The Adoption of New Smart-Grid Technologies

Incentives, Outcomes, and Opportunities

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Preface

New technologies have created significant opportunities for electric-grid modernization that will allow for enhanced communications between transmission and distribution operators and consumers. This communication layer, its associated enabling technologies, and the infrastructure necessary to deliver electricity are collectively known as the smart grid. A fully functional smart grid has been estimated to bring large net benefits to society through the ability to more efficiently manage transmission, distribution, and consumption of electricity, as well as incorporate and integrate intermittent renewable-resource fuels and distributed-generation technologies. However, some evidence suggests that either the net benefits have been overestimated or incentives are not aligned for current utilities and customers to fully modernize the grid.

This report reviews the current status of smart-grid development, including some entrepreneurship opportunities and the barriers to achieving a fully modernized grid. We identify some recommendations to help overcome these barriers and detail the policy levers available to regulators under the incumbent regulatory system to incent (or discourage) adoption.

This research was sponsored by the Kauffman-RAND Institute for Entrepreneurship Public Policy (KRI), housed within the RAND Institute for Civil Justice. KRI is dedicated to assessing and improving legal and regulatory policymaking as it relates to small businesses and entrepreneurship in a wide range of settings, including health care and civil justice.

The intended audience for this report includes electricity industry professionals, consumers of electricity, researchers, and policymakers who help shape the environment in which the electric market operates. The report should be of interest to any group or individual seeking to understand the barriers to grid modernization and some of the potential opportunities that overcoming these barriers may present. This study complements previous RAND research conducted within the RAND Environment, Energy, and Economic Development Program, which addresses topics relating to environmental quality and regulation, water and energy resources and systems, climate, natural hazards and disasters, and economic development, both domestically and internationally. Prior research with a focus on the topic of energy can be found at http://www.rand.org/topics/energy.html.

Kauffman-RAND Institute for Entrepreneurship Public Policy

The Kauffman-RAND Institute for Entrepreneurship Public Policy is dedicated to assessing and improving policymaking as it relates to entrepreneurship. Entrepreneurship can help address critical issues and enhance value in important sectors, including health care and civil justice, by developing new ways to serve people whose needs are not currently being met, better addressing those needs that are being met, or doing so at lower cost. The institute seeks to improve understanding of the ways in which public policy promotes and impedes entrepreneurs and small business. It was founded in 2004 as the Kauffman-RAND Center for Regulation and Small Business with funding from the Ewing Marion Kauffman Foundation. The institute leverages and extends RAND research on a wide range of policy topics, including health, civil justice, defense, employment law, consumer law, and securities regulation.

The center is part of RAND Justice, Infrastructure, and Environment, a division of the RAND Corporation dedicated to improving policy and decisionmaking in a wide range of policy domains, including civil and criminal justice, infrastructure protection and homeland security, transportation and energy policy, and environmental and natural resources policy.

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Summary

Electric grids around the world are in the midst of a transformation that involves upgrades to their distribution, transmission, and generation systems, primarily in the form of monitoring and communication technologies that allow for much more-precise information about the state of the system at any point in time. In the United States, this layer of communication infrastructure integrated with the stations, substations, and transmission and distribution lines that move and distribute electricity is collectively known as the smart grid. Although there are differing notions of what exactly the smart grid might and ought to look like, virtually every vision includes greater automation at every node, combined with data communications and operations between all agents in the system, including distributors, transmission operators, and consumers.

Two-way communication between the grid and the consumer via smart meters can provide information regarding energy use at a much finer scale than traditional metering practices, effectively increasing the price elasticity of demand and enabling more-efficient rate and pricing regimes, such as real-time dynamic pricing. With prices that more closely reflect the incremental costs of supplying electricity, the overall economic efficiency of the electric system can be enhanced. This occurs primarily through the reduction of peak loads so that more-expensive generation sources need not enter the generation mix, and via a delay in costly infrastructure investments that are ultimately passed on to consumers.

In addition, there are opportunities for entrepreneurial activity related to the smart grid in "big-data" applications. By applying analytical tools to smart-meter readings, utilities will be able to extract value from not only offering energy-efficiency solutions but also better understanding the habits and needs of the electricity consumer. If concerns about privacy can be assuaged and utilities can overcome the technical hurdles associated with the organization of vast amounts of data, then utilities may be able not only to optimize operation of the electricity grid but also to move to a business model in which they commoditize not just electricity but alzo information. Additional opportunities could accrue in other sectors looking to take advantage of this new flow of information, such as building designers, appliance makers, marketers, and public safety officials.

Estimates of the net benefits of the smart grid from the standpoint of the overall system and society as a whole suggest that the modernization effort will be worthwhile. With the implementation of new automation technologies, the smart grid will more easily integrate intermittent renewable sources of electricity (an oft-cited energy-security and environmental objective) and distributed generation. Furthermore, grid operators' ability to monitor the system can result in efficiency gains through more-precise supply-and-demand balancing, lower metering costs, and fewer and shorter outages.

Despite the predicted net benefits, the pace of smart-grid investments absent federal government incentives (such as the federal Smart Grid Investment Grants [SGIGs] provided through the American Recovery and Reinvestment Act of 2009 [Pub. L. 111-5]) has not been as rapid as one might expect. Although SGIGs and other programs have increased the pace of smart-meter and other technological adoptions, these incentives for adoption are not permanent. In addition, some utilities and consumers have had less-than-positive experiences with smart-grid technologies. When SGIG funding expires, there is considerable uncertainty related to the path and pace of smart-grid development.

From a policy perspective, we thus seek to analyze the following questions:

- What categories of potential benefits could the smart grid have for utilities and for consumers of electricity?
- What entrepreneurial opportunities are likely to present themselves in the smart-grid space?
- What does the empirical evidence suggest about the likely materialization of the potential benefits?
- What technological, economic, and regulatory barriers tend to reduce either the size of these benefits to utilities and consumers or the likelihood of adoption of technologies and policies that could generate these benefits?
- What policies could be implemented or changed to help overcome the identified technological, economic, and regulatory barriers?

In order to address these questions, this research report reviews the literature related to smart-grid development and analyzes the potential barriers and opportunities related to grid modernization. We identify the key sources of theoretical potential benefits and analyze the potential benefits and costs of entrepreneurial opportunities related to the smart grid, with a focus on data analytics and the commodification of information. We then briefly review the empirical evidence related to smart-grid technology adoption and analyze the economic incentives that the dominant regulatory, economic, and technological environment creates for the support and adoption of smart-grid technologies and pricing policies. We then discuss the policy levers that can be used to promote (or discourage) adoption and provide some broad principles for regulators to follow.

Our findings suggest that, although the benefits of the smart grid are likely positive on net when viewed from a societal standpoint, several barriers to adoption (i.e., costs) can reduce the size of the overall benefits and create both winners and losers across households and other consumers. Technical solutions at the transmission and distribution levels (such as the increased ability to monitor the system for problems and incorporate intermittent renewable energy sources) can provide some benefits to both utilities and customers (through passed-through savings), and the efficiency benefits associated with real-time pricing and demand response enabled by smart-grid technologies can be significant.

However, although the potential ex ante benefits and opportunities suggest that the evolution toward a modern electricity grid is worthwhile from society's perspective, economic and regulatory barriers to voluntary adoption of smart-grid technologies could impede development once federal funding is no longer available. These barriers include the following:

- the likelihood that real-time or near-real-time pricing enabled by the smart grid will result in higher electricity bills for some consumers, even if others do realize savings
- increased consumer costs from information monitoring and, possibly, the purchase of "smart appliances"
- the potential for increased short-term electric rates to pay for infrastructure investment, coupled with a risk that promised benefits will not materialize
- the possibility that smart-grid investments will not qualify for cost recovery in rate cases
- concerns about the implications of placing vast amounts of customer data in the hands of a regulated monopoly
- a lack of technology standards that renders investment in new technologies riskier
- potential mismatches between regulatory objectives and adoption of smart-grid technologies
- disagreements about which parties should ultimately pay for transmission-specific smart-grid technologies because of the public-good nature of the transmission system.

To help overcome these barriers, we make the following policy recommendations:

- Regulators should use the levers at their disposal to promote adoption of smart-grid technologies based on the principle of maximizing net benefits to the system (versus just cost minimization of the investment).
- Regulators should develop efficient pricing regimes for distributed generation, reflecting the overall net marginal benefit (or cost) of generation and recognizing the use of the distribution system as a type of public good.
- Technological performance standards should be developed at the federal level to decrease investment uncertainty.
- Regulators should recognize that the net benefits of smart-grid technologies may differ from subsystem to subsystem because of system-specific variables, such as previous investment paths and the degree of customer responsiveness to electricity prices.
- Regulators and utilities should be realistic about the distribution of net benefits from smart-grid solutions, recognize uncertainties where they exist, and refrain from over-promising benefits to consumers.
- Regulators should require utilities to develop privacy policies as applied to data management and release and encourage utilities to market those policies to consumers.
- Regulators should consider forward-looking test cases because historical data will not adequately represent the new functionality of a modernizing grid.

Acknowledgments

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Abbreviations

ACS	American Cancer Society
AMI	advanced metering infrastructure
ARRA	American Recovery and Reinvestment Act of 2009
CAMP	comprehensive advanced metering plan
CFL	compact fluorescent lamp
CPP	critical peak pricing
DOE	U.S. Department of Energy
DPU	Massachusetts Department of Public Utilities
EIA	U.S. Energy Information Administration
EISA	Energy Independence and Security Act of 2007
EMI	electromagnetic interference
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulation Commission
GAO	U.S. Government Accountability Office
GW	gigawatt
HVAC	heating, ventilation, and air conditioning
IEEE	Institute of Electrical and Electronics Engineers
IRES	intermittent renewable energy source
ISO	independent system operator
IT	information technology
kWh	kilowatt-hour
MMLD	Marblehead Municipal Light Department

NETL	National Energy Technology Laboratory
NIST	National Institute of Standards and Technology
OG&E	Oklahoma Gas and Electric
PG&E	Pacific Gas and Electric Company
PTR	peak-time rebate
PV	photovoltaic
RPS	renewable portfolio standard
RTO	regional transmission organization
RTP	real-time pricing
SGIG	Smart Grid Investment Grant
TOU	time of use

CHAPTER ONE

Introduction

The legacy power grid of the United States was developed in order to provide almost-universal electric service to customers around the country. It is based on a system of decentralized generators that provide electricity to the transmission (high-voltage) and distribution (low-voltage) systems in a one-way flow from generator to consumer. Given the natural monopoly characteristics of the distribution system, electricity at the retail level is typically regulated, with consumers not facing real-time pricing (RTP) that reflects the true marginal cost of delivery. Because electricity cannot be stored and demand is volatile over time, the result is economic inefficiency. In addition, the negative externalities associated with fossil fuel–based electricity supply provide another source of increased social costs and have resulted in renewable portfolio standards (RPSs) that require generation from wind, solar, and other sources. These sources, however, are problematic to incorporate into the legacy grid.

