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SPECIAL THEME

Adoption of smart grid technologies by electric utilities: factors influencing organizational innovation in a regulated environment

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Abstract Incorporation of information and communications technologies has the potential to reduce the environmental impacts of electricity generation and distribution while improving the quality, reliability and efficiency of electricity supply. However, integrating smart grid technologies presents major organizational challenges to utilities, and adoption rates are still low. New knowledge is needed on organizational innovation in response to this potentially disruptive technology in the context of a regulated monopoly. This study examines factors influencing the adoption of smart grid technologies using data from 15 interviews with 12 U.S. utilities. The study provides useful insights and implications for utilities and regulators.

Keywords Smart meter · TOE framework · Policy · Investor-owned · Municipal · Demand response

JEL classification O33

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Introduction

There is great interest in bringing information and communications technology (ICT) to the electrical grid to improve the quality, reliability and efficiency of electricity supply and to manage demand and reduce stress on the system (U.S. Department of Energy 2008). Smart grid technologies can support more distributed generation of electricity, with less need for expensive new power plants and transmission lines. These changes could lead to significant reductions in environmental impacts, including greenhouse gas emissions. Yet integrating smart grid technologies presents major organizational challenges to utilities, whose decisions about pricing, investments and operations are often determined or constrained by government regulations.

There is extensive research on technology adoption and diffusion (e.g., Rogers 2003; Fichman 1992), and on organizational adoption of new technologies (e.g., Tornatzky and Fleischer 1990; Robey et al. 2008). Yet there is limited research that focuses on technology adoption decisions in highly regulated sectors such as the electric utility industry (an exception is Rose and Joskow 1990). Given the practical implications of the smart grid, and the lack of well-developed theory to understand the adoption process in this context, there is a need for research that addresses the issue of smart grid adoption by utility companies.

The research questions are as follows: (1) What factors determine the motivation and ability of utility companies to adopt smart grid innovations? (2) How does the highly regulated nature of the electric utility industry affect adoption? (3) How does the regulated nature of the industry influence the impacts of other factors on adoption? We focus on the United States electric utility industry, using data from a series of interviews with 12 utility companies representing ten states with different regulatory environments.

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Background

The electric utility industry

Aging infrastructure, obsolete technology, costly power outages, and public resistance to location of new generation and transmission facilities characterize the electric utility sector in the U.S. Furthermore, the industry is regulated by a patchwork of federal and state regulation that hampers efforts to create coherent national objectives, policies and standards (Joskow 2010). Historically, utilities have been considered "natural monopolies" that achieve economies of scale by serving all consumers within a geographic region utilizing a single infrastructure for generation, transmission and distribution of electricity (Energy Information Administration 2000). There are over 3,000 utility companies, but the primary suppliers are investor-owned utilities (IOUs) that serve approximately 69 % of all consumers in the United States. In addition, 13 % of Americans are served by electric cooperatives, 11 % are served by municipal utilities, and the rest by other suppliers (Edison Electric Institute 2011).

In the past, most IOUs were vertically integrated and their prices and profits were controlled by state Public Utility Commissions. These regulatory bodies determined fair rates of return for utilities based on their investment scale, operating costs, depreciation rates and taxes (Sanyal and Bulan 2007). Under this regulatory framework the rates that utilities charged customers were fixed and the profits they earned were protected.

However, a wave of deregulation beginning in the late 1970s partially opened the market to competition and provided opportunities for many new firms to enter the market, especially in power generation and retail markets. In line with federal deregulation, many states have taken a proactive role in restructuring the electricity industry. Starting in the 1980s, many states separated generation, transmission and distribution, and energy markets, and many IOUs divested their power plants.

Challenges facing the utility industry

Today, utilities face unprecedented challenges including growing electricity demand on an overburdened grid as well as the need to increase the security and reliability of the energy supply. In 2003, a northeastern blackout affected 45 million people in eight U.S. states, causing $6 billion in economic losses (Minkel 2008). Utility companies in the New York area came under heavy criticism for their responses to outages caused by Hurricane Sandy in 2012 (DiSavino et al. 2012). Given the condition of the grid and local opposition to building new power plants and transmission lines, utilities need alternative solutions for addressing the problems associated with the current power grid.

The utility industry also faces environmental challenges. Production of electrical power accounts for about 25 % of greenhouse gas emissions globally (Feisst et al. 2008). In 2005, the Energy Policy Act encouraged the use of alternative energy sources for electricity by offering tax credits for purchasing hybrid fuel or investing in clean energy production. Many states established their own renewable portfolio standards. However, resources like solar and wind power are intermittent and need to be supplemented with other power sources and/or by energy storage to maintain a steady supply. In order to make full use of various energy generation mixes, utilities need a more flexible grid that accommodates the aggregation and use of alternative energy (Blaabjerg and Guerrero 2011).

Smart grid as a solution

The vision of smart grid is to use information technology to improve the performance of the electric grid. "Smart grid" has been defined in many ways. Kranz and Picot (2011) list 12 definitions from different sources. We use the term to refer to an electric grid whose operations employ information technology for communications, monitoring, computation and control purposes (SGMM Team 2010). Smart grid technologies are categorized by the Department of Energy (2012) into customer systems (CS), automated metering infrastructure (AMI), electric distribution systems (EDS), and electric transmission systems (ETS).

