail-level level market.

The system was operated with different constraints on the distribution feeder at different times of year. From Apr 1 to Sep 22, the feeder capacity was set to 1500 kilowatts (kW) and the mid-Columbia River (MIDC) wholesale price of power reported by Dow Jones was bid at the feeder level. From Sep 22 to Dec 8, the feeder capacity was reduced to 500 kW, and from 8 Dec to Mar 31, it was increased to 750 kW. Altering the feeder capacity enabled us to test how capacity constraints would affect retail prices, and how customers would respond to those prices; it also created the opportunity to observe the extent to which these decentralized decisions would aggregate into system reliability and other beneficial system characteristics.

In this paper we focus on the behavior of the residential customers on the RTP contract, and on the features of the real-time retail markets in which they participated. Figure 1 represents how the active RTP households and the DG resources could interact to determine the market-clearing price in 5-minute intervals.

Figure 1: Representative Supply and Demand in 5-Minute RTP Market



These institutional design and technology features provided the environment in which participants made their own electricity consumption and behavior automation decisions.

III. Results and Analysis

A. Consumer Benefits

We focus on some of the most important economic results of this project: household energy consumption, prices paid, household savings, and changes in overall load duration. Table 1 presents the average hourly household energy consumption by contract group. The average household in the TOU contract group consumed the least electricity per hour (1.42 kW), followed by the average fixed price customer (1.79 kW), the average RTP customer (2.1 kW), and finally the control group (2.116 kW).

Table 1
Mean and standard deviation of hourly household energy use by group

Group	Mean (kilowatts)	Standard deviation	Number of observations
Control	2.116	1.25	8759
Fixed price	1.790	0.84	8759
TOU	1.420	0.77	8759
RTP	2.100	1.00	8759

These consumption patterns differ statistically from each other based on nonparametric pairwise Wilcoxon signed-rank test across the groups (Hammerstrom et. al. 2007, p. 7.6). Thus we found that the type of dynamic pricing contract did shape individual behavior. Furthermore, note that the incentives inherent in different forms of pricing led to different average consumption beyond just having the technology, as was the case for the control group. This result suggests that simply the transparency and information provided by the technology does not necessarily reduce electricity consumption as effectively as the combination of the technology and the dynamic pricing with its embedded economic incentives.

The consumption data presented in Table 1 suggest that the TOU contract households consumed less energy than the other customers. After controlling for price response, weather effects, and weekend days, the TOU group's overall energy consumption was 20 percent lower than the fixed price group's (Kiesling 2008, Chapter 4 Appendix). This result indicates that the TOU (with occasional critical peaks) pricing induced the greatest overall energy conservation and reduction in electricity use.

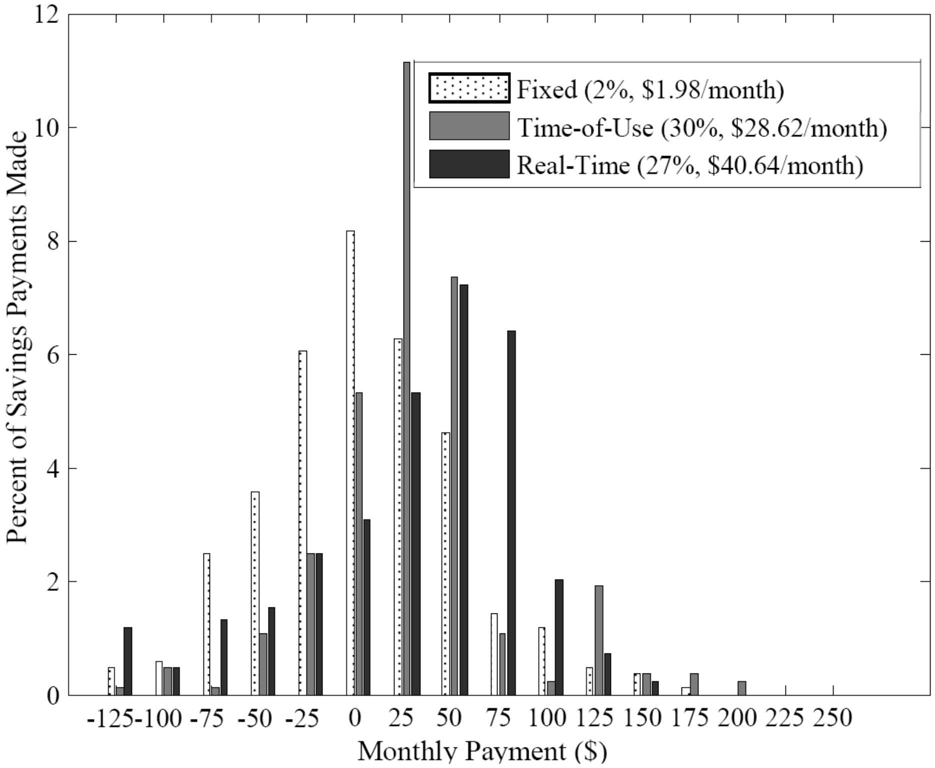
Table 2 reports the average hourly price per megawatt hour (MWh) by contract group. This was computed as a blended average by dividing the total energy consumed by the total payments made for each contract group. In the case of the control group, this price could not be computed because they did not pay for energy used.