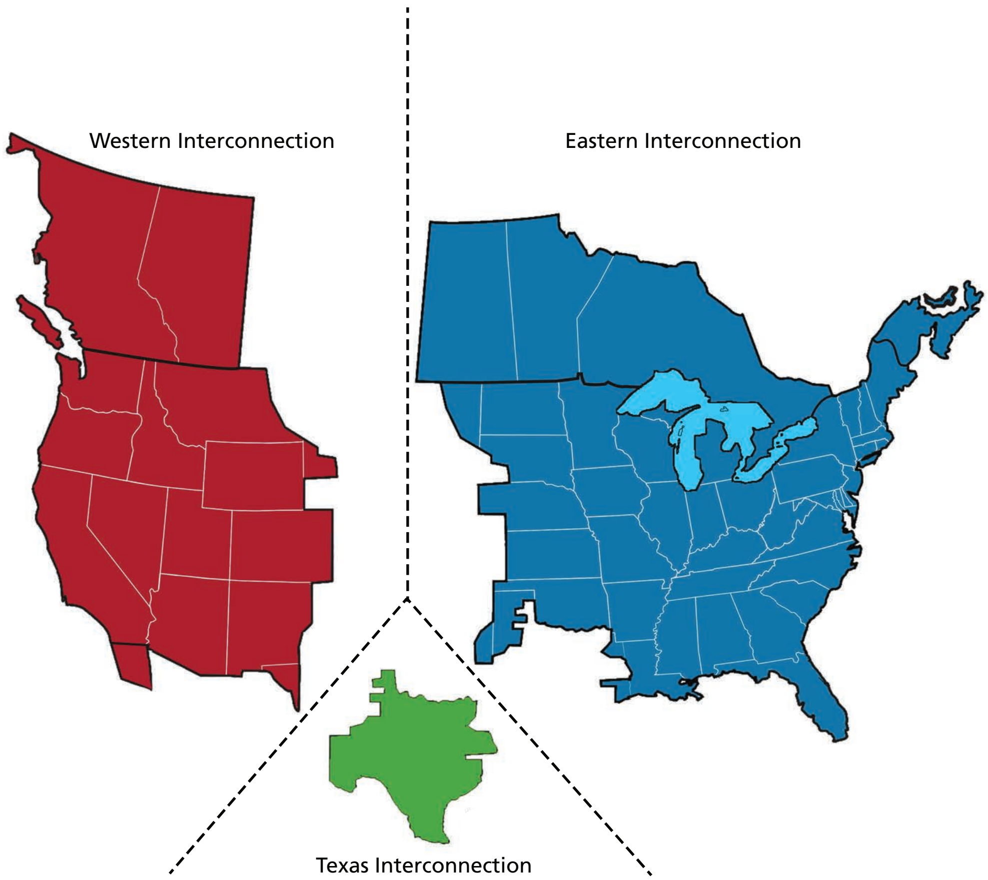
This chapter provides an introduction to the legacy power grid of the United States, including the infrastructure and regulatory structures used in the electricity market. We document the key challenges facing the current grid and introduce the concept of the smart grid that has been proposed to overcome these challenges.

Electricity Infrastructure in the United States

The electric grid in the United States is composed of three almost-independent subgrids named the Eastern Interconnection, the Western Interconnection, and the Electric Reliability Council of Texas (ERCOT), or the Texas Interconnection (see Figure 1.1). Prior to deregulation beginning in the 1990s, the subgrids were vertically integrated systems of generators and transmission and distribution utilities. Deregulation essentially decoupled the generation and transmission and distribution functions of the grid at the interstate level, and a number of independent system operators (ISOs) were formed to manage transmission infrastructure (U.S. Government Accountability Office [GAO], 2008). The formation of regional transmission organizations (RTOs), further developed the competitive wholesale market (GAO, 2008). There are currently six RTOs managed by the Federal Energy Regulation Commission (FERC), with a seventh (ERCOT) regulated by the state of Texas (GAO, 2008). After the California energy crisis and the collapse of Enron in the early 2000s, however, retail deregulation slowed, and the model of a local regulated monopoly (a utility) supplying electricity to most customers has been maintained.[1]

[1] There are, however, exceptions across states and customer classes (Joskow, 2008).

Figure 1.1
Subgrids of the North American Electric System



SOURCE: U.S. Department of Energy (DOE), undated.
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The Supply of Electricity

The electric grid in the United States serves virtually the entire population, encompassing 144 million customers through approximately 60,000 substations and 600,000 distribution circuits (Resnick Institute, 2012). Generators provide electricity from a variety of technologies, which feeds into the high-voltage transmission network, which transports electricity through a series of transformers that "steps down" the voltage so that the electricity is suitable for consumption at the retail level (U.S. Energy Information Administration [EIA], 2014a). Distributors, typically shareholder-owned or municipally operated utility companies, are responsible for delivering power to industrial, commercial, and household consumers.[2] Coordination across the interconnected network is ensured through a system of voluntary standards developed after World War II (EIA, 2013b). See Figure 1.2 for an illustration.

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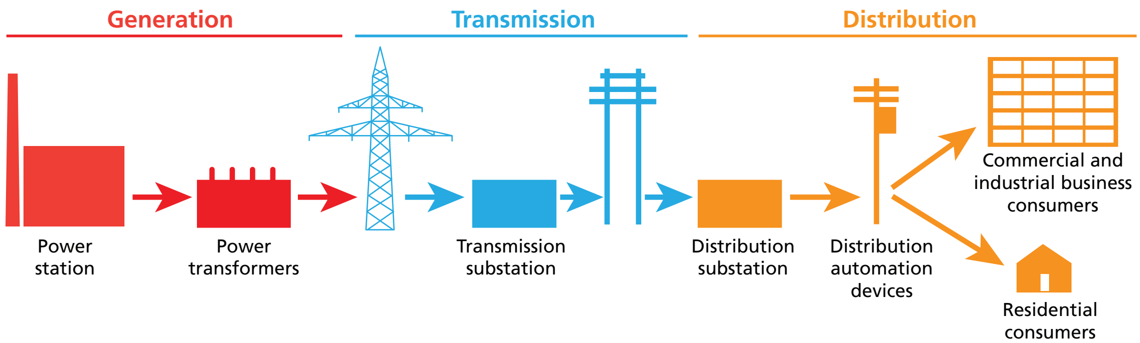
2 Joskow (2002) notes that distributors also perform a retailing function, including purchase of power from generators, metering and billing, and other functions. (Other elements in the supply chain can perform this function, but distributors are the primary actors in this role.) In this report, we lump these functions with distributors (utilities).

Figure 1.2
The Electric Power Delivery System



SOURCE: Byrne, 2010.
RAND *R717-1.2*

Electricity cannot be stored or inventoried in an economic manner, making it the ultimate "just-in-time" commodity (Joskow, 2002). A lack of balancing of supply and demand can have serious consequences, such as blackouts or even large system collapse. In addition, there is no direct connection between a generator and a consumer, with demand and supply linked through the transmission and distribution networks. These physical networks are congestible, in that the physical constraints of the system require the dispatch of higher-cost generation that would not necessarily be used absent the constraints (Lesieutre and Eto, 2003). This negative externality results in differential marginal costs of supplying energy to each node in the network.

The Demand for Electricity

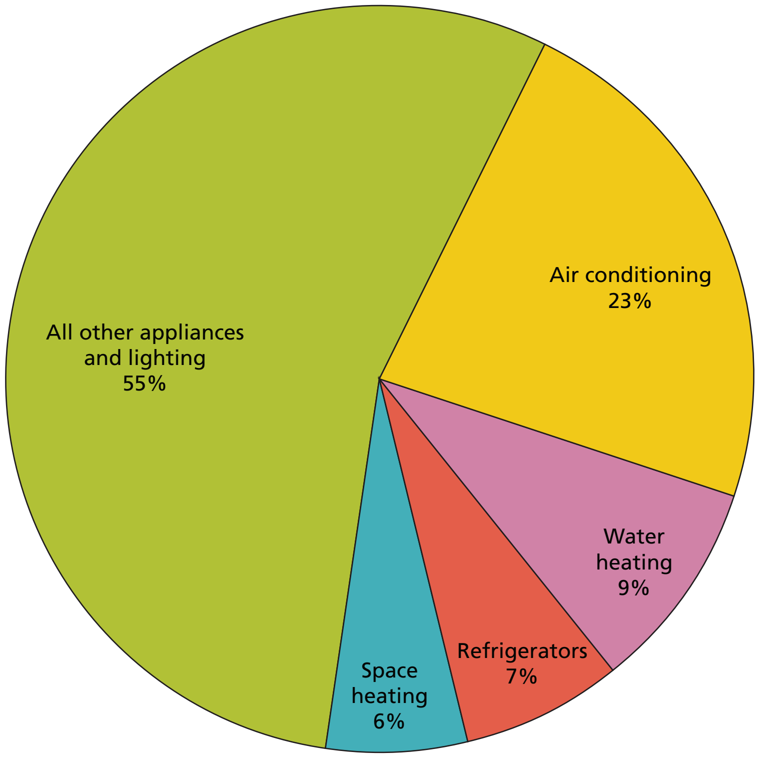
Currently, electricity consumed in the United States is divided roughly evenly across three major sectors: residential, commercial, and industrial (EIA, 2013c). A relatively small proportion of electricity is consumed by a fourth sector, transportation, primarily for powering trains and electric vehicles. Figure 1.3 provides a representative snapshot of electricity use within a home.

Consumers of electricity do not demand a constant, predictable level of electricity. Driving factors of electricity demand include weather conditions, energy-efficiency regulations, macroeconomic conditions, and personal preferences. Blistering temperatures during summer and frigid temperatures during winter increase demand for electricity, leading to daily and seasonal variations in demand. Services that are used only intermittently throughout the day (e.g., lighting) lead to variations in demand hour by hour and even second by second, though daily patterns are fairly stable.

Regulation in the Electricity Market

At the distribution level, most consumers (residential, commercial, and industrial) purchase electricity from monopoly suppliers known as utilities (Joskow, 1997). Utilities can be investor-owned, can be owned by municipalities, or can operate as cooperatives. By law, utilities must

Figure 1.3
Residential Electricity Consumption



SOURCE: EIA, 2014b.
RAND *R717-1.3*

supply electricity to customers within their service regions via universal service obligations and plan future investments (Joskow, 1997; Crew and Kleindorfer, 2002; Tomain, 2002).

Given their status as natural monopolies (for which the costs of supplying the market will be lower with a single supplier), utilities are regulated via state commissions responsible for setting prices (Tomain, 2002). The rationale for regulation is based on the facts that certain industries make up a significant share of the infrastructure uniquely prerequisite to economic growth and that the costs of this infrastructure can be viewed as sunk prior to committing to positive levels of output, thus creating barriers to entry (Kahn, 1970; Joskow, 2007).