In this paper we focus on customer systems, AMI, and EDS, because some of our utility participants are not involved in generation or high-voltage transmission of electricity, so ETS is not relevant to them.[1] These can be grouped into three interconnected layers (Table 1): electrical circuitry or power layer, communications networks, and information technologies or applications (Leeds 2009; Farhangi 2010).

Among its capabilities, the smart grid enables outage management, grid self-healing, demand response, dynamic pricing, preventive maintenance of grid assets, integration of distributed generation resources, and two-way communications between utilities and customers (Morgan et al. 2009; Kossahl et al. 2012; Farhangi 2010). For instance, data on electricity consumption from smart meters can be used to identify, locate and isolate outages to reduce their impacts and enable faster response by repair teams. Longitudinal data can be used to predict demand under different conditions and take steps to shift load away from anticipated peaks.

[1] Also, ETS is somewhat "smarter" to begin with, as many centralized transmission systems already incorporate monitoring and control systems such as SCADA.

Table 1 Components of the smart grid

	Customer systems	AMI	EDS
Information technology/ application layer	Price and usage data, analytics, billing, web portal, mobile apps	Remote meter reading, connect/ disconnect, meter data management	Asset monitoring, outage management, demand forecast and response
Communications layer	Home area network	Two-way wired and wireless networks	Backhaul WAN between AMI and utility
Power layer	Smart appliances and thermostats, distributed generation, electric vehicle charging	Smart meter, two-way power flow	Substation and grid automation, (e.g., sensors, PMUs, integrated Volt/VAR)

Leeds 2009; Farhangi 2010

Current state of smart grid adoption in the U.S.

In spite of its potential advantages, smart grid adoption by utilities has been slow. For example, in 2011, just 23 % of U.S. customers had smart meters installed, with penetration rates less than 10 % in many states (Energy Information Administration 2012). The Department of Energy provided $4.3 billion in smart grid grants as part of the American Recovery and Reinvestment Act (ARRA) of 2009, yet even among utilities receiving grants, many had only adopted one or two of the four categories (CS, AMI, EDS, or ETS) (U.S. Department of Energy 2012).

Given the urgent need to modernize the U.S. electrical infrastructure and reduce its environmental impacts, it is important to sort out these issues and understand the factors that are driving or preventing adoption of the smart grid by utilities. To do so requires a comprehensive and theoretically sound conceptual framework, supported by empirical research on the utility industry. We address this need through qualitative research on the U.S. utility industry.

Factors influencing organizational adoption of innovation

Theories of technology diffusion and assimilation distinguish between individual adoption and organizational adoption (Fichman 2000; Jeyaraj et al. 2006). Our interest is in smart grid adoption by utility companies, so we draw on theories of organizational adoption. A widely used conceptual framework for organizational adoption is the technology, organizational, and environmental framework, or TOE (Tornatzky and Fleischer 1990). This framework has been used in the information systems literature, including studies of Electronic Data Interchange (Kuan and Chau 2001), e-business (Zhu et al. 2004), material resource planning systems (Cooper and Zmud 1990), open systems (Chau and Tam 1997), and information systems adoption by small businesses (Thong 1999).

The posited factors and relationships in the TOE framework come from economics, technology diffusion, organization science, institutional theory and public policy. While specific factors vary from study to study, there are a number of factors supported by theory and a body of empirical evidence (Fichman 1992). In studies of organizational adoption of IT, consistent predictors of adoption include top management support, external pressure, professionalism of the IS unit, and external information sources (Jeyaraj et al. 2006).

One of the things that makes smart grid adoption especially interesting is that it is occurring in a highly regulated environment. While other studies treat regulation as one of several environmental factors directly influencing adoption, we also look at how the regulatory environment affects the relationships of other TOE factors to smart grid adoption.

Technology factors

Technology characteristics posited to influence organizational adoption include the relative advantage or perceived benefits of an innovation; cost; compatibility with technologies in use; complexity of implementation; uncertainty of technology paths; "trialability" (i.e., feasibility of trials); and observability (Rogers 2003; Robey et al. 2008). Diffusion is likely to be more rapid and widespread when the relative advantage over existing technologies is greater, when an innovation is compatible with existing technologies and practices, when complexity is relatively low, and when an innovation can be tried out and observed in use.

Organizational factors

Organizational factors influencing innovation have been studied both conceptually and empirically. A wide range of organizational determinants of innovation adoption have been identified and tested, such as firm size, financial resources, technical skills, centralization of management functions, top management support, and the presence of change agents or champions for a particular technology (Damanpour 1991; Tornatzky and Fleischer 1990; Zhu et al. 2004).

Innovation decisions by organizations are not necessarily based on a purely rational process in which costs and benefits are weighed and acted upon. Instead, decisions may be partly path dependent, driven or constrained by the cumulative effects of previous decisions and the organizational structures and culture that have built up over time (Rycroft and Kash 2002). Most utilities are mature organizations, but there are major differences in size, ownership form, and corporate history (e.g., mergers, acquisitions, divestitures) that might lead to different adoption outcomes.