Table 2
Mean and standard deviation of hourly average price/MWh by group (dollars)

Group	**Mean ($/MWh)**	**Standard deviation**	**Number of observations**
Control	n/a	n/a	n/a
Fixed price	81.000	0.000	8759
TOU	63.271	35.904	8759
RTP	49.198	47.462	8759

The low average price for those on the RTP contract indicates that the RTP customers used their automation and control capabilities to shift their use to less expensive times. The customer savings achieved corroborate this observation. Figure 2 shows average household savings by contract group.

Figure 2: Monthly Savings Estimate By Contract Group



Participants in the fixed-price contract received about 2 percent savings relative to the control group; the TOU group saved 30 percent and the RTP group saved 27 percent. Note the difference in the distribution of the savings across the three groups. The RTP savings are skewed substantially to the right of the other two groups. This distribution of RTP savings indicates the significantly greater savings earned by the RTP customers who selected the most economical appliance settings, relative to those who selected more comfort and did not earn such savings.

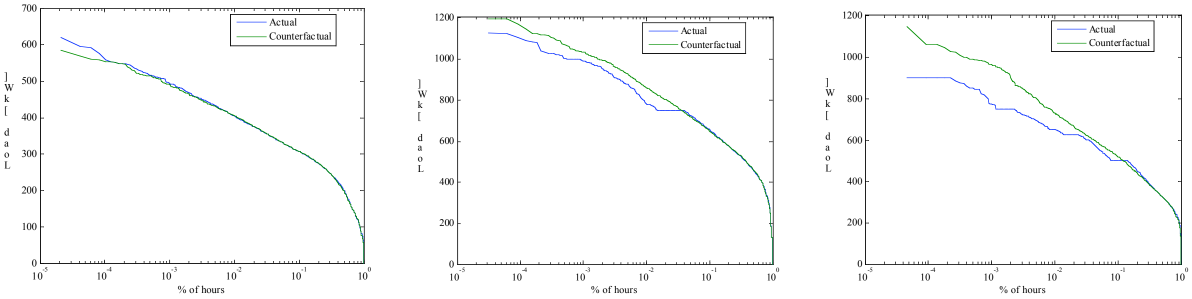
Finally, the project's participants were very satisfied with the technology and the pricing with which they experimented during the project. Final project participant surveys indicate that 80 percent of participants were either very satisfied (51%) or somewhat satisfied (29%) with the end-use technology, and that 82 percent were either extremely likely (48%) or very likely (34%) to participate in a program like this one if it were offered again (Hammerstrom et. al. 2007, p. A.11).

B. System Benefits

In terms of peak demand reduction, the RTP group saw peak consumption decreases of 15-17 percent relative to what the peak would have been in the absence of the dynamic pricing. Figure 3 shows the actual and the counterfactual load duration curves (graphed logarithmically) divided among the three system condition categories during the year: when the distribution feeder was unconstrained, moderately constrained, and severely constrained. The horizontal axis shows the total number of hours, in percentage terms, that consumption occurred at a particular level; the vertical axis shows the level of consumption, expressed logarithmically.

In essence a load duration curve shows the distribution of consumption over time; if consumption were distributed uniformly, the load duration curve would be a straight line, and capacity utilization or load factor would be the same at all times. Flattening the load duration curve, which indicates shifting some peak demand to non-peak hours, improves capacity utilization and reduces the need to invest in additional capacity, for a given level of demand. The peak load reduction due to the RTP group is seen at the top left corner, where the actual curve is substantially below the counterfactual curve. Note Figure 3(c) in particular, which presents the load duration when the distribution feeder was most constrained. This result shows how extensively the RTP market and demand response automation reduced demand relative to the level of demand without the combination of the RTP market and the distributed residential automation technology. A 15-17 percent reduction is substantial, and is similar in magnitude to the reductions seen in other projects, such as the California Statewide Pricing Pilot (CRA 2006).