Public utility commissions regulate price, directly or indirectly, subject to keeping the utility in business. This occurs through setting both the level and the structure of rates. The rate level or retail price of electricity translates into total utility revenues and profits. It also determines the overall net benefits of electricity consumption for consumers. Typically, the regulatory agency approves capital investments or contractual agreements of the utility. Prices are set (on an amortized basis) such that the utility can recover allowable costs and earn a reasonable rate of return on the rate base of capital; i.e., prices are just, reasonable, and not unduly discriminatory (Joskow, 1997, 2007; GAO, 2008).

A rate case is the quasi-judicial hearing at which investments and rates are approved. If all expenditures are passed through to consumers, consumers ultimately bear all of the costs of investment, but they benefit through the savings in operational costs that are generated (assuming that these savings are passed through as well). This type of regulatory structure in the electricity market is known as traditional rate-of-return regulation, or cost-plus regulation.

During the initial period of electrification, this regulatory structure ensured adequate development of infrastructure and generally protected consumers from monopoly prices (Tomain, 2002). However, once the necessary capital was developed, the system provided no incentive for utilities to innovate to reduce costs but an incentive to overdevelop capacity (Tomain, 2002; Gilbert and Newbery, 1994; Joskow, 2007).[3] In response, various incentive-regulation regimes have been developed. Incentive regulation decouples total revenues from costs, unlike a system in which rates are explicitly set to cover the expected costs. Examples include allowing a fixed price that does not vary with costs and price-cap systems. Incentive regulation thus provides an incentive for firms to minimize costs but runs risks of not ensuring that costs are covered if prices are not set high enough and potentially allows positive rents (or profits) for utilities (Guthrie, 2006; Joskow, 2014). Hybrid regimes, in which a portion of investment and operating costs are passed to consumers through the rate base, are also possible.

Another model involves competition at the retail level. Under this system, customers directly participate in the wholesale market, with distributors providing access and billing services (Joskow, 1997). The negative experience of California in the early 2000s, which resulted in very high electricity prices accompanied by rolling blackouts, contributed in large part to limited retail competition in the United States.

At the generation and transmission stages, regulation occurs primarily at the federal level. Reform efforts toward the end of the 20th century focused on the ability of competition between generators at the wholesale level to increase the efficiency of generative functions and thus pass the savings on to consumers through utility companies (Joskow, 1997).

As a result, the structure of the generation sector is competitive in many areas, with wholesale purchasers facing RTP, but retail (distribution) markets have tended to operate under the incumbent regulatory structures of cost-plus pricing.

Key Issues and Challenges with the Current Grid

Three key characteristics of the current electricity market that grid modernization could improve are (1) demand risk from the utility's standpoint, (2) differences between wholesale and retail prices, and (3) the difficulty of integrating intermittent renewable sources of electricity into the existing grid. We briefly discuss each in turn.

Demand Risk

Because consumer demand is variable and unpredictable, utilities face demand risk. Demand risk is uncertainty about whether the electricity for which contracts exist will be sufficient to meet load demands. Supply in the system is determined through a dispatching system in which power plants are brought on and offline, with lower (marginal) cost plants generally dispatched first. In addition, certain reserves sources are kept "spinning" in order to respond quickly to increases in demand. The end result of variable and unpredictable demand, inability to store

[3] In particular, these are problems with adverse selection and moral hazard. The former occurs because of the information asymmetry between the firm and the regulator regarding the true level of costs. The latter occurs because of the positive correlation between firm profitability and managerial effort, which erodes the incentive to minimize costs.

electricity efficiently at large scales, and dispatching different sources of generation capacity to meet different levels of demand is a widely varying wholesale spot price over time. In the case of an inability to match supply and demand, the system can become inoperative.

Differences in Wholesale and Retail Prices

The majority of residential and small commercial consumers face time-invariant retail prices per kilowatt-hour (kWh); i.e., prices do not vary in real time according to system-wide demand.[4] As a result, retail prices are not reflective of the marginal cost of electricity generation and distribution, but instead they reflect average costs given past capital investments and signed contracts (Joskow, 1997). The mismatch between dynamically changing wholesale prices and time-invariant retail prices leads to inefficiencies.

When electricity consumers face retail prices that do not reflect marginal generation costs, they will fail to conserve when marginal costs are higher than retail rates (during peak periods), and they will conserve too much when marginal costs are lower than retail rates. These distortions in consumption lead to deviations in generation capacity investment and utilization relative to what is optimal from society's perspective (Joskow and Wolfram, 2012). Although the idea of moving from time-invariant pricing to RTP tied to marginal cost was introduced more than 50 years ago, the practical application of theory has lagged (J. Nelson, 1964; Turvey, 1968; Steiner, 1957). Proposed reasons include the cost of installing advanced metering infrastructure (AMI), as well as fears (from regulators and utilities alike) that consumers may react negatively to higher peak prices (Faruqui and Sergici, 2010; Costello, 2004).

In addition, the retail price of electricity varies across (local) distribution because of differences in regulatory structure that the consumer faces, which consists of generation, transmission, and distribution components. Prices also vary according to the type of consumer and the nature of business operations. They are highest for residential and commercial consumers because of the greater costs of distribution and the cost of providing uninterrupted service. Additional regulations mandate that utilities purchase power from renewable fuel sources, and cogenerators contribute to the disparity between marginal costs and prices (Joskow, 1997).

Integration of Renewable Sources of Energy

Renewable resources used in electricity generation include wind, solar, geothermal, biomass, some types of hydroelectricity, and some other minor sources (EIA, 2012a). Nationwide, in 2012, renewable sources accounted for 12.4 percent of all electricity generation (EIA, 2013b).[5] As of January 2012, 30 states had RPSs, also known as renewable electricity standards, that mandate that a certain percentage of generation come from renewable sources, while another seven have nonbinding goals (EIA, 2012a).

Because the key aspect of renewable-resource generation with respect to the electricity grid is the intermittent nature of electricity supply to the high-voltage system, renewable resources

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4 In certain cases, consumers can opt for time-of-use (TOU) or seasonal time-of-day metering, which charge different preset prices during predetermined peak and off-peak load periods. A 2010 FERC survey found that only 1 percent of residential customers were on time-of-usage rates (FERC, 2011).

5 This percentage includes conventional hydroelectric sources (e.g., dams). Fifty-five percent of total renewable generation (in kilowatt-hours) was conventional hydropower. Wind (28 percent), wood and other biomass (7 percent), municipal waste (4 percent), geothermal (3 percent), and solar, not including off-grid photovoltaic (2 percent) make up the remaining renewable sources.

for electricity generation have been termed intermittent renewable energy sources (IRESs). Unlike traditional fossil-fuel or nuclear sources of energy, IRESs do not create a constant flow of current through the grid; rather, they produce electricity only under certain environmental conditions (e.g., when the wind blows or when the sun is shining). The variability creates a problem due to a lack of controllability over inflows to the system (Resnick Institute, 2012). A lack of controllability (through computer-aided human management, as the grid is managed presently) can create stability problems in the grid, increasing the probability of failing to meet all load demand on the system or more-dramatic system interruptions (e.g., rolling brownouts or regional blackouts). These problems exist for both large-scale renewable sources at the transmission level and smaller-scale distributed systems designed to provide power to one or more customers at a local level.

Using Technology to Overcome Problems: The Smart Grid

Developments in monitoring, communication, and other technologies (such as smart meters and supporting infrastructure) provide the means for suppliers to learn about the overall technical state of the electric grid and demand-side conditions while providing the capacity for individuals to learn about (and possibly adjust) their consumption. These same technologies can enable retail-level pricing schemes that more closely match the varying marginal costs of supplying that energy, which, in principle, should increase the overall allocative efficiency of the electricity market.[6]

Furthermore, as additional federal- and state-level policy incentives are provided for the incorporation of IRES technologies in response to concerns about the burning of fossil fuels, many of these same monitoring and communication technologies can be used to more efficiently incorporate intermittent sources of electricity into the grid in a cost-effective manner or provide the ability for surplus generation from distributed local sources to be sold back to distributors. Collectively, these technologies can help transform the legacy grid into the smart grid.

Functionally, *smart grid* refers to the modernization of the electricity-delivery system to allow for greater automation in grid operation at virtually every node, including facilitating data communications and operations between all agents in the system, which include generators, system operators, and final demanders (consumers) (Electric Power Research Insti-

[6] *Allocative efficiency* refers to the relationship between the benefits to consumers and producers of consuming electricity and the costs of providing it. A market is efficient if the overall net benefits corresponding to the quantity consumed are maximized. From a societal standpoint, the benefits and costs include all nonmarket values, such as pollution.

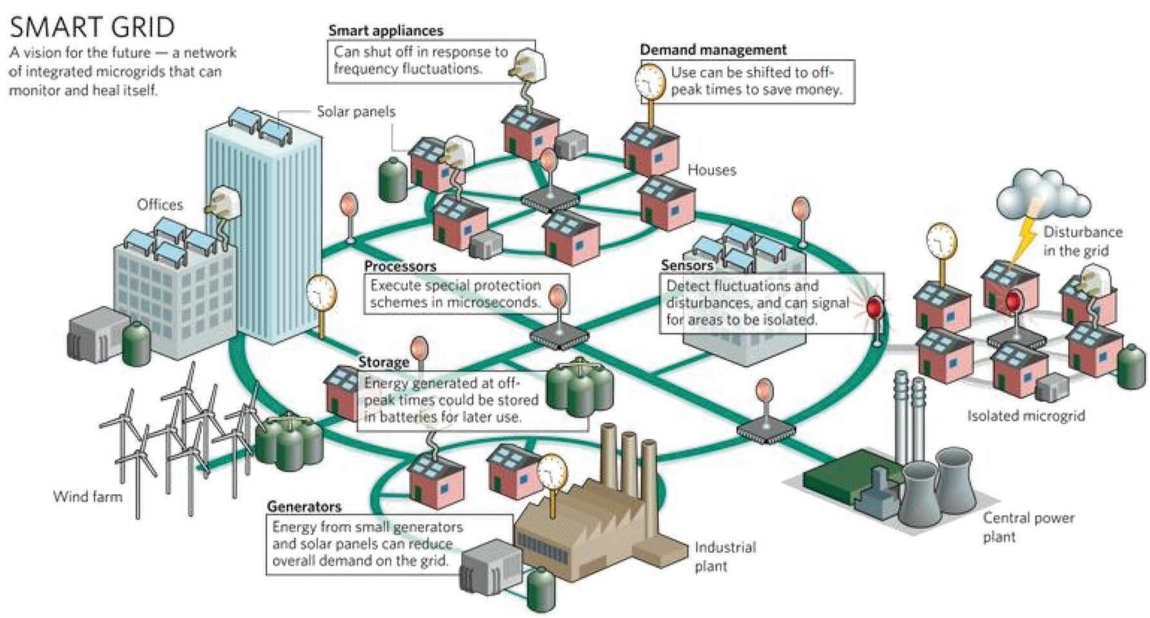
tute [EPRI], 2011; Joskow, 2012). The National Energy Technology Laboratory (NETL) has defined five categories of smart-grid systems to describe this modernization (GAO, 2011):

1. integrated communications, including broadband and wireless communication between and within devices; homes, offices, and plants; and other agents
2. advanced grid components to improve system performance, including smart devices as part of the grid (e.g., switches, transformers) and at final demand, as well as storage devices and microgrids[7]
3. advanced control methods, including methods that automate distribution and locate or correct faults or potential faults
4. sensing and measurement technologies that enable information flows from physical grid components to system operators and consumers
5. improved interfaces and decision support, which organize the information in item 4.