Prior research (e.g. Picot and Kaulmann 1989) found that privately owned firms generally outperformed government-owned corporations in profitability and productivity, but does not address technology adoption. Rose and Joskow (1990) develop a model of new technology adoption by electric utilities, considering size and ownership as factors. They predict that larger utilities will be more likely to adopt than smaller ones, and that investor-owned utilities (IOUs) will be more likely to adopt than cooperatives or government-owned utilities. They test the model using historical data on new power generating technologies and find evidence to support their predictions.

Environmental factors

The motivation for organizations to innovate, and their ability to do so, is greatly influenced by the environment in which they operate. Innovation may be motivated or discouraged by competitive pressure, customer relationships, industry structure, regulatory requirements, and pressures from various external stakeholders.

Business organizations need to earn a return on their investments in innovation. Their ability to do so depends on the nature of competition in the market and strength of customer relationships, both of which influence their expected future demand and ability to reap returns from their investments. Helper (1995) found that firms' adoption of computer-numerically-controlled machine tools depended on the adopter's market power and stability of customer relationships as much as on the expected efficiency gains from adoption. On the other hand, firms with a dominant market position and secure customer relationships may focus on protecting their position and lack incentive to innovate.

Organizational innovation can be influenced by a range of stakeholders who have an interest in an innovation outcome and the ability to influence that outcome (Donaldson and Preston 1995). In the case of utilities, these can include owners, customers, suppliers, industry associations, government agencies and activist groups. Depending on the relative power of these stakeholders, one would expect different innovation outcomes.

The TOE framework has been applied in the utility context by Kossahl et al. (2012), who identified seven factors influencing adoption: perceived benefits, barriers, cost, regulatory support, need for standardization, internal knowledge, and dedicated staff.

Impacts of policy and regulatory environment

One factor influencing innovation adoption by firms in many industries is the policy and regulatory environment (Zhu et al. 2004). In the case of electric utilities, the role of regulation is pervasive. A state public utility commission must approve almost every major decision made by a U.S. investor-owned utility. Utilities also fall under federal regulation through the Federal Energy Regulatory Commission (FERC), which sets policies that are implemented by other federal agencies or by state legislatures and regulators. Local regulation in the form of zoning and operating permits can also affect utilities. As a result, regulators can create many hurdles to adoption through their decisions. On the other hand, when a segment of the market is monopolized, regulators can ease potential bottlenecks to integration that can occur if the monopolist creates barriers to discriminate against competitors (Kranz and Picot 2011).

Given the highly regulated nature of the electric utility industry in the U.S., we look at the direct impacts of regulation, but also look at how the regulatory environment can moderate the impacts of other TOE factors. For instance, it is argued that utilities whose revenues and profits are determined primarily by regulatory process lack incentives to invest in innovations that might otherwise improve financial performance. Likewise, the unwillingness of many regulators to allow dynamic pricing reduces the perceived benefits of implementing automated metering that can bill customers according to real-time changes in supply and demand (Kassakian and Schmalensee 2011). We look for instances in which the policy and regulatory environment interact with other factors associated with smart grid adoption.

Methodology

While there is a large body of research on innovation adoption, the range of factors that influence adoption outcomes varies across studies of different technologies in different organizational and environmental contexts. To understand the factors that are involved in adoption of smart grid technologies by U.S. utilities, we chose an exploratory qualitative approach. Such an approach allows us to study an emerging set of technologies in a natural setting in the early stages of adoption (Yin 1994; Dubé and Paré 2003).

The sampling frame was weighted towards utilities that are more advanced in smart grid adoption, as there would be limited benefit from interviewing many non-adopters. The final sample comprised utilities that were recipients of ARRA funding (U.S. Department of Energy 2012), as well as companies identified as early adopters, plus one utility that has been identified as a "laggard" by an industry publication

(Greentech Media 2012;). Utilities were contacted via email in two phases. Phase 1: thirteen utilities identified as early adopters from reports in trade journals and studies by industry analysts, plus a utility that had cancelled a pilot project after failing to receive regulatory approval. Phase 2: twenty-seven utilities representative of varied state policy environments and ownership types from the DOE's list of ARRA grant recipients. From these two rounds of contacts, 15 interviews with 20 representatives of 12 utility companies were conducted (for two IOUs, we conducted interviews with two people; for one municipal, five people were involved).

We conducted semi-structured interviews, asking executives and managers about the adoption process, the extent of adoption and assimilation, and the factors driving or discouraging adoption. The interview protocol evolved over time to add new questions or topics suggested by previous interviews.

To address our first research question, we asked participants about the factors that influence their adoption decisions. With an exploratory approach, we could identify factors consistent with the literature but we also remained open to finding factors that do not fit neatly into existing categories, and thus may be specific to this context. To answer the second and third questions — the impacts of regulatory environment — we looked at the direct impacts of regulatory environment and how the other TOE factors were influenced by the regulatory and policy environment.

Interviews were recorded and transcribed prior to data coding. Data analysis was a combination of inductive and deductive thinking using open and axial coding. Transcripts were read multiple times during open coding to compare, conceptualize and categorize the data. At least two researchers coded each interview, and results were compared to ensure inter-coder reliability (Krippendorff 2004; Popping 2010). Reconciliation was done through discussion of coding discrepancies found in the same unit of text.