Figure 3: Actual and counterfactual load duration curves for (a) unconstrained, (b) moderately constrained and (c) very constrained systems



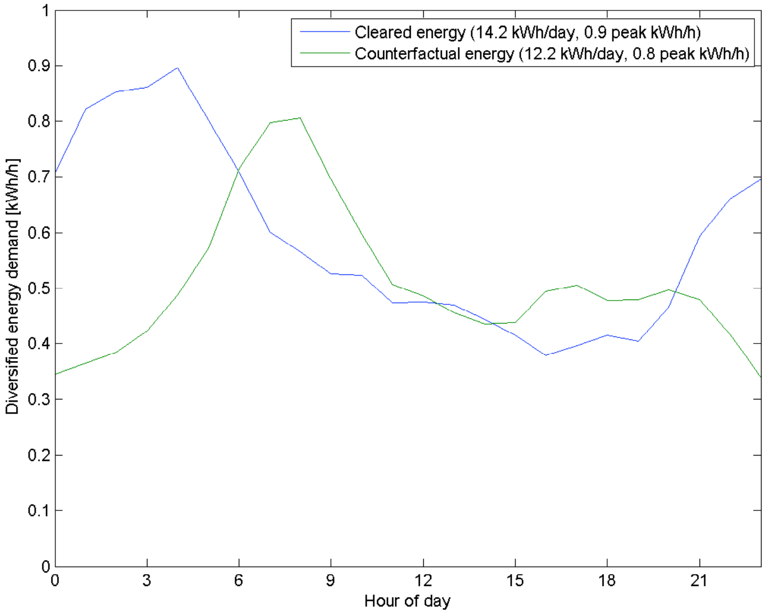
(a) (b) (c)

In addition to the reduction in peak demand in the RTP group, they also had a shifted load shape as a result of the dynamic pricing and the automated technologies that responded directly to market price signals. Figure 4 shows the actual and counterfactual thermostat loads for thermostatically controlled space conditioning of RTP contract homes during the most-constrained and least-constrained periods on the distribution feeder. Because all participant bids for RTP contracts were recorded when the market cleared every 5 minutes, and the bid price formula based on the thermostat status is reversible given the information gathered during the project, both the actual and the counterfactual energy could be computed for each market period. The counterfactual energy is the amount that would have been consumed at the average price in that market period instead of the market-clearing price as determined by the double auction.

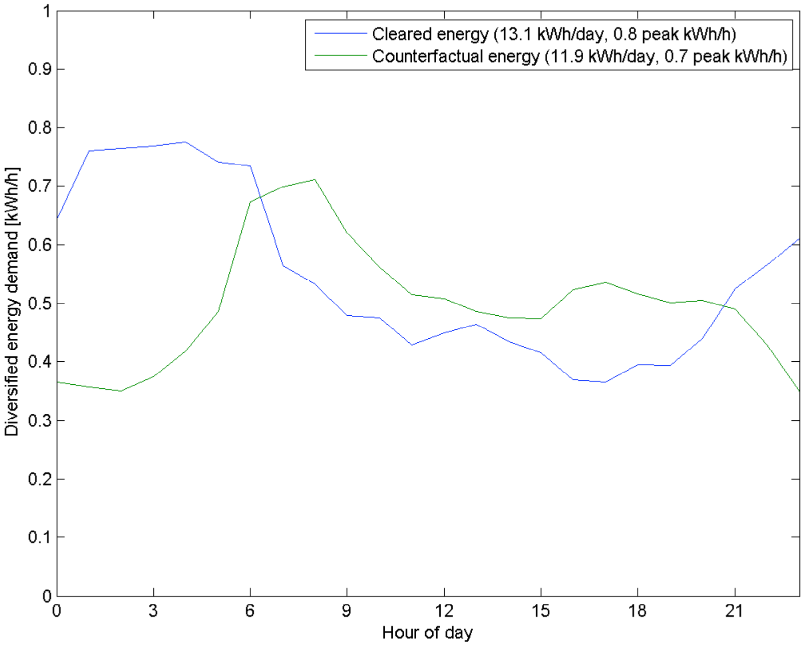
The RTP induced an interesting shift in this automated consumption in both constrained and unconstrained feeder conditions. When demand was high and the feeder was constrained, the shift of demand from peak to off-peak was large, induced by the differential between peak and off-peak market-clearing prices. On unconstrained feeder days, however, the moderation of price volatility meant that the thermostats were sensitive to smaller diurnal price variations. While the transactive control strategy did not explicitly forecast future prices, the diurnal nature of the price movements themselves effectively induced opportunistic pre-heating or pre-cooling. The use of pre-heating/pre-cooling is generally viewed as an essential mechanism to mitigate the effect of load curtailment rebound phenomena. Effective pre-use strategies can be very difficult to engineer, and it is encouraging to see that market-based strategies are at least as effective as administered ones. Figure 4 shows the diurnal load duration curves for the RTP group during the period of constrained feeder (4a) and unconstrained feeder (4b).