These categories of systems are not necessarily independent of one another, but rather require interdependence. Figure 1.4 provides an illustrative example of how the smart grid works and how various components interact with one another.

The development, deployment, and adoption of these different technologies affect several groups in different ways. For instance, power-sector manufacturers are affected by the shift in demand for new technologies. Electric utilities need to find ways to economically upgrade their

Figure 1.4
The Smart Grid Decomposed



SOURCE: Marris, 2008. Used with permission.
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[7] A microgrid typically includes distributed-generation resources and smart controls that enable it to operate in conjunction with and separately from the main grid. In a microgrid configuration, customers can buy power both directly from the utility and from other customers on the same microgrid (King, 2006).

legacy systems. Consumers are faced with decisions about whether and the extent to which they adopt emerging technologies.

Various studies (e.g., EPRI, 2011; SmartGrid Consumer Collaborative, 2013) have found that the overall potential benefit–cost ratio associated with development of the smart grid and adoption of the smart grid–enabled dynamic pricing policies is expected to be well above 1, suggesting considerable net societal benefits from grid modernization coupled with changes in rate design. These studies rely on ex ante projections of the effects of new technologies on demand and supply conditions and assume that the major players adopt these technologies.

However, despite predictions of large net benefits from smart-grid applications (see Chapter Two), the American Recovery and Reinvestment Act of 2009 (ARRA) appropriated $4.5 billion to "jump-start grid modernization through the deployment of several smart grid programs and related efforts" (DOE, 2012a, p. 1). Full modernization is expected to cost hundreds of billions of dollars in private capital (DOE, 2012a). Yet despite the apparent availability of technologies that distributors and transmitters could adopt, ex post empirical evidence suggests that adoption rates are not consistent with large-scale net benefits, especially in the absence of special federal programs designed to share investment costs between utilities and the general public. Furthermore, real-world experiences with smart-grid technologies have not always lived up to expectations, and the benefits cited by smart-grid proponents have sometimes failed to materialize. If these barriers can be overcome, however, existing utilities could have significant opportunity for entrepreneurial activity.

Research Questions

Given the conflict between theoretical projections of society-wide net benefits of the smart grid and empirical observations that sometimes suggest otherwise, this research report addresses the following research questions:

- What potential benefits could the smart grid have for utilities and consumers of electricity?
- What entrepreneurial opportunities are likely to present themselves in the context of the smart-grid space?
- What does the empirical evidence suggest about the likely materialization of these benefits?
- What technological, economic, and regulatory barriers tend to reduce either the size of these benefits to utilities and consumers or the likelihood of the adoption of technologies and policies that could generate these benefits?
- What policies could be implemented or changed to help overcome the identified technological, economic, and regulatory barriers?

Approach

This report reviews the literature related to smart-grid development and analyzes the potential barriers and opportunities related to grid modernization. After reviewing the literature on grid modernization and discussing some additional entrepreneurship opportunities associated with continued technological development, we use a microeconomic framework to examine the incentives related to smart-grid technology adoption and dynamic pricing from the standpoint of the major players in the market (e.g., distributors, utilities, transmitters, and consumers). Our major objective is to identify the real-world factors that may influence the adoption of smart-grid technologies, rather than requantifying the benefits and costs of a fully modernized grid. After identifying these barriers, we describe some policy levers that can be used to shape smart-grid development, as well as some principles of regulation that can help regulators make better decisions regarding grid modernization.

Organization of This Report

This report is organized as follows. Chapter Two provides a discussion of the potential ex ante benefits of smart-grid development to generators and suppliers, distributors and utilities, and consumers, as well as society at large. Chapter Three discusses the possibilities and challenges of an emerging area of entrepreneurship in the smart-grid space—namely, the use of big data, which can generate additional benefits. Chapter Four reviews some of the real-world experiences with smart-grid technologies, including the experiences of utilities and consumers under the ARRA, which included a large program to promote grid modernization, and a few selected case studies that highlight some of the more-negative experiences with smart-grid technologies. Using these three chapters as a foundation, Chapter Five provides an analysis of the barriers to smart-grid innovation from a microeconomic perspective, with a particular focus on some of the costs and risks faced by utilities and consumers. Chapter Six provides policy guidance that could be used to shape the direction of smart-grid growth.

CHAPTER TWO

A Review of the Potential Benefits of the Smart Grid

According to GAO, full deployment of the smart grid would have some potential benefits (GAO, 2011). These are generally independent dimensions and include the following:

- lower electricity rates due to the ability to improve the overall efficiency of the system operation, in particular by shifting peak demand
- improved reliability: fewer and shorter outages
- improved ability to detect and respond to attacks and outages related to the grid
- improved ability to incorporate intermittent alternative energy sources, such as wind and solar
- improved information to consumers, allowing them to make more-informed choices about electricity consumption.

In the sections that follow, we document the potential categories of expected benefits of the smart grid for three groups—generators and suppliers, distributors and electric utilities, and consumers—as described in the literature. We consider the smart grid's effects on generators as if they were operating as independent entities. We lump high-voltage transmission and distributors and utilities together because they are either operated on a nonprofit basis or are typically regulated, recognizing that, as a result of this regulation, consumers should ultimately see a pass-through of any benefits. We also include a subsection on society at large.

Potential Benefits to Generators and Suppliers

For current generators of electricity, net benefits from the smart grid could be positive or negative.[1] From an operational standpoint, a flattened load profile from demand-side response (i.e., less peak-load demand) might reduce operating and maintenance costs resulting from fewer high-cost generators being brought online (termed *ramping*) (NETL, 2010). There may be modest benefits from improved reliability (defined as decreases in the frequency and duration of outages and the number and intensity of quality disturbances) to generators because greater uninterrupted generation may reduce the rate of depreciation on the input side and increase in quantity sold on the output side (NETL, 2010).[2]

1 We assume at the micro level that these generators are price-takers. However, Joskow (2002) notes that, primarily because of grid congestion, local monopolies could develop, and strategic firms could manipulate the market.

2 All else equal, less disruption in the grid means that the generator can sell more energy in a given period of time. A similar benefit could be expected from increased security and safety from improved detection of threats and shorter recovery

Potential suppliers of intermittent electricity (e.g., solar, wind, geothermal) might also benefit from smart-grid technologies. Coupled with mandates, such as renewable-energy portfolios, these technologies will enable the larger grid to more cost-effectively integrate renewable sources. However, the introduction of new IRES producers with low marginal costs of generation can also negatively affect incumbent nonrenewable generators through reductions in quantity demanded and increased ramping.

Interestingly, it has been suggested that smart-grid technology will enable the decentralization of the power-generation process (Römer et al., 2012; Resnick Institute, 2012). Renewable technologies, such as wind and solar photovoltaic (PV), generated at a local (i.e., commercial building or household) level can provide a substitute supply for consumers, thus decreasing centralized-grid demand, as well as provide additional sources of generation capacity when the weather cooperates. Thus, assuming that smart-grid technology can be used for net metering, in which billing takes into account both the production and the consumption of locally generated electricity, the prosumer (one who can both produce and consume electricity) can benefit on net.

Potential Benefits to Distributors and Utilities

The transmission system (high voltage) and distributors (low voltage) of electricity serve as the intermediary between power generators and final demand. This collection of firms, RTOs, and ISOs manage the linked infrastructure that is used to deliver electric power. Because of the just-in-time nature of electricity distribution, the ability of grid operators at both the high- and low-voltage levels to balance (and perhaps shift) patterns of supply and demand is crucial to the efficient delivery of the product (Joskow, 2012; Denholm and Hand, 2011).

Smart-grid technologies focused on two-way communication from grid to consumer and back again (such as AMI) provide quantity information about final demand from the consumer to the grid and price information from grid to consumer. For producers, the quantity information can be used to increase efficiency in transmission and distribution by theoretically increasing delivery efficiency through improved load-management predictions at a technical level and by reducing the transaction costs in billing through automated metering (Joskow, 2012; Römer et al., 2012).

Communication technology can provide state-of-the-system information to the transmission and distribution systems when used in conjunction with sensors deployed at several levels of the power-delivery system. In some cases, potential problems and stressors in the grid can be identified automatically, thus potentially increasing power quality and reducing outages and their associated costs, including those related to operations and maintenance (Joskow, 2012; EPRI, 2011; NETL, 2010).[3] In other cases, these technologies can be used to identify and locate system problems, such as faults; isolate them from the rest of the grid; and rapidly fix them, thus reducing outage times and search costs. EPRI (2011) states that, with smart-grid technologies, "utilities can provide more reliable energy, particularly during challenging emergency conditions, while managing their costs more effectively through efficiency and informa-

time (NETL, 2010; Moynihan, 2010).

[3] *Power quality* refers to small variations in the physical properties of the electricity being delivered.

tion" (EPRI, 2011, p. 2-2). Thus, the smart grid may improve both the quantity (fewer outages and associated costs) and quality of power delivered to consumers.

A second-order benefit of these effects is the reduced costs of immediate grid capacity expansion (overall net present value) due to the ability to generate higher-quality power with essentially the same "wire" infrastructure (i.e., the transmission and distribution lines) (EPRI, 2011; NETL, 2010). An improvement in efficiency is thus a substitute for investment in the capacity of that network and thus may generate (potentially unobservable) net benefits if the cost of efficiency gains is less than the costs of new infrastructure.

Although the above benefits focus on technical efficiencies, the transmission system and distributors face an allocative efficiency issue with respect to the integration of IRESs and distributed-generation resources. From the standpoint of grid operators, the need to incorporate IRESs and distributed generation is exogenous. However, because of the nature of these sources, there are four major challenges to significant penetration of these sources while maintaining system reliability and quality (Denholm and Hand, 2011):

- frequency regulation
- the increase in ramping rate (the speed at which load-following units must increase and decrease output)
- the uncertainty in renewable generation and hence net load
- the increase in overall ramping range (daily minimum and maximum demand).