Analysis and results

Once open codes were identified, axial coding made connections. Open codes were grouped under a higher order concept of axial hierarchical coding. During axial coding, links between the concepts became clearer. The connections that were made produced 16 axial codes. We list these codes and elaborate below.

Factors identified as influencing adoption

1. Integrating new energy sources and uses

   Upgrading of the grid is needed for widespread integration of intermittent and distributed generation sources, and electric vehicles. This is a significant factor for some utilities where rooftop solar or EVs are more widespread, including a utility commonly acknowledged as an aggressive early adopter, but is not a critical factor in other locations.

2. Operational benefits

   Another factor is the ability to improve performance and reliability of the grid infrastructure, through technologies such as distribution automation, monitoring of key equipment, sensors that report damage to the grid, and outage management systems. These investments are less visible than smart meters, but can have a significant benefit for firms with large distribution infrastructures.

   "We introduced a project called Condition Based Maintenance (CBM) where we started to measure the behavior of substation transformers, which cost a few million dollars. Failures are very expensive. We have deployed CBM in an average of 25 substations a year and have avoided numerous large outages and failures."

3. Cost reduction

   The most commonly cited financial impacts were cost reduction and cost avoidance. An IOU in our sample emphasized cost reductions from "automated meter reading, bidirectional communications with the meters for remote disconnect and final reads". These tangible cost savings from AMI made it easy for many utilities to justify the business case internally and with regulators. Another factor that was important to some utilities is the ability to reduce peak demand and thus avoid the cost of investing in new generation capacity. This factor was only relevant to vertically integrated firms that generate their own power.

   "We were looking at having to build a plant in 2015 or 2016 time frame, and set forth a goal to defer the construction of the next plant by 5 years to get this done by 2020. We have lower prices off-peak and higher prices during on-peak and through this technology (AMI) we can send information to customers and automate it through these thermostats and help customers reduce their peak demand…That is our goal and that is really what drives our efforts there…"

   Improved asset utilization through some type of dynamic pricing where retail price points are closely related to wholesale prices has the potential to reduce peak demand and make utilities' distribution network operations more energy efficient and reliable while also cutting the cost of operations. This is a compelling business case, and nearly every respondent was looking beyond automation to integrate these different technologies and business practices. But it remains to be seen when they will make the transition from automation to informatization, where smart meter data are combined with communications and real-time energy use and granular price data to further reduce costs.

4. Possible loss of revenue

On the downside, there is concern among some utilities that energy savings associated with smart grid adoption could reduce revenues. Since most utilities' revenues are based at least in part on the volume of power sold, energy efficiency gains could actually have a negative financial impact unless utilities are able to delink revenues from the amount of kilowatt hours sold. In some states, this is already the case, but in others, utilities expressed concern that the effect of increased efficiency will be a loss of revenues.

5. Cost of implementation

Smart grid technologies are costly to deploy. Initiating customer-facing programs like demand response and variable pricing regimes impose additional costs on the utility, and ancillary investments in upgrading data communications capabilities may be required. Assessing investments in smart grids in strict cost/benefit terms is a complex undertaking and not all costs are easily quantified and weighed against potential benefits. As one respondent put it, the decision to adopt smart grid stemmed from an expected "basket of benefits without either fully identifying or quantifying those benefits. So from my own perspective, I would call it belief based investment as opposed to quantifying (sic) based investment". Regarding the difficulty of applying strict cost/benefit metrics, one utility has had time-of-use pricing as well as peak time pricing, but, as they were implementing demand response, the incentive structure got a little complicated. The respondent observed:

"But with natural gas prices very low, the cost of energy is lower, making demand response less cost effective. DR programs costmoney. If there is no price on carbon or emissions costs, the lower the cost of natural gas, the harder it is to justify demandresponse".

6. Firm size

Contrary to the findings of Rose and Joskow (1990), a few utilities regarded their smaller size as an advantage, enabling them to respond more flexibly and to try out technologies without facing bureaucratic delays.

7. Top management leadership

Leadership by top management was mentioned consistently by utilities that have advanced farthest in smart grid adoption. One manager argued that the kinds of organizational changes required can only be made through top-down mandate.

8. Experience with precursor technologies

Many of the companies interviewed have a history of introducing smart grid-related technologies, although they didn't call them "smart grid" technologies at the time. Such experience put those utility companies in a better position to respond to the ARRA funding opportunities, and to deploy smart grid technologies.

"One of the reasons that we worked on this grant is that we were shovel-ready for much of the work… We have been doing smart grid-related work for a number of years."

Another utility noted

"We piloted different meter reading and other technologies through the '90s and early 2000s, and we sort of saw the opportunity for putting the costs of the projects in the ARRA funding. That's why we applied and I think that's part of the reason why we are successful".

9. Technical expertise

Respondents identified the need for new areas of expertise. These include network engineering, software development, system integration, large-scale data analysis, information security, and effective customer communications. The rate of adoption is influenced by the resources and capabilities they can draw on to deploy and utilize smart grid technologies effectively.