Figure 4. Diurnal load duration curves, RTP group

4a. Constrained feeder, high demand



4b. Unconstrained feeder, low demand



These results suggest that the institutional design and technology led to consumption behavior in the RTP group that is consistent with important system (and therefore policy) objectives – reliability, real-time system balancing, and increased capacity utilization.

C. The Real-time Market as a Self-Organized Complex Adaptive System

To understand the individual and aggregate behavior of the technology-enabled customers on the RTP contract, we draw insights from the literature on complex adaptive systems.[5] As Tesfatsion (2001, p. 1) observes,

> Decentralized market economies are complex adaptive systems, consisting of large numbers of buyers and sellers involved in massively parallel local interactions. These local interactions give rise to macroeconomic regularities such as shared market protocols and behavioral norms that in turn feed back into the determination of local interactions. The result is a complicated dynamic system of recurrent causal chains connecting individual behaviors, interaction networks, and social welfare outcomes.

Markets are complex adaptive systems that involve large numbers of distributed actors and rules, or institutions, governing their interactions. A complex adaptive system has a large number of diverse actors, or agents, that interact. These agents react to the actions of other agents and to changes in the environment. The agents are autonomous, so control and decision-making are decentralized and distributed in a complex adaptive system. Through their interactions, the agents in the system adapt to the changes that they themselves help to bring about through their independent decisions. This distributed learning and decision-making process leads to potentially unanticipated changes in the environment, but a principal defining characteristic of a complex adaptive system is that it is self-organizing, and that self-organization, or order, emerges from the interaction (i.e., is an emergent property).

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[5] This discussion draws on the more extensive treatment in Kiesling (2008), Chapter 3.

1. Technology + institutional design => a self-organizing complex adaptive system

Modeling markets as complex adaptive systems enables social scientists to explore several important features that characterize real-world markets, including the real-time retail market in the Olympic Peninsula project. These features include:

- Individual agents (most simply, buyers and sellers) with diffuse, and often tacit, private knowledge. This distributed intelligence characterizes complex systems, whether or not a system has the capacity to be adaptive.
- Agents who can respond both proactively and adaptively to changes in constraints and in the environment.
- Institutions, both formal and informal, that shape the rules that agents use to make decisions.
- In aggregate, the emergence of coordination and order from these decentralized decisions and actions, leading to self-organization.[6]

In the presence of knowledge constraints and cognitive limitations, such as sheer ignorance (Kirzner 1992) or bounded rationality (Simon 1996), market processes enable these agents to achieve their plans mutually. In the process of doing so market processes generate and aggregate information that reduces uncertainty and ignorance; this information also enables agents to adapt by revising their plans and actions. Following Hayek (1945), here we take diffuse, private, and tacit knowledge as given, and focus on the role of economic, legal, and social institutions in aggregating that diffuse knowledge and enabling decentralized agents to coordinate their plans and actions.

How does this decentralized coordination occur? In market processes, it occurs through prices (Hayek 1945). Prices allow for the decentralized coordination of plans among distributed, heterogeneous agents with private knowledge. Price signals act as coordination mechanisms in two distinct ways (Kirzner 1992, pp. 144-146). First, in a market in equilibrium, the equilibrium price signals to individual agents what their decisions should be. In particular, price signals to

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[6] A good recent articulation of economic coordination and self-organization from a complexity science perspective is Page (2004).

lower-value consumers and higher-cost producers that they are low value and high cost, respectively. Second, in a market in disequilibrium, price signals communicate information that results in agents making systematic changes to their bids and offers; these changes themselves enhance the degree of coordination via feedback mechanisms. Note that this type of coordination is the primary reason why the double auction design, in which buyers and sellers make simultaneous bids and offers that are visible to all agents, is the most efficient market design; its information richness provides ample opportunity for feedback mechanisms to enable enhanced coordination. Price signals are an information flow that may lead agents to revise their decisions, resulting in a higher degree of coordination of plans. This set of ideas is at the core of the Olympic Peninsula's real-time market design.

Achieving decentralized coordination in complex human systems requires institutions. Institutions are the "rules of the game" (North 1990, p. 6), the "incentive structure of economies," (North 2005, p. vii), the rules that structure the actionable situations in which agents interact. Ostrom gives a broad definition of institutions:

> Institutions are the prescriptions that humans use to organize all forms of repetitive and structured interactions including those within families, neighborhoods, markets, firms, sports leagues, churches, private associations, and governments at all scales. Individuals interacting within rule-structured situations face choices regarding the actions and strategies they take, leading to consequences for themselves and for others. (Ostrom 2005, p. 3)

This definition encompasses both formal and informal rules in a variety of contexts, addressing a range of different challenges that arise in social interaction. Such rules include property rights and use rights; they govern contracts, and they shape the extent to which agents organize transactions through firms or through market processes.