Smart-grid technologies can either smooth loads or provide storage services that can help reduce the costs associated with these issues (Denholm and Hand, 2011; Römer et al., 2012; Boisvert and Neenan, 2003). Finally, implementation of RTP or dynamic pricing regimes can provide a short-term benefit to utilities from eliminating the need to purchase power from the high-cost generators, boosting profitability. However, in the long term, the utilities do not benefit because the lower average price of wholesale power will be passed on to consumers.

Potential Benefits to Consumers

The standard argument on how introduction of the smart grid will yield potential benefits to consumers follows a two-step process involving the passing on of savings from the system to the consumer:

1. Smart-grid technologies lower the costs of delivering electricity to consumers.
2. Electricity suppliers pass these savings to the consumer.

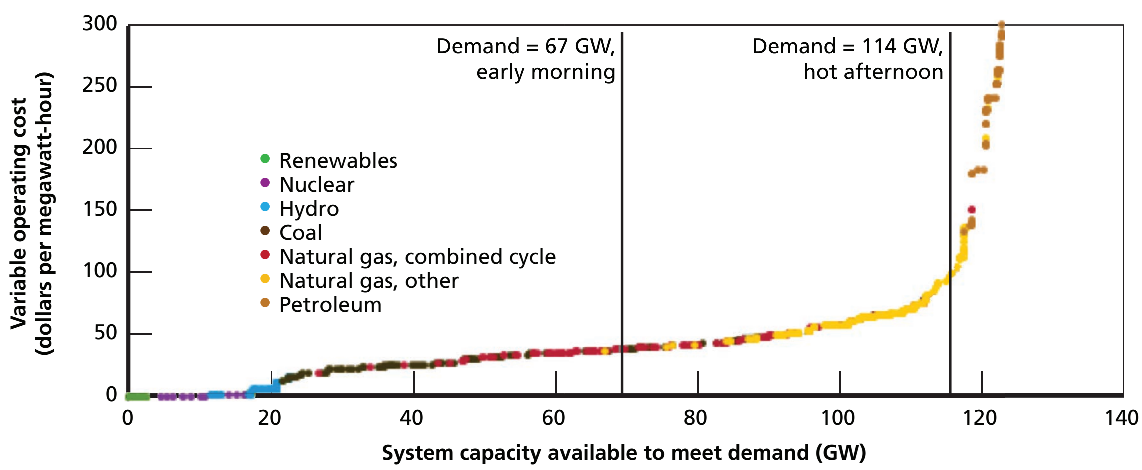
On the supply side, this process is straightforward; various technologies serve to decrease operating costs or increase power quality. For example, the increased potential for monitoring and controlling system health that the smart grid affords can automate the process of identifying outages, reducing costs. Similarly, these same technologies can improve voltage regulation and power quality—an important factor for some customers with critical electronic devices connected to the grid. The enabling of clustered distributed-generation resources in the form of microgrids can help to alleviate system stress during regular operation, also lowering costs and increasing quality.

On the demand side, however, the operational savings manifest themselves through changes in consumer behavior. AMI (such as smart meters) enables wholesale price signals to be sent directly to the consumer in real time, thus aligning the price of electricity to its marginal cost of production. For price-responsive consumers, this will tend to decrease quantity demanded at high-cost, peak-load times, with the effect of eliminating higher-cost generators from the overall production mix (see Figure 2.1). This is termed *load flattening*. Furthermore, because peak demand typically drives investment in generating capacity and transmission and distribution infrastructure, the flattening of the load curve can reduce the need for expensive investments by utilities in supporting excess generating capacity. Less than 1 percent of hours, which constitute high peak-demand hours, are estimated to account for 10 to 18 percent of the capacity needs in North America (Faruqui, Hledik, and Tsoukalis, 2009).

There is no consensus in the demand response research on whether higher peak prices simply reduce peak demand, leaving nonpeak demand unchanged, or whether they shift the demand from peak to nonpeak periods (Joskow, 2012). Regardless, however, a reduction in peak loads reduces the total cost of delivering a given quantity of energy over a fixed time period. When passed on to the consumer, these expenditure savings are often cited as a key benefit of the smart grid.

Furthermore, RTP can stimulate innovations in appliances inside the home or business. This secondary-control-technology channel requires consumers to upgrade their own infrastructure to support automatic response to utility control technologies or RTP signals. For example, a programmable communicating thermostat would turn off air conditioning (or increase target temperatures) when electricity prices are high. Common household appliances, such as refrigerators and dishwashers, would come with smart chips installed to receive signals to enable the timing of certain functions to be controlled remotely (DOE, 2012a). These appli-

Figure 2.1
Sample Dispatch Curve for Electricity Supply



SOURCE: EIA, 2012b.
NOTE: GW = gigawatt. "The variable operating cost of electric power generators is a key factor in determining which units a power system operates (or 'dispatches') to meet the demand for electricity. Other things being equal, plants with the lowest variable operating costs are generally dispatched first, and plants with higher variable operating costs are brought on line sequentially as electricity demand increases. This sequence can be seen in an electricity supply curve—also referred to as a dispatch curve—that represents the order in which units are dispatched to meet the demand" (EIA, 2012b).
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ances would reduce the costs of shifting energy demand, allowing consumers to take advantage of lower off-peak electricity prices.

Potential Benefits to All Market Participants and Society at Large

In addition to the private benefits that accrue to consumers and producers and distributors of electricity, the literature discusses several additional sources of benefit. First, smart-grid technology is expected to promote grid safety and cybersecurity (EPRI, 2011). This can protect against potential cyber- and other attacks through greater redundancies in a more distributed, less centralized system, as well as increased monitoring (Moynihan, 2010).[4] Enhanced safety and security can lessen damage from terrorist and other attacks, a fact that benefits both consumers and producers. Second, as noted above, smart-grid technologies are expected to facilitate the incorporation of noncarbon IRES, reducing environmental pollution and the associated external costs (EPRI, 2011; Moynihan, 2010). The damage caused by emissions related to electricity generation is a negative externality, meaning that producers and consumers of electricity do not generally take into account the costs of the damage. RPSs (a quantity instrument) and price instruments, such as taxes on fossil-fuel use and subsidies for renewably sourced energy generation, can change the generation fuel mix to sources perceived as less damaging to the environment, thus reducing the amount of damage caused by negative externalities.[5]

Finally, the ability to more effectively incorporate clustered distributed-generation resources in the form of microgrids may improve system operators' ability to provide sustained electricity to critical social services in the event of power blackouts (Narayanan and Morgan, 2012).

Total Potential Benefits of the Smart Grid

In economic terms, EPRI estimated that the potential benefits of a fully deployed smart grid are in the range of $1.3 trillion to $2 trillion, compared with total costs between $338 billion and $476 billion over 20 years (EPRI, 2011). In a less comprehensive quantitative study,[6] SmartGrid Consumer Collaborative (2013) estimates a net present value of direct benefits over a 13-year time horizon of between $307 and $773 per customer, with additional indirect benefits from outage management and fault location of $390. Costs were estimated to be $450 per customer. Taken together, these figures imply a benefit–cost ratio of between 1.5 and 6. In each case, the expected benefits of a fully modernized smart grid are expected to exceed

[4] This assumes a fully implemented smart grid with additional monitoring capabilities, storage, and distributed generation and microgrids that increase system redundancies. Of course, increasing the number of entry points may also serve to increase risk.

[5] In the case of a tradable permitting system, the incorporation of renewables may not reduce total emissions if the cap is binding. Furthermore, some interactions between renewable mandates and transmission congestion could be aided by smart-grid technologies, similar to the benefits from IRES. An evaluation of the optimality or desirability of various environmental policies to reduce emissions in the electricity sector is beyond the scope of this research, especially because market participants will likely not take into account the damage costs from pollution.

[6] The collaborative chose to qualitatively, rather than quantitatively, treat some categories of benefits. Hence, the results are more conservative than those from EPRI.

the expected costs by a comfortable margin. Furthermore, much of the necessary information technology (IT) is readily available in the marketplace, and there appear to be few technical barriers to smart-grid innovation.

These numbers are not without critics. Joskow (2012), for example, expresses some degree of skepticism. In the context of automation of local distribution networks, he states that, "Unfortunately, I found the benefit analyses to be speculative and impossible to reproduce given the information made available in EPRI's report" (p. 38). In his conclusion, he also states that estimates regarding the impact of RTP programs are not precise enough "to do convincing cost–benefit analyses" (p. 45).

Nevertheless, most studies predict that the benefits of full adoption of smart-grid technologies will be greater than the costs, and the United States has invested heavily in grid modernization through the ARRA. The purpose of this report is neither to verify the estimates of the benefits and costs nor to argue in favor of acceleration or deceleration of adoption of those technologies. Rather, we seek to understand the underlying environment that might contribute to perverse adoption incentives in the absence of policy changes, even if the predicted net benefits of a fully implemented smart-grid system are positive. We then discuss potential policy levers that can be used to overcome these barriers and identify some potential entrepreneurship opportunities related to the smart grid.

CHAPTER THREE

Potential for Entrepreneurship with Smart-Grid Technologies: Opportunities and Challenges Leveraging Big Data

The smart grid will generate a wealth of new information on electricity consumption at a detailed level that could be leveraged to create economic value while influencing the benefits derived from grid improvement. Currently, the utility industry is not fully equipped with the analytical capabilities to capitalize on the new information.

In this chapter, we discuss some potential opportunities associated with use of this information that can create additional benefits not always considered in the current literature. We first describe how the characteristics of electricity data will be changing in the next decade, what it means to disaggregate smart-meter data, and current methods to do so. We then explain the usefulness of disaggregation, forecasting the processes and possibilities in monetizing electricity data. This includes a general taxonomy of business opportunities tied to using smart-grid data. We will discuss barriers to entrepreneurship and how public policy may influence development of new business opportunities described in Chapter Five.

Description of Electricity Big Data

Digital electric smart meters stream electricity-use data to a central utility system, in which those data are recorded in intervals of 60 minutes or less. A significant amount of Smart Grid Investment Grant (SGIG) money from the ARRA was targeted toward AMI, which enables dynamic electricity pricing through real-time or near-real-time monitoring information.

In order to reliably and securely stream the data collected from a meter to a central data system, utilities make choices that differ not only in the medium of communication but also the type of network used.[1] The two main types of networks used are fixed wireless and mesh networks. Fixed wireless networks are centralized and require a high-power transmitter and receiver that can reach all networked devices. In decentralized wireless mesh networks, which were first designed for military applications, each node is fully connected to all the other nodes, allowing for "self-healing" connections around broken nodes or blocked connections. An example of an implementation for smart-meter communications in the United States is the ZigBee mesh-network specification. ZigBee utilizes low-powered, low-cost radio chips to transmit small amounts of encrypted data short distances. In a ZigBee network, each smart

[1] This is due to environmental factors, such as geographic terrain, potential for radio interference, or availability of wireless Internet-connected networks. Utilities with meters located in rural locations deal with different communication challenges from those in densely populated urban areas. Proposed mediums include cellular networks, satellite, licensed and unlicensed radio, and power-line communication. With power-line communication, data are carried on the same conductor used for electric power transmission (Tung, Tsang, and Lam, 2010).

meter acts as a node, and data are propagated from smart meter to smart meter until the data reach a terminal connection to the utility data system (Daintree Networks, 2014).