One utility mentioned that their prior experience helped them to deal with the skill requirements internally:

"We've actually leaned on our existing staff quite a bit in terms of bringing the systems up and managing the systems".

Others relied on outside suppliers initially, but were shifting the work in-house as their own skills developed.

10. Technology champions/change agents

Several participants pointed to the role of an internal champion for smart grid technologies in driving awareness of the potential benefits.

"He [director of engineering and operations] is a more forward-thinking and enlightened individual with respect to smart grid. He has been championing distribution automation for a very long time".

11. Culture of innovation

Although the utility industry often is characterized as lacking in innovation, a few utility companies mentioned that their innovative culture motivated them to pursue smart grid technologies.

"We benchmark against the best utilities…we have a culture that has come from executives that have their roots in the company. We don't like to be number one, but we do implement change readily."

12. Ownership form

We heard from some municipals that they were able to invest in innovations that might not have immediate or tangible benefits, because they did not face pressure from shareholders to show an adequate return on investment.

"We are not driven like IOUs by return on investment. We don't have to go to anyone for a rate increase. We can spend what wehave in our cash flow estimates without having to get approval from a regulator. Some of the benefits of smart grid areintangible. IOUs have to show tangible benefits to make such investments”

This finding is contrary to the predictions of prior research (Picot and Kaulmann 1989; Rose and Joskow 1990), although it only represents the views of a few municipal utilities.

13. Competition

We found that utilities that faced competition, particularly in retail sales, were more motivated to adopt innovations to gain a competitive advantage. One firm competing in the retail market stated:

“In Texas, the utility industry was deregulated into 3 different markets about 10 years ago: power generation in the wholesalemarket; the traditional transmission and distribution utilities… and retail electricity providers…“We compete with 40 companiesevery day. We are a market leader. We are very innovative and new things that we roll out to customers include things likepricing plans as well as these technologies and services”.

14. Consumer attitudes

Consumer attitudes influence the ability of utilities to implement smart grid. Utilities we interviewed rely on voluntary cooperation from consumers to manage their energy use, so consumer acceptance and engagement are critical to achieving smart grid goals such as reducing peak demand. Consumer concerns center around safety and privacy concerns and fear of higher electric bills. There can be a lack of trust and understanding on the part of consumers as well. The comments of several respondents are reflected in the following statement:

“Most customers have very little understanding of the differences between a retail bill and a wholesale bill, particularly in terms of how costs vary with time, and that concept is surprisingly difficult to get across to the customers in a way that could be understood. The whole industry is struggling with communicating new technologies with customers…Utilities probably don’t have a very strong understanding of their customers’ behavior drivers. So there is kind of a knowledge understanding gap in my perspective on both sides”.

15. Policy and regulatory environment

One of the critical factors for utility companies interviewed is the regulatory environment. Among our interviewees, the regulatory environment ranged from obstacle to driver. On the negative side:

“We requested a rate increase, but the commission only approved one-third of it. This caused us to cancel a pilot project on smart grid.”

More positively,

“The commission encouraged us to submit the application for the (ARRA) smart grid funding”, and once the funding was obtained, “we got the regulatory approval for moving forward” on the adoption.

Federal and state policies can drive smart grid adoption directly through incentives, such as the ARRA grants, or mandates, such as California’s requirement that its large IOUs develop detailed smart grid plans. The Energy Independence and Security Act(EISA) in 2007 provided support for the Department of Energy smart grid activities and reinforced its role in coordinating national grid modernization efforts.

Policies also can have indirect effects, such as through incentives for renewable energy. The federal government has driven investment in renewables through direct subsidies and tax incentives such as the Production Tax Credit for wind energy, while many states have targets for renewable energy use by utilities. For instance, California required all energy service providers to increase purchases of renewable energy to 33% by 2020. State legislation serves as a motivator for one IOU.

“There are aggressive and progressive energy policies in California. In the absence of better ways of doing things, these could substantially increase the cost of service. We are using smart grid technologies to achieve policy goals at a reasonable cost”

However, in one case, aggressive promotion of smart grid was seen as premature, leading to investments in technologies that were not ready for widespread implementation.

“Policies tend to create targets before the technology is ready. The state promotes technologies that are not fully baked. For instance, some technologies that they think might help them to mitigate the vulnerability of the grid such as storage tech or battery systems are too expensive and new technologies are not proven. The technologies that they think they could bring to solve the problem are less than proven at this point. There may be mistakes in rolling out immature technologies”.

16. External information sources

One way to develop the knowledge needed to deploy smart grid technologies is through access to external information sources. Outside suppliers already provide many of the necessary technologies, but utility companies need the skill to integrate multiple technologies into an existing electrical infrastructure. One respondent said “we monitor other utilities through membership in EPRI working groups and conferences. We benchmark with over 60 companies in the U.S. and have a network of contacts in the industry”. Some of the utilities mentioned collaboration with technology vendors and researchers from universities as helping to overcoming their own knowledge limitations. As one utility company stated,

"We work with IT companies as well as electrical equipment vendors like Cisco and GE. Some of them are transactional — put out request for proposals for specific projects. Some are partnerships to solve problems".

Many utilities also talked about various formal and informal networks which they participate in, with peers, suppliers, professionals and others. These are important in understanding successful practices in everything from technical standards to customer education.