Institutions affect the coordination of diffuse private knowledge. Take the simple example of a financial market for a commodity. Suppose the market rules say that sellers submit (price, quantity) offers – how many units they are willing to sell and the price at which they are willing to sell – and buyers then choose how many units to buy. This institution, or set of rules, will lead to different outcomes, convergence paths, and strategies than, say, a double-sided market where buyers and sellers submit bids and offers simultaneously. The latter institution taps into diffuse knowledge more deeply because it elicits bids from buyers that the other institution does not. Similarly, retail price regulation elicits only information on how much electricity different consumers are willing to consume at that price (and analog meters do not enable the firm to gather that information in anything even approximating real time!).

Institutions or rules enable agents to form expectations, which is crucial for any form of non-simultaneous, inter-temporal exchange. We form expectations of the potential benefits and costs of our actions, of the behavior of others, of the ability to get a benefit in the future if we incur a cost now, and so on. Therefore institutions help us create focal points that facilitate our attempts to coordination individual actions and plans (Schelling (1978)).

2. Self-organization in the Olympic Peninsula project

In the Olympic Peninsula project's real-time market, the combination of technology and institutional design created a self-organizing complex adaptive system. The real-time market was a network of individual agents, including individual residential customers with private, and often tacit, information about their preferences over electricity consumption and all other goods. We cannot over-emphasize the uniqueness of this feature of the Olympic Peninsula project's real-time market design – no other retail electricity environment has ever enabled such deep participation and information aggregation from all of the demand-side participants, especially residential customers.

The digital end-use devices make it possible for these agents to behave proactively and, more importantly, adaptively, by reducing transaction costs of their participation in such a market. Consumers can participate by programming devices to behave autonomously on one's own behalf, with simple rules that reflect individual preferences, and without having to make dramatic changes in lifestyle to participate in these markets that clear every five minutes. The technology enables decentralized individual bidding into the double-auction market, which creates the capacity for individuals to adapt to changes in their constraints and environment. Moreover, this highly granular bidding by so many distributed agents is what creates the adaptive capacity at an aggregate system level as well, through the interaction of their choices and the feedback effects from their choices into subsequent prices and system conditions.

Although the technology is crucial, institutional design also plays an important role in facilitating a complex adaptive system that is capable of self-organization. In this project, institutions shaped behavior in three distinct ways. First, the rules that allow dynamic pricing are necessary for making this system adaptive. Price regulation stifles that adaptation process; even when regulators approve rate changes because of fuel cost increases, the implementation lag disconnects behavior from the changes in the environment, and hence stifle adaptation. Second, a double auction is an efficient, information-rich market institution for aggregating the diffuse private knowledge of market participants. Choosing a double auction market design instead of another alternative changes outcomes in terms of convergence to equilibria, the efficiency of information transmission, and the distribution of the gains from trade (Smith 1962). Finally, the five-minute market clearing period allows for rapid adaptation to unexpected changes in constraints and the environment, such as weather effects or unplanned outages in generators, wires, or substations. Such unexpected changes can have dramatic effects in electric power networks, and such a fine-scale, granular clearing process allows information about those changes and the effects of the distributed responses to those changes to feed back through the system more quickly.