Given the rapid growth in smart-meter installations due to the ARRA, the current challenge faced by utilities is how to integrate and optimize all the information collected across a much larger customer base. Right now, there are not many uses for second-by-second consumption data, but we anticipate certain entrepreneurial innovations in such areas as customer engagement and housing efficiency that will be possible given the new data. The benefits from such innovations may justify the costs of storage. In the following sections, we discuss what can be done with electricity data of sufficient quality and granularity.

The Disaggregation Problem

To effectively analyze consumption data for the purposes of shifting behavior, it is necessary to disaggregate "raw" whole-building energy consumption into individual appliance-level data containing an itemized list of appliance usage, energy consumption, time, and duration of consumption. There are currently no commercially available solutions to perform disaggregation in a way that is accurate, cost-effective, and easily deployable. In the past, the most practiced technique was to perform field surveys, in which households self-report appliance use. These surveys are unable to provide a rich, comprehensive data set and suffer from self-reporting bias.

In contrast, the two main automated approaches to obtain appliance-specific data rely primarily on either hardware solutions or software solutions. We briefly highlight the advantages and disadvantages of each in turn. This discussion describes the primary technological challenge that must be overcome before any economic value can be extracted from electricity big data.

Hardware Solutions

Hardware solutions require installation of individual plug monitors on each appliance. Plug devices (e.g., Kill A Watt, ThinkEco products, EnergyHub software, the Enmetric Systems platform) on individual appliances are then connected using a communication protocol to create a home-area sensing network. Although this is the most straightforward and potentially the most accurate method, hardware solutions suffer from some glaring flaws that may ultimately prevent their viability in practical environments. First, installation is expensive, at $25 to $50 per appliance monitor (Armel et al., 2013). Furthermore, many appliances are hardwired (e.g., water heaters, lighting), operate at high voltages in difficult-to-reach areas (e.g., kitchen appliances, laundry dryers), or may not be installed permanently inside the home (e.g., power tools, hot tubs). If consumers are less likely to install monitors on such appliances and are limited to the number of devices that can be monitored, some of the most electricity-intensive appliances could be omitted from the data. In summary, hardware solutions can provide highly accurate data if the entire house is filled with sensors, but they generally require higher costs and greater installation effort than software solutions do. Consequently, we anticipate low adoption rates in using hardware solutions for disaggregation.

Software Solutions

A software solution seeks to connect the aggregate consumption data stream from the smart meter onto a single source and use a set of statistical approaches to extract patterns characteristic of a given appliance. By avoiding installation of individual sensors, using smart meters already installed by utilities makes this approach lower in cost with no additional installation effort. Given the adoption rates for smart meters, the ability to apply software disaggregation on a large scale is expected to be high. The main disadvantage is accuracy in disaggregation because disaggregation algorithms are still works in progress.

There has been substantial prior research in the area of nonintrusive load monitoring. Each appliance is assumed to have a unique feature, whether it is the tendency to draw a certain amount of power, a start-up characteristic, or a voltage signature (Hart, 1992; Froehlich et al., 2011; Gupta, Reynolds, and Patel, 2010; Zeifman and Roth, 2011). Current research attempts to develop ways to classify the voltage noise signatures in order to characterize the operation of home appliances. Figure 3.1 provides two examples of disaggregation using a range of voltage signatures, both transient and continuous. On the left, turning on a light switch produces a burst of electromagnetic interference (EMI), which can be detected as a transient voltage noise signature. On the right, we can see continuous voltage noise signatures for multiple devices during various periods of operation. Many appliances (e.g., washing machines, dryers) and heating, ventilation, and air conditioning (HVAC) have predictable states of usage and usage directions.

The number of appliances that can be identified determines the level of disaggregation detail. The level of detail depends on the type of sensing hardware installed, the pattern-matching algorithms employed, the cost of installation, and the ease of calibration. At the coarsest level, smart meters capable of low-rate data sampling (i.e., 1 hour to 15 minutes) are only able to differentiate among broad device categories: devices that run continuously, devices that are time-dependent, and devices that correlate with outdoor temperature.

Smart meters capable of medium-rate data sampling (i.e., 1 minute to 1 second) can differentiate among the major appliance types, such as stoves, heaters, compact fluorescent lamps (CFLs), air conditioners, refrigerators, washers, dryers, and pool pumps. With high-rate–sampling smart meters, current disaggregation methods are able to identify and track up to 40 specific appliances, including toasters, computers, DVD players, charging units, and dif-

Figure 3.1
Example of Disaggregation

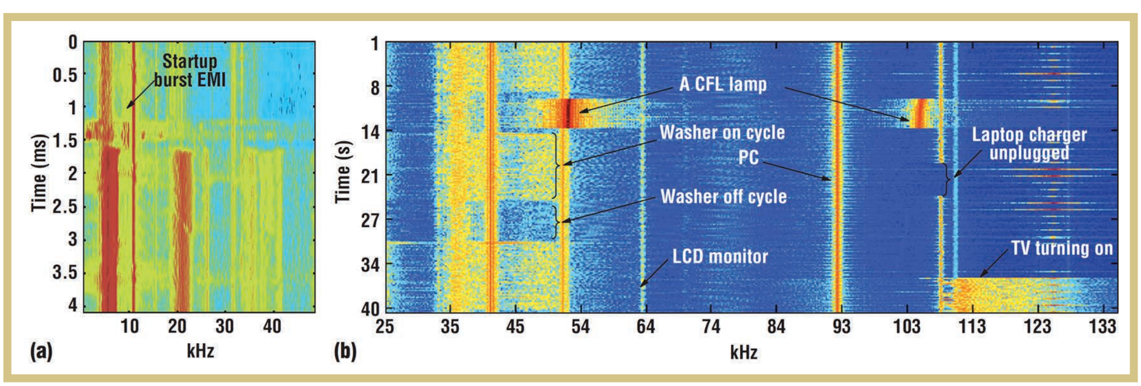

Figure 2. Spectrogram. (a) Transient voltage noise signatures of a light switch being turned on. Colors indicate amplitude at each frequency. (b) Steady-state continuous voltage noise signatures of devices during various periods of operation.

SOURCE: Froehlich et al., 2011, p. 34. Used with permission.

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ferent types of lighting. At this level, appliances can be identified even when they are always turned on. Almost all current smart meters are able to support high-rate sampling without any hardware upgrades, although firmware upgrades may be necessary (Armel et al., 2013).

Issues in Disaggregation

The presence (or absence) of EMI signatures can inform whether a particular appliance is in use, but, because of the large number of appliances typically drawing power in a home, the solution to the disaggregation problem is not straightforward. In order to make inferences about the appliance class given a particular signature, machine learning and probabilistic models are required to account for human appliance-usage patterns (e.g., coffee machine and toaster in the morning versus lights in the evening) and weather patterns (air conditioning during the summer versus heating during the winter). To further complicate matters, an appliance's signature can also vary over time because of the operating conditions and the mode of operation.

Finally, current software disaggregation efforts take place given known appliances within a household. In order to validate software prediction accuracy, an "answer-key" data set, in which appliances in a house are completely inventoried and their usages are recorded over several days, is required. Algorithms are first trained on the answer-key data set by validating disaggregation over the observation period. Then the algorithms are given raw aggregate data for a different time period but for the same house. Currently, software prediction for this type of problem is accurate approximately 90 percent of the time ("Belkin Energy Disaggregation Competition," 2013). However, a more realistic challenge would be to extract appliance data for a house with *unknown* appliances.

In summary, the hardware solution is less scalable—it is really only viable for a small subset of total households. The software solution requires a substantial up-front investment but has negligible marginal costs. In the next section, we explain why deriving disaggregated appliance-level data may be worth the trouble.

The Economic Value of Disaggregated Data

The benefits of disaggregated data can be classified into consumer benefits, utility and policy benefits, and research and development benefits. This section compiles and expands on benefits mentioned in Pratt et al. (2010), Froehlich et al. (2011), and Armel et al. (2013).

Consumers

As discussed in previous chapters, an often-overlooked assumption in demand-response programs through RTP is that consumers possess adequate self-awareness of their electricity use (by appliance) to be responsive to prices. However, if consumer self-awareness is poor, consumers' ability to moderate their electricity consumption and participate in demand response is limited. Without appliance-level data, a consumer may know that aggregate electricity consumption has increased but may not be able to detect the source of the increase. This is an issue because misunderstandings about how electricity is consumed will be reflected in the measures consumers take to conserve electricity.

In fact, misconceptions about home electricity consumption abound. Consumers tend to estimate an appliance's proportional energy cost by its perceived salience—how noticeable it is as part of daily life (Kempton and Montgomery, 1982). Often-on appliances, such as televisions and lighting, are thought to contribute more to the monthly bill than they actually do. They also may overestimate energy use for machines meant as substitutes for manual labor, such as dishwashers and washing machines. In general, the contributions of appliances are overestimated, while the contributions that heating and cooling make to the bill are underestimated (Costanzo et al., 1986). In terms of the managing an electricity bill itself, recent surveys and economic research find that many consumers are not aware of how many kilowatt-hours of electricity they use daily and may not understand the marginal rates of nonlinear electricity pricing schedules (Ito, 2012).

These misconceptions, which could be corrected with additional informative appliance-level data, influence the measures consumers take to conserve electricity. The procedure for traditional energy audits, meant to inform consumers of their specific usage and find conservation measures, is very manual. A professional technician will visit the home, examine the insulation, inspect the furnace and ductwork, and perform a blower door test using an infrared camera. These audits are time- and labor-intensive and are used by only a subset of households. Disaggregated data allow for a new way of conducting energy audits that is cheaper and more automated. Instead of a house visit, a software program would examine the smart-meter data, and this could be done for any household at any time. Most importantly, these measures would be tailored for the *specific* household rather than general recommendations for the average household. For example, a tailored recommendation might be as follows: "Given your usage patterns, you could save $400 per year by switching to a newer heating unit, which would pay for itself in five months."

Another useful application for disaggregated data would be the ability to diagnose overconsumption and detect faulty electronics that lead to overconsumption. Presently, detecting faults is labor-intensive and time-consuming, often requiring an on-site visit by a qualified electrician. Disaggregated data would allow for quick, automatic, inexpensive diagnosis.