Categorizing factors in the TOE framework

The factors that were raised in our interviews fit into the TOE framework. Table 2 shows the 16 factors that we identified in our coding, along with matching concepts from diffusion of innovation and organizational adoption literature. Sometimes our coding directly matches factors in the literature. In other cases, specific codes match with general categories. For instance, the ability to integrate new energy sources and uses is specific to smart grid, but fits in the general category of perceived benefits. In the case of experience with precursor technologies, this fits with the concept of computer experience, but that concept has mostly been applied at the individual adoption level (Jeyaraj et al. 2006). Most studies of innovation adoption focus on private sector enterprises, and some on government agencies, but few compare adoption by different ownership forms in the same industry.

Interaction of policy and regulation with other factors

We identified a number of instances in which policy and regulatory environment can influence the impact of other factors, either enhancing or reducing their effects. These are listed in the third column of Table 2.

Integrating new energy sources and uses

The need to integrate renewables is driven in part by renewable portfolio standards that require utilities to deliver a certain percent of their power from renewable sources by a specific date, and by requirements that utilities allow customers to produce their own energy and feed it back into the grid. Price is another factor, as most states have "net metering" rules that require utilities to pay their customers the retail rate for energy that the customers generate, making distributed generation more attractive.

Operational benefits

For the most part, customers reap the operational benefits of smart grid, such as fewer and shorter outages. In some states, regulators penalize utilities for failing to meet reliability targets, but rarely are they rewarded financially for exceeding targets. Without regulatory incentives to improve operations, utilities may not make investments unless they directly reduce their own cost structure.

Possible loss of revenue

While some state regulators have delinked utility revenues from the volume of kilowatt hours they provide, in most states the relationship is still there. Thus, smart grid investments that improve efficiency and reduce demand may actually reduce utilities' revenues, discouraging adoption.

Cost of implementation

The regulatory process in many states requires utilities to ask for cost recovery for investments after the investments have been made. Thus, utilities must invest without being sure if they can add the cost of their investments to the rate base of capital for which they can earn a return on investment. Also, the "used and useful" criterion for evaluating investments after the fact discourages investment in newer technologies whose usefulness is uncertain. On the other hand, the smart grid grants offered under the American Recovery and Reinvestment Act in 2009 reduced the cost of implementing new technologies. This encouraged investments that would not otherwise have been made, or in some cases led utilities to accelerate planned investments, according to recipients we interviewed.

Culture of innovation

The long-term effects of operating as a regulated monopoly have encouraged a conservative approach to innovation by utilities according to some respondents. In states that have deregulated and encouraged competition, we found utilities with a more aggressive attitude toward innovation.

Ownership form

Investor-owned utilities must go through a lengthy approval process to set prices or make investment decisions. Thus, their decision-making autonomy is constrained.

The situation is different for municipals, which generally do not require approval from regulators to set prices or make investments, giving them greater autonomy to invest in smart grid and use pricing to create incentives for customers to reduce peak demand. However, even among IOUs, some of them have more control over their investment decisions:

Table 2 Adoption factors, related theory and interaction with regulatory/policy environment

Factors identified in coding	Related theoretical factor	Interaction with regulatory and policy environment
Technology		
Integrating new energy sources and uses	Perceived benefits (+)	Net metering pricing. Renewable portfolio standards.
Operational benefits	Perceived benefits (+)	Rate setting process, via formal rate cases and ex post approval of cost recovery.
Cost reduction	Perceived benefits (+)	
Possible loss of revenues	(−)	Cost-plus revenue model based on volume of power sold.
Cost of implementation	Cost (−)	Judicial process for determining cost recovery is unpredictable. "Used and useful" criteria for determining whether to allow cost recovery discourages riskier investments.
Organization		
Firm size	Size (+/−)	
Top management leadership	Top management support (+)	
Experience with precursor technologies	Computer experience (+)	
Technical expertise	Technical expertise (+)	
Technology champions	Technology champion (+)	
Culture of innovation	Organizational culture (+)	Historical regulated monopoly status may discourage innovation.
Ownership form	Private ownerhip (−)	IOUs regulated by state PUCs, municipals free from most regulation.
Environment		
Competition	Competitive pressure (+)	Deregulation and divestiture, interconnect requirements for generators and retail suppliers. "Natural monopoly" treatment for transmission and distribution.
Consumer attitudes	Customer relationships (+/−)	Rate case process ensures input from consumer representatives.
External information sources	External information sources (+)	
Regulatory/policy environment	(+/−)	

"(Our state) is kind of different. In our case, we decided that this is the course of action and we put together a business case and plan and then we went to our regulators and said 'this is what we want to do' and we requested their approval of it".

A difference here is not just the formal regulatory process, but the working relationship of utilities with regulators. In one state, we interviewed a utility that had lost a rate case and had abandoned a pilot project, while another utility claimed to have a good working relationship with the same state utility commission.