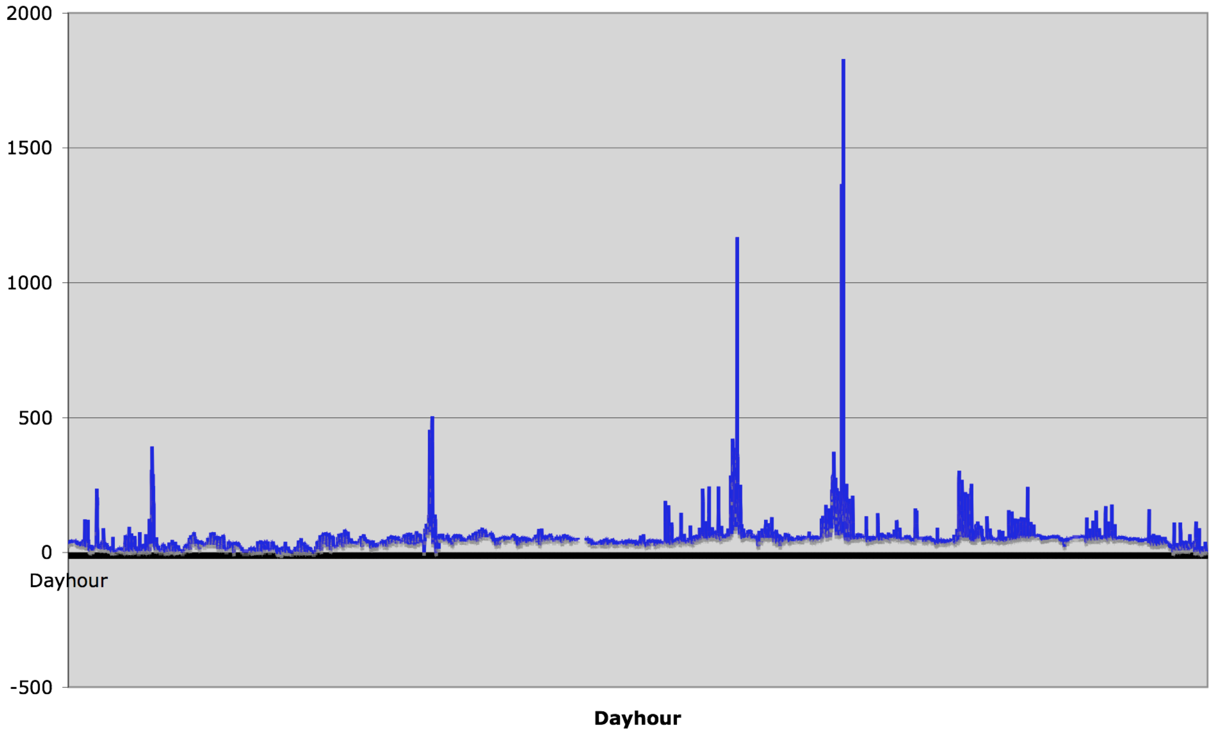
The real-time market in the Olympic Peninsula project demonstrated decentralized coordination and self-organization in several important ways. We highlight three pieces of evidence that are consistent with self-organization: relative price stability, reliability of service, and the distribution of individual household bid data.

Over the course of the year prices in the real-time market were relatively stable while reflecting underlying costs and changes in those costs. In this market, cost differences (and therefore price differences) were driven primarily by weather events. The combination of price signals and the ability of consumers to respond autonomously ensured that the real-time market had feedback mechanisms that led to relative price stability. Figure 5 depicts the hourly average price in the real-time market over the duration of the project. The short-lived price spikes in November and

December 2006 coincide with weather events (ice storms) that both increased the demand for heating and threatened to reduce supply by damaging wires and substations.

Figure 5

Hourly price in real-time market, April 2006-March 2007



A second indication of self-organization in the real-time market was the reliability of service achieved during the project. There were no unplanned outages during this project that resulted from a control room decision to reduce consumption to maintain system balance.[7] Recall that one of the motivations for the project was the increasingly binding constraint of distribution network capacity; as that constraint becomes even more binding, unplanned outages often occur, and take the form of a control room operator deciding to power down an entire substation. In this case, the price signals in the real-time market indicated to consumers when that constraint was more binding, and their autonomous consumption control choices provided a more granular control strategy than having a centralized operator power down an entire substation. Moreover, the

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[7] There were also no unplanned outages due to weather, but it would be incorrect to give the credit for that outcome to the institutional design!

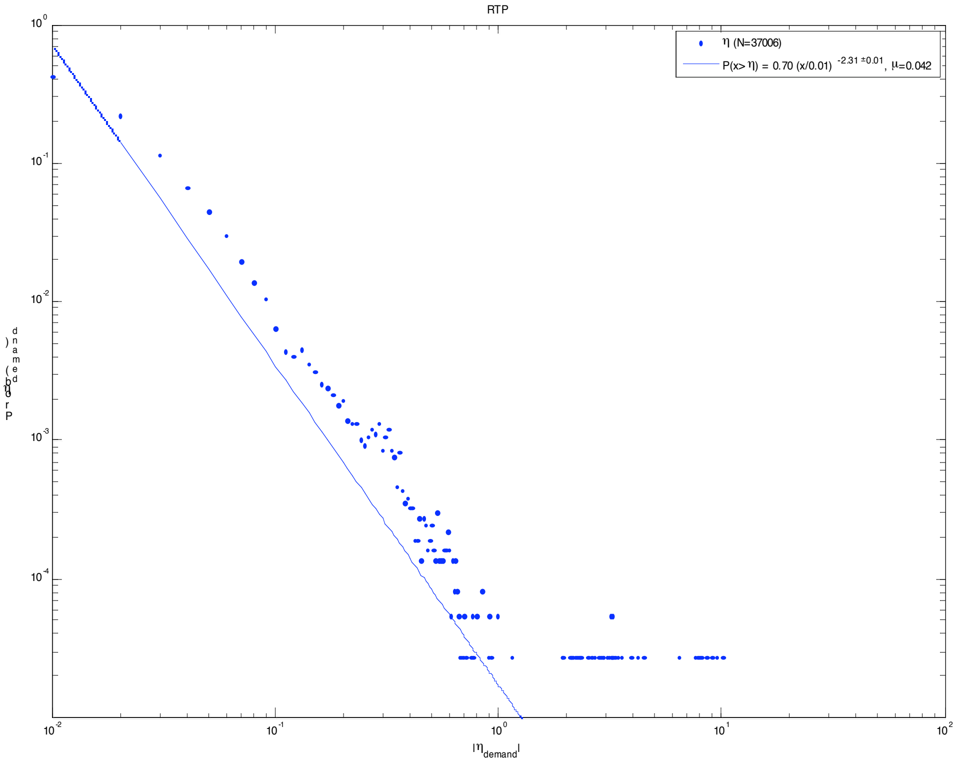
demand reduction that occurred in response to price signals reflected the relative value of different uses of electricity to different consumers, so the lowest-valued uses were reduced first. This reduction in priority order of value does not occur when a centralized control operator forces an outage. Even during ice storms in November and December, the price signals coordinated decentralized responses in a way that maintained system balance. This outcome is extremely important, because it indicates that decentralized coordination is possible *even in a system that requires real-time physical balancing*.