A recent *Wall Street Journal* article contains stories of consumers using their smart meters to find problems (Smith, 2013). One homeowner was able to identify a malfunctioning pool pump that was adding $100 per month to his bill. A commercial business used smart-meter data as part of an energy audit, which recommended upgrading light bulbs, installing fans, and purchasing a programmable thermostat. These actions cut the bill from more than $400 to $200 per month.

Because the flow of consumption data from smart meters is continuous, opportunities to find savings are also continuous. Alerts can be sent automatically when overconsumption is detected and to remind the consumer about behavioral corrections. This perpetuates a virtuous cycle of providing direct and timely feedback to the consumer.

Utilities and Policy

Utilities would benefit from improvements in the quality of their demand-forecasting models. Accurate demand forecasting is important for a utility company when making decisions regarding generation capacity, infrastructure development, load-switching, and energy-purchasing contracts. More-granular, appliance-level data would facilitate a better understanding of residential and commercial electricity-usage behavior, which would improve the representation of consumption patterns in forecasting models.

Utilities also often run conservation and retrofit programs but have difficulty evaluating and prioritizing these programs. Better data allow for more-conclusive program-evaluation efforts, with the possibility of establishing causality. Before, results from programs that target specific appliance usages (e.g., heating, cooling, and lights) would be lost in the noise of aggregate data. The availability of disaggregated before and after the program strengthens the sensitivity and conclusiveness of such evaluations. This includes a greater ability to quantify the savings from incentive programs. Desired end results would be improved programs and diversification of new programs.

A final benefit for utilities is better interaction and communication with their customers. Instead of facing a homogenous market, utilities armed with disaggregated data could segment the market by demand characteristics. Learning more about how their customers use electricity helps utilities identify customers and customer groups for marketing purposes. Having real-time data also helps utilities quickly find the location of network problems and dispatch support services. Pricing innovations would also be possible. Prices would not just vary by time of day or total system demand but also by type of usage. For example, utilities could have one level of pricing for essential heating, cooling, and lighting and another for nonessential appliances, such as dishwashers, hot tubs, and clothes dryers.

Likewise, policymakers would also benefit from better insight into how energy is consumed across different segments of the population. Disaggregated data would allow them to structure energy policies, rebate programs, and efficiency programs in ways that are more evidence-based. They could also become more aware of the distributional effects of regulations and taxes. For example, policy interventions aimed at reducing electricity consumption may affect low-income residents more adversely if the majority of their usage is dedicated to heating.

Benefits Outside of the Electricity Market

Two additional areas in which disaggregated data could be valuable involve appliance innovation and building research and development. Appliance manufacturers have traditionally relied on measurements and tests in controlled laboratory environments when developing their products. With access to disaggregated data, manufacturers could get more-realistic measurements in a wide range of actual operating conditions. Better consumption data would aid in redesigning appliances for efficiency and reliability and in meeting improved efficiency standards. Disaggregated data would contain the timing and duration of appliance usage. This might uncover nonintuitive insights into how different consumers actually use their appliances.

Furthermore, better appliance-use data could aid in validating building simulation models, which are valuable tools in increasing the operational efficiency of commercial buildings. The data might uncover that consumers might use appliances and buildings differently from the intended design. For example, for health and comfort reasons, building occupants often leave windows open to get fresh air even while the heat is on.

Business Opportunities from Smart-Grid Data

This section provides a general taxonomy of possible services and entrepreneurial opportunities that could capitalize on newly available smart-grid data. This is not meant to be a comprehensive guide to all possible opportunities, but rather a discussion of general directions in which the market may move. We discuss two broad categories of opportunities: ventures in support of energy savings and ventures aimed at refinement of disaggregated data.

Energy-Efficiency Ventures

The most direct application of real-time consumption data is to guide efforts to improve energy conservation and empower the consumer to save on monthly bills. One valuable service might be conducting data-assisted energy audits in order to identify the best ways to improve energy efficiency. As mentioned earlier, a traditional energy audit is performed by a qualified inspector. It requires physically visiting each home; bringing professional equipment, such as blower doors and infrared cameras; and interviewing homeowners to understand usage patterns. The process is manual, expensive, time-consuming, and simply not scalable to a broad community.

A more cost-effective alternative would involve leveraging disaggregated consumption data from smart meters and building asset data to automatically create a living energy model of any building. Appliance-level consumption data from smart meters avoid the time, cost, and inaccuracy of interviews. These newly available data are also capable of detecting faults in the home without necessitating a home visit. Benchmarking, which is intended to compare efficiency across households in a range of situations, would be immensely more accurate with data from hundreds of other prior energy audits, as well as appliance-level performance data.

Once possible conservation measures have been identified, either the utility or a third-party venture could reach out to the consumer with personalized recommendations. A service might entail matching consumers with appliance retailers for new appliances or contractor options for house upgrades. A hypothetical recommendation might be a heater upgrade that can be shown to save 20 percent off the consumer's monthly bill (given the consumer's historical usage patterns) and break even within five years. Such a service would take into account utility rebate programs and tax incentives.

There could also be value in behavioral feedback services that monitor behavior and encourage convenient energy conservation. Such a service might communicate with consumers via text alerts when nonoptimal behavior is detected or when the energy supply is constrained. It would rely on observing household behavior—i.e., intelligently learning the patterns of the household. It would then offer personalized recommendations for behavioral modifications. The system would continually monitor activity in hopes of constantly refining and maintaining energy savings.

Data Refinement

Given the nascent nature of disaggregated data, prediction of further refinement and application of disaggregated data comes from combining insights from surveying start-up activity in the energy sector with a degree of technological foresight. One trend in companies that deal with issues of big data is a movement toward better data organization and visualization.

A visual presentation of electricity consumption and appliance operation may be useful on an individual household level or on a regional level. For utilities, creating visualizations of appliance use within individual households would be an important component of demand-response programs. Current web portals depict historically aggregated consumption data with fairly straightforward graphs and tables, but, with more-granular appliance-level data, proper organization and schematic representation of consumption are critical.

In addition, depicting granular consumption data on a regional level aids utilities and other energy service companies in better understanding their customers. This could involve integration of data from disparate sources (e.g., smart meters, network sensors, weather, and utility records) to provide utilities with more situational awareness and control over their networks. Such control would extend beyond current HVAC remote management into electric-car charging and the use of other major appliances.

A further refinement of disaggregated data would be to map appliance-level consumption data into household activity data. For example, the use of an electric stove or microwave would be recognized as a specific activity (cooking), and the use of a vacuum cleaner would be recognized as cleaning. Such a translation offers a powerful ability to monitor and learn about behaviors within a household. This ability could be monetized in several ways. First, just as credit-card companies track consumer shopping patterns and Internet search companies track Internet browsing patterns, utilities would have the ability to track home activities. Such information would be helpful in conducting marketing. As an illustration, suppose that a household is observed as rarely utilizing cooking appliances but heavily utilizing entertainment appliances (e.g., televisions, gaming systems). Combined with billing and publicly available information, these activity data would characterize the inhabitant as a single male between 25 and 30 years old. Such data would be especially useful for marketing companies and advertisers and could provide an additional source of revenue for the utility.

Household activity data inferred from disaggregated electricity data could also have security applications. Because smart-grid data are often transmitted wirelessly, police agencies could tap into the encrypted feeds. This would provide them with an easy way to monitor activities within a suspect's home. Consider one's everyday activities—most of them are indicated by electricity use. In the morning, an alarm clock wakes us up before we trudge into the bathroom, turning on lights above the vanity mirror and unplugging the electric toothbrush from the charging station. When we leave and return from work, we use our electric garage-door opener. In the evening, lights and appliances are shut down prior to falling asleep. By tracking electricity usage, police agencies could know the habits and activities of any house's inhabitants without the cost and manpower of conventional surveillance methods. For concerns that could arise from such applications, see Chapter Five.

In this section, we have presented a variety of services and ways in which entrepreneurial companies could make use of newly available smart-grid data. Many of the business models require investment in sensor networks, software to refine the data, and staff to interpret the output. However, these benefits do not come without potential costs. In the next chapter, we discuss some of the empirical evidence related to smart-grid technology adoption, which helps to highlight how ex post experiences can differ from ex ante predictions. This is followed by a discussion of the potential costs associated with grid modernization, including the potential costs of entrepreneurial activities.

CHAPTER FOUR

The Smart Grid in Practice: Some Empirical Evidence

The preceding chapters documented the categories of expected benefits and opportunities of potential smart-grid development, based on particular assumptions about what the technologies might be able to deliver. In practice, the adoption of smart-grid technologies began in earnest only following the passage of the ARRA. The legislation authorized federal investments totaling $4.5 billion to utilities nationwide to further their smart-grid projects as part of the SGIG program, with $5.5 billion in matching funds from utilities and customers (Joskow, 2012).[1] Ninety-nine SGIG projects involving more than 200 utilities and other organizations were funded, with implementation focusing in large part on AMI (DOE, 2013). This investment has spawned smart-grid developments nationwide, initiated both by grant recipients and by other utilities seeking to remain competitive. However, as recognized in the latest SGIG progress report, this total funding is "a relatively small down payment on the hundreds of billions of dollars the electric power industry will need to fully modernize the electric grid over the next several decades" (DOE, 2013, p. iv).

The necessity of SGIG in spurring significant smart-grid development leads to a particular question: If the net benefits of grid modernization are so large, why did it not happen absent the passage of the ARRA? To motivate the analysis that follows, this chapter reviews some of the actual experiences of consumers and producers in adopting smart-grid technologies. In going from the theoretical (ex ante) to empirical (ex post), questions might include the following:

- Does adoption of the technology deliver the expected changes in the system?
- What are the realized benefits and costs of the actual changes in the system?

Of particular interest is the empirical evidence related to consumer response to dynamic pricing, in which electricity rates change with changes in the marginal cost of supplying that electricity. Consumers' willingness and ability to shift their demand in response to price signals are key elements in the benefit calculations of the smart grid. It is this demand shift that allows for the flattening of loads, thus decreasing long-run prices and deferring investment decisions. In addition to summarizing the research on consumer demand, we examine the evidence from the private sector regarding smart-grid development, focusing on experiences generally unrelated to the ARRA.[2]

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[1] The SGIG program was funded at $3.4 billion, with a match of $4.4 billion from the private sector.

[2] The reasoning here is that projects related to SGIG distort the incentives of transmitters and utilities by providing financial assistance specifically linked to smart-grid infrastructure improvements. This "stimulus" funding is temporary and will likely not be indicative of the environment in which agents will make investment decisions in the future.

Response of Consumers to Alternative Pricing Structures

Residential consumers commonly face a pricing schedule that does not vary with time but may increase once consumption reaches certain thresholds (Ito, 2012). Such an increasing block-rate pricing scheme is designed to encourage conservation, assuming that consumers optimize their electricity usage based on the price of every incremental unit of electricity used. When more electricity is used, the marginal cost to consumers increases, which discourages additional consumption.