Competition

The extent of competition in utility markets is directly determined by policy and regulatory decisions. These are driven by the FERC at the federal level, but implementation varies greatly by state, where decisions are made by public utility commissions

Consumer attitudes

Another constraint on action comes from the regulatory and legal systems through which consumers, environmentalists or other interests can act to prevent action by utilities. For instance, consumers in northern California and elsewhere have sued to block installation of smart meters, and some utilities are required to offer an opt-out option to deal with the resistance of a small number of customers. Thus, some interviewees admitted that they took a slower approach as they don't want to ruin their customer relationship or face challenges due to the aggressive adoption of smart grid technologies.

"In our state we have really low barriers of entrance to the regulatory process; people can essentially submit complaints and (the PUC) willinitiate the investigation… So it has caused lots of discussions in the regulatory environment from customers".

Adoption

The extent of adoption by the utilities in our sample varies quite a bit, even though our sample frame was tilted towards more aggressive adopters. Most of the firms (nine) deployed smart meter/AMI and associated communications networks. These can be seen as a basic infrastructure for demand response, distribution automation, and providing information to consumers about usage, as well as offering immediate cost savings. A second area is distribution automation and outage management systems, adopted by five utilities. Seven have implemented customer information systems such as web portals.

Most companies are at the earliest stages of adopting information systems to collect and manage the large amounts of data that will come in from smart meters and sensors. As one utility commented, "in smart grid, analytics are following implementation, not being deployed with the new technologies." A few companies provide data to consumers via web portals. Most are only in the planning stages in considering how they can turn this data to their advantage through data analytics. Table 3 shows the scope of adoption of a set of common smart grid technologies by our interviewed companies.

Conclusions

We have developed a conceptual framework (Fig. 1) for smart grid adoption that extends the familiar TOE model from Tornatzky and Fleischer (1990) by identifying interactions of policy and regulatory factors with other TOE factors.

In this conceptual model, the interactions are dynamic and factors are likely to change over time. While space limitations prevent a full discussion of the implementation process and its impacts, interviewees discussed the need for changes such as breaking down organizational barriers and siloes, and creating cross-functional teams to implement different projects. They also said that new skills and expertise were required, and spoke of challenges in managing change in organizations unaccustomed to rapid transformational change. In addition, the smart grid enables and requires new ways of interacting with customers and requires changes in the regulatory process.

Table 3 Smart grid adoption by participating utilities

Retail Competition	Utilities	Project Type		
		AMI	CS	EDS
N	IOU1	Y[a]	N	Y
N	IOU2	Y[a]	Y[a]	N
N	IOU3	Y	Y	Y
Y	IOU4	N	Y[a]	N
N	IOU5	Y	Y	Y
N	IOU6	Y	N	N
N	IOU7	Y	N	N
Y	IOU8	N	N	N
N	Municipal1	Y[a]	Y[a]	Y[a]
N	Municipal2	N	N	Y[a]
Y	Municipal3	Y[a]	Y[a]	Y[a]
Y	Municipal4	Y	Y	Y

AMI advanced metering infrastructure, *CS* customer systems, *EDS* electric distribution system

Interviews and (U.S. Department of Energy 2012) for ARRA funded projects and definitions

[a] Projects that received ARRA funding

These findings have implications for utilities and policymakers as they face increasing pressures to address the challenges described above. Utility companies need to develop new technology skills in areas such as systems integration, networking, security, and data analytics. This requires upgrading skills of existing employees and also opening up to external sources such as suppliers, consultants and academics who offer needed knowledge. Top management needs to provide leadership and support for adopting new technologies and strategies, while also shaking up the culture of innovation. In the words of one respondent, organizational siloes need to smashed, which can only be accomplished with top management leadership. Utilities also need to take the time and effort to inform customers about the new technologies and earn their trust, as some of our respondents have done.

Based on our findings regarding the impacts of policy and regulation, we would argue that there is a need for regulators to move beyond the current model of regulating prices, revenues and investments via formal rate cases, which approve investments after they are made. The "used and useful" criteria for approval should be modified to enable investment in new technologies whose usefulness is not proven. Our findings also suggest that capturing the potential value of the smart grid requires shifting to new pricing and revenue models. Those utilities in our sample whose revenues were tied to the volume of power sold were more hesitant to adopt technologies that improved energy efficiency and reduce usage. Those in states where revenues are delinked have been more aggressive. Finally, respondents in states with retail competition were more likely to offer new customer services, suggesting that introducing competition is consistent with increasing adoption and innovative use of new technologies.

The results of this study also may be relevant to other regulated industries or other economies. The interaction of regulatory factors with other adoption factors may well be present in industries such as telecommunications and railroads, or in other countries. While the specific relationships likely depend on context, it would be useful to look for such interaction effects when regulation plays a major role in shaping adoption decisions.