Our third set of evidence for self-organization in the real-time market is in the data on individual household bids. Unlike other markets or other demonstration projects, in the Olympic Peninsula project data we can evaluate these questions using direct data drawn from the actual submitted bids of the RTP households in the real-time market. Because the market is a double auction we have data on the actual bids submitted by the devices in the households (and the 2 commercial consumers). Using those actual bids, we calculated price elasticity relative to the market-clearing price, using the bids as the structural demand function. Thus, the demand elasticity is simply

$$\eta = \frac{Q_{clear}}{P_{clear}} \frac{P_{clear} - P_{bid}}{Q_{bid}}$$

Analyzing those structural price elasticities in 5-minute increments reveals that they are not normally distributed. Rather, the price elasticity data follow a Pareto distribution, which is a power law distribution. Figure 6 shows a plot of the structural price elasticity data on the x-axis and the probability of that elasticity occurring in the data on the y-axis (both measured logarithmically). The asymptotically linear nature of the relationship seen in Figure 6 is consistent with data drawn from a power law distribution.

Figure 6: Structural price elasticity of RTP bids have a Pareto distribution



Exhibiting a power law distribution has two important implications for this analysis. In complex systems a power law relationship indicates robustness and self-organization, and is thus consistent with the real-time double auction being a self-organizing system (Holland 1995). In applications ranging from cascading blackouts in electric networks (Carreras et. al. 2004) to information cascades (Watts 2004), power-law relationships have been consistent with emergent patterns of self-organization in a variety of complex systems that have fluctuations over time due to agent interactions. Amaral et. al. (2000) and Stanley et. al. (2002) apply this model to analyzing the distribution of individual stock returns over time, and they find a similar relationship to the one shown in Figure 6.

Second, when data exhibit a power law relationship they are scale-free or scale-invariant. Power laws are frequently associated with scale-free phenomena because power laws are themselves scale-free distributions; however, power laws are not proof of complexity or of scalability *per se*, although they are consistent with scale-free phenomena. The power law distribution of the elasticities from the individual bid data suggests that as more households have automation capabilities in response to price signals, the results we have observed in this project would not change meaningfully at different scales or market sizes. Another way to think of the scale-free characteristic is if the same project were run on populations of different sizes, even dramatically different sizes, the pattern seen in the elasticity data would not change. This implication is particularly meaningful for policymakers, who are in decision-making positions and would like to have some comfort that the beneficial results of projects like the Olympic Peninsula project would scale up to larger communities and systems.

IV. Conclusion

In the GridWise Olympic Peninsula Testbed project, distributed, price-responsive technology and institutional design that allowed dynamic pricing combined to create a complex adaptive system that was capable of self-organization. The real-time price contract group achieved this self-organization, and the resulting beneficial outcomes, through decentralized coordination. The combination of technology and institutional design made this decentralized coordination possible by making the network of residential customers, commercial customers, and generation suppliers a transactive network. Historically, such decentralized coordination in the electric power network was impossible because the network did not have this transactive capability, so economic and physical management relied on centralized control strategies. Thus the combination of technology and institutional design changes the nature of system-level issues in the electric power network from centralized control to decentralized coordination.