Limitations and future research

The analysis in this study is limited to the U.S. market and may not generalize to other national markets. In the U.S. we

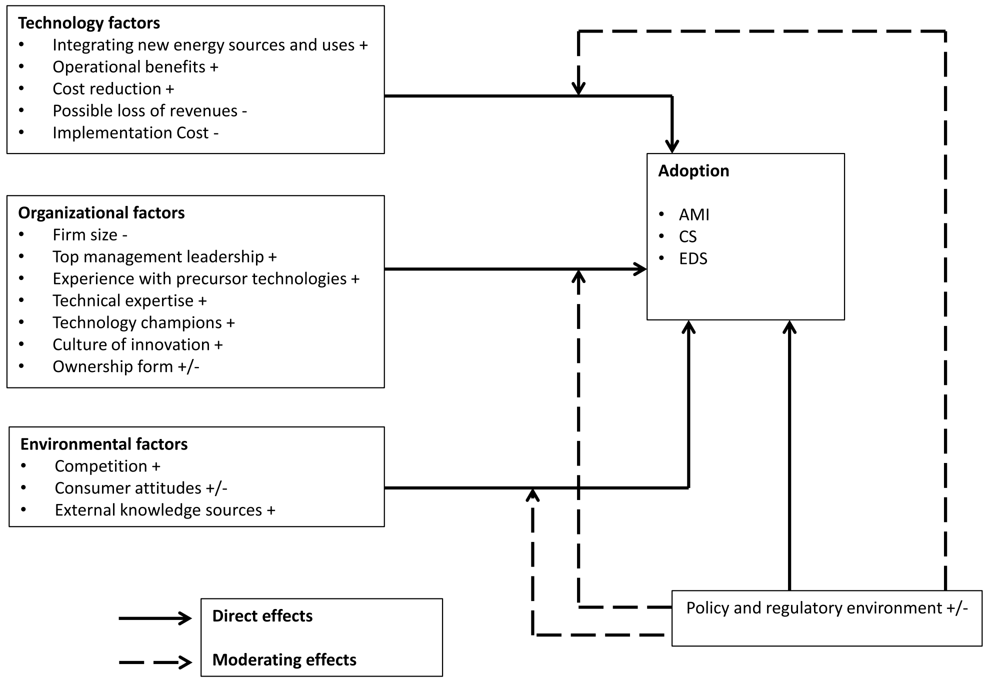

Fig. 1 Conceptual model derived from results

only interviewed a small number of the 3,000 utilities. The goal was not to test theory or to generalize to the entire industry, but to explore factors influencing smart grid adoption and consider the influence of government policy and regulation on adoption.

Future research could build on our work by testing the proposed relationships quantitatively with a large sample survey. Researchers also could examine adoption factors outside the United States, as some already have begun to do (e.g. Kossahl et al. 2012). The smart grid involves a complex set of technologies being adopted in a variety of market and regulatory environments. Understanding the process and the factors influencing adoption will require extensive research over a long period of time. Future research also could look at the relationship of causal factors with adoption of specific smart grid technologies, rather than looking at smart grid more broadly.

Appendix 1

Interview protocol

The researchers used the following protocol before, during, and after the interview.

Before the interview

Contact interviewee via email requesting a 30-min phone conference interview. Provide information about the study, informed consent document and a listing of general questions. Assure the participant that all responses will be kept confidential.

Upon receiving a response of interest, schedule an interview with participant.

Research on public information about interviewee, utility smart grid projects and other essential background information. Circulate to research team.

Design/modify interview questions tailored to the interviewee, choosing from among the questions listed in this protocol.

Reserve a toll free telephone conference line.

Communicate conference number and confirm meeting with participant

Test recording equipment, ensure that it is fully charged and has available memory

During the interview

Reiterate highlights about the study

Request permission to record the interview.

Reiterate to the participant that all responses will be anonymous and kept confidential.

Record interview (if permission is given). Take supporting and contextual notes throughout the interview.

Interview questions

The following are some of the main themes explored in the semi-structured interviews. Probe questions were asked depending on the nature of the responses.

Background

Please describe your role in the utility company with regard to smart grid.

Smart grid experience of the utility

Please discuss your utility company smart grid strategy

According to documents, your smart grid plans includes (information/data from literature) How much progress has been made in implementation?

Factors that influence adoption

What are the motivations or driving factors?

Can you identify specific persons who have driven or championed smart grid within the organization?

Why did your utility choose to pursue the DOE grant?

What is the business case for smart grid? What are the objectives?

Challenges by internal and external sources

What are the biggest obstacles to smart grid adoption, either inside or outside the organization?

How are your decisions driven or influenced by government policies or regulations?

Categories of technologies

What was the rationale for your mix of technologies?

How do you outreach to customers?

What has been the public reaction to smart grid and smart meter introduction?

Do consumers have the option to opt out? If so are many consumers opting out?

Can you tell us a little about your use of dynamic pricing? (if applicable)

Data management and required skills

How do you plan to capture, manage and use the large amount of data coming in from the system and devices?

What kinds of skills are needed to implement your plans (especially IT-related skills)? Did you have them within the company, have you hired new people, or have you turned to outside suppliers to provide them?

Does your utility company also look at what others (co-op/municipal/IOU) are doing in the industry? If so, what are some of the ways that you interact with people from other utilities (industry conference, workshop, personal ties, etc.)?

Conclusion

Are there any specific questions you have for us or is there any things you would like us to clarify.

After the interview

Save and transcribe recorded interview.

Supplement notes by defining any special terms or explanations used that might be unknown.

Describe any insights that may not have registered through the recording, or any other unusual occurrences during the meeting.

Write letter of thanks to interviewee and ask for confirmation of promised materials or any extra information or follow up interviews.

Assign transcription of interviews for coding.

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