This decentralized coordination and the resulting emergent order are possible where they were not before in the electricity industry because of technological change. The analog electro-mechanical technology that has formed the core of the electricity infrastructure for a century necessitated central control – service reliability and network stability would not exist without central control. Distributed digital technology now makes decentralized coordination possible, and can lead to reliability and to reduced infrastructure costs. But the central control of the analog mechanical era persists.

The burgeoning "smart grid" technologies (including price-responsive devices) illustrate this point. Imagine an electric power network capable of connecting the agents in the system using digital communication technology.[8] These agents can enter into contracts and transact in ways they could not before, enabled by communication technology. If these agents have distributed generation, they can transact and interconnect within the network more readily because of digital technology. The technology also makes it possible for such an agent to be either a buyer or a seller, depending on price signals and market conditions. Wires owners can use digital remote sensing and fault location devices to identify and correct line problems before they result in an outage (this capability is at the core of the "self-healing grid" concept). The visibility and transparency that digital technology provides also increases the ways that we can ensure reliability. Devices with digital automation of dynamic reactive power mean that we could have a wholesale market for reactive power as an ancillary service, instead of just relying on dumb analog capacitors to inject reactive power statically, at fixed intervals in fixed locations.

Most importantly, digital end-use devices and metering technologies enable retailers to offer a range of differentiated products and services to customers. These services can range from time-differentiated dynamic pricing contracts to contracts for different levels of service quality and reliability; they could also bundle these services together, or bundle them with complementary services like home security, home entertainment, building systems automation, and so on. Digital metering and end-use devices also give the retailer more visibility into the behavior and consumption patterns of consumers, enabling them to devise new products and services to attract customers. This visibility also brings operational benefits, allowing firms to optimize their maintenance and investment decisions.

The policy implications of these results relate both to specific institutional design recommendations and to the broader culture and mindsets of regulation. One of the most effective institutional changes to enable decentralized coordination is to open retail electricity markets to competitive entry. Removing retail entry barriers and enabling retail competition

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[8] The electricity wires network has this communication capability already, which is the basis on which broadband over power line (BPL) technology operates, and enables electricity wires owners to compete with broadband providers.

would facilitate the promulgation of dynamic pricing options and product differentiation that could include green power and priority insurance, among other things.

Some of the more cognitive and cultural implications of these results are more challenging, because they suggest that in their decisions policymakers should recognize that distributed intelligence and complexity are beneficial, especially when institutions facilitate the self-organization of a complex adaptive system. These results suggest that policymakers should design institutions that facilitate decentralized coordination, and reduce transaction costs that prohibit private agents from engaging in mutually beneficial exchange.

This industry and its regulatory organizations are highly risk-averse and resistant to change, despite all of the potential value creation that they are foregoing by resisting change. Lasting changes in institutions and behavior requires overcoming status quo bias. How do we overcome this historical, cultural, and economic inertia?

The first step is to recognize the shortcomings of the existing regulatory institutions and business models; those shortcomings include overinvestment to build to meet peak capacity, which leaves underutilized assets for most of the year; higher levels of pollution than we might otherwise experience because of the lack of product differentiation to allow green products and the lack of dynamic pricing that correlates with true marginal costs of electricity consumption; and a resource portfolio mix that is too supply-oriented, too dominated by central generation, and too divorced from consumer preferences because of the truncation of retail price signals. The next step in overcoming this inertia is in recognizing that policymakers do not know the future, and cannot pick specific outcomes, particularly in such dynamic environments as our modern economy. Traditional regulation picks an outcome, which stifles innovation and drives it outside of the industry.

Given these realizations, it is important to re-focus the regulatory mission away from protecting consumers by mandating low, stable prices for a regulated commodity service, and toward a mission of protecting consumers by facilitating the growth and operation of integrated wholesale and retail markets that can adapt to change. This dynamic mission relies on reducing entry barriers and transaction costs.

By establishing preconditions for markets to function and creating an institutional environment in which they thrive, regulation will adapt to change because markets are complex adaptive systems that achieve ordered outcomes through decentralized coordination. By allowing markets to function, regulation will also benefit consumers by delivering differentiated products and services at different price points; note also that competition-facilitating regulation also enables entrepreneurial producers to profit from meeting the needs of consumers (who have diverse preferences and diffuse private knowledge). Market processes are positive-sum interactions in ways that traditional regulation cannot anticipate or duplicate.

A final recommendation arising from this coordination framework is humility. As analysts and policymakers, "we need to … be better facilitators of building adaptive institutional design – in contrast to presuming we are the experts who can devise *the* optimal design to solve a complex problem." (Ostrom 2005, p. 254) Adaptive institutional design that allows the agents in the electric power network to achieve decentralized coordination while allowing new services to develop and diffuse is consistent with a dynamic, forward-looking, modernized industry that creates benefits for consumers and entrepreneurs alike.

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