However, recent research suggests that consumers may not respond to nonlinear electricity pricing precisely as theory predicts. Surveys suggest many residential customers face information constraints and do not fully understand the pricing schedule (Ito, 2012). In practice, it is difficult for the consumer to track the current status of hourly, daily, or monthly consumption and anticipate additional electricity demands before the end of the billing cycle.

Nevertheless, in order for benefits of dynamic pricing to materialize *in practice*, consumer behavior needs to change consistently enough for utilities to adjust their expectations of demand, allowing them to optimize their operations in supplying electricity and cut the cost of building excess capacity. Therefore, estimating the magnitude of the demand response to RTP structures is critical. In this section, we highlight two types of demand-response studies and the challenges of each in determining the value of benefits from smart-grid investments:

- pilot programs and pricing options
- large-scale, system-wide deployment studies.

Pilot Programs

Pilot-program studies have been the predominant vehicle for understanding customer demand response to prices. Although there is wide variation in the experimental design, all pilot studies compare a control with time-invariant prices and a dynamic pricing scheme with time-varying prices. Dynamic pricing includes TOU, critical peak pricing (CPP), peak-time rebate (PTR), and RTP. TOU varies prices in a predetermined way over the course of a day or week. CPP is even more dynamic and varies prices between critical and noncritical days, which change based on demand. PTR programs return cash to customers for each kilowatt-hour reduction relative to a baseline during peak hours. RTP is the most dynamic pricing scheme, with prices that respond immediately to changes in demand and supply.

From 2000 to 2010, California's energy crisis sparked an interest in time-varying rates.[3] In fact, there have been at least 109 dynamic-pricing studies to date (Joskow, 2012). Taken as a whole, these studies conclusively find that consumers do respond to higher prices by decreasing usage during peak periods. However, the magnitude of the response varied more than tenfold across studies due to the difference in the experimental designs, the availability of enabling technologies, and the price rates tested. Studies of TOU pricing with predetermined time periods and prices found an average 5-percent reduction in peak load, while more-dynamic pricing schemes, such as CPP with very high prices during critical periods, achieved more than a 50-percent reduction in peak load. The wide variation in demand response also reflects wide

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[3] Faruqui and Sergici (2010) profile 15 significant TOU, CPP, PTR, and RTP experiments conducted in California, Colorado, Florida, Idaho, Illinois, Missouri, New Jersey, Oregon, Washington (state), New South Wales (Australia), Ontario (Canada), and France. Since then, Baltimore Gas and Electric, the PowerCents DC program, and the Chicago Energy Smart Pricing Plan have performed additional pricing studies (Wolak, 2010; Allcott, 2011).

underlying variation in consumer attributes. A point of difference from simulation analysis results is a common pilot-study finding that higher peak prices reduce peak demand with no offsetting shift in consumption to off-peak times. Joskow (2012) notes that this result could change once plug-in vehicles and other technologies for which TOU is easily chosen become more widely adopted.

Differences in consumer behavior change the interpretation of the pilot programs' demand-response estimates because overall consumer response depends on individual response in conjunction with program participation. Many of the pilot programs include only volunteers, a fact that introduces selection bias.[4] The problem with selection bias is that people know the type of consumer they are, and those who anticipate that the benefit from treatment will be greater than the cost of treatment will adopt a dynamic pricing scheme over the time-invariant prices. Thus, we can foresee that the people who stand to gain the most from RTP will sign up and exhibit higher elasticity of demand. Critically, it would be incorrect to assume that the treatment effect from the pilot studies can simply be extrapolated to the entire population across heterogeneous consumers. For example, if the pilot study consists of 5 percent of the consumer pool and dynamic pricing is rolled out to 100 percent of the population, we cannot expect 20 times the estimated benefits. In fact, the anticipated benefits could be less because of the heterogeneity of the consumers.

A critique of the pilot experiments conducted to date is that few pilot programs analyze the distribution of responses or bill impacts across customers. There is evidence that most of the reduction in demand comes from a relatively concentrated number of consumers, but we have little understanding of who these customers are and how persistent their behavior is over time (*Future of the Electric Grid*, 2011). In addition, few studies present the temporal distribution of the demand response, which affects the decision to ultimate reduce generating capacity. For example, the benefit from a demand response of –5 percent every day is different from –10 percent for half the days and 0 percent for the other half. Finally, pilot experiments can capture only short-run response. The long-run response may be greater when consumers invest in technology to integrate with the smart grid, such as smart appliances. On the other hand, the long-run response could be moderated if older habits resurface after the novelty of the pilot program wears off.

Large-Scale Studies

Large-scale, system-wide deployment studies would be ideal in truly estimating demand response because they would capture a large population over a long time period and provide information about actual costs of implementation. Borenstein (2007b) uses data on RTP from large industrial and commercial customers in northern California to show that some customers with consumption patterns weighted unfavorably toward peak times actually may see higher bills with real-time rather than time-invariant rates. However, results from large industrial customers cannot be confidently translated to residential consumers. Only very recently have initial results been reported (DOE, 2012a, 2012b). Three projects have preliminary quantitative evaluation reports from Oklahoma Gas and Electric (OG&E), Marblehead Municipal Light Department (MMLD), and Sioux Valley Energy. Using CPP and web portals to transmit the information, peak demand reduction was between 25 and 37 percent. Customer acceptance

[4] Recognizing this problem, some of the demand studies associated with SGIG programs alleviate the sample-selection problem. However, the final results of these studies were unavailable at the time of this writing.

was generally positive, with many reduced electricity bills in the OG&E program (an average reduction of $150 over summer periods) and all customers saving money on the CPP scheme in the MMLD program. The Sioux Valley program compared customers who had opted into the CPP rate and those who were placed into the CPP rate and did not choose to opt out. It found that the opt-in customers provided greater peak demand reductions than those who chose not to opt out, which supports the idea that consumer heterogeneity is critical in determining results as the program rolls out to a larger portion of the consumer base.

Negative Consumer Experiences and Concerns

Although pilot studies suggest some degree of demand response associated with AMI and time-varying rates, this does not necessarily imply that all consumers benefit from the new pricing structures. For example, some Sioux Valley Energy customers complained after CPP events were called on consecutive days.

There has been evidence in news outlets of customer backlash against Pacific Gas and Electric Company's (PG&E's) SmartMeter program in Bakersfield, California (Smith, 2010). After installation of the new meters as part of a broad meter-upgrade program in northern California, some residents were shocked to find their monthly bill doubling compared with the previous year. Opponents of SmartMeters have filed a class-action lawsuit questioning the devices' accuracy (Chediak, 2009). To further compound the confusion, these customers were not enrolled in any type of experimental rate plan but blamed the meters for what they believed to be faulty measurements.

Upon investigation, PG&E concluded that the meters were not malfunctioning and that, in fact, the cause for the backlash was simply unfortunate timing. New-meter installation had coincided with an increase in conventional rates, which had also coincided with unseasonably hot temperatures (Smith, 2010). This episode revealed a lack of customer awareness of basic rate structures and price changes and a need for better customer education about smart-meter technology.

In addition, some communities and regulators are concerned that peak pricing may negatively affect certain vulnerable members of society who are not able to adapt their electricity usage. For example, an elderly person with medical equipment would still have to run the equipment regardless of peak times and would be disproportionately harmed by RTP (Smith, 2010).

Selected Issues and Experiences with the Smart Grid: Brief Case Studies

In this section, we discuss two experiences in smart-grid implementation that highlight some of the tensions that underlie large-scale smart-grid projects. We make no claims as to the representativeness of these experiences or that the issues are inevitable.

SmartGridCity: Boulder, Colorado

The city of Boulder, Colorado, was known as the nation's first "smart-grid city." Xcel Energy, operating as Public Service Company of Colorado, was the city's electricity supplier and embarked on a large-scale project known as SmartGridCity in 2008, including installing two-way fiber-optic communication technology and smart meters for one-quarter of the population (Skinner, 2013; Jaffe, 2012). The project was initiated prior to passage of the ARRA. The company did not pursue regulatory approval to cover costs in advance, opting instead to wait until the benefits were proven (Smith, 2008).

As of October 2012, the overall cost of the project stood at $45 million, double to triple the initial estimate. After previously approving $27.9 million in capital cost recovery in a 2011 ruling, the Colorado Public Utilities Commission denied Xcel's request to recapture an additional $16.6 million of those costs in 2013 (Skinner, 2013; Jaffe, 2012; Gomez, 2013). The reasoning was that Xcel failed to show any substantial "consumer-facing" benefits from the investments commensurate with the cost overruns of the project (Gomez, 2013). It also failed to provide sufficient information to the commission, including a cost–benefit analysis regarding SmartGridCity (Gomez, 2013).

The Denver Post investigated the development of the SmartGridCity project and found that Xcel underestimated construction costs, lost support of partner companies, did not meet its goals regarding in-home energy devices, and opted for a broadband-over–power line system in conjunction with a fiber-optic network whose installation costs were significantly higher than anticipated (Jaffe, 2012).[5] The final report on a pilot pricing project of approximately 4,000 households (including CPP, PTR, and TOU rates), however, showed that peak demand was, in fact, reduced under each pricing structure, with CPP exhibiting the highest-percentage reductions of near 30 percent (EnerNOC, 2013). Information about electricity consumption was available to the consumer only on a 15-minute delay and in a form that was not particularly desirable, which apparently led to some disappointment with the program (Skinner, 2013). A benefit–cost analysis of the pricing program, with benefits measures by avoided energy and capacity costs as compared with the cost of program design and implementation, suggested a benefit–cost ratio of 0.07, indicating that administration of the program cost significantly more than the benefits. Analyses also predicted that average electric bills would increase in the long run relative to the incumbent pricing system. In 2013, Boulder voted to municipalize its electric system.

Xcel views the project as "very successful" from a research perspective, according to Michael Lamb, company operations chief of staff (Helms, 2013). He also stated, "[w]e were penalized for trying to do something risky": "I hope that the fact that some people think of SmartGridCity as a failure doesn't have an impact on the utility industry, but it does provide a bit of a disincentive to be innovative, to take a risk" (Helms, 2013).

Massachusetts Electric Grid Modernization Process

On October 2, 2012, the Massachusetts Department of Public Utilities (DPU) issued a notice of investigation to explore opportunities for grid modernization (*Massachusetts Electric Grid Modernization Stakeholder Working Group Process*, 2013). Among the objectives were to enhance reliability, reduce electricity costs, empower consumers to better manage their electricity, increase system efficiency, promote clean energy resources, and provide new offerings. Distribution companies operating under the auspices of DPU include NSTAR Electric and Gas, Western Massachusetts Electric Company, Massachusetts Electric Company and Nan-

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[5] Broadband-over–power line communication is not widely used in the United States.

tucket Electric Company both doing business as National Grid, and Fitchburg Gas and Electric Light Company doing business as Unitil Corporation.

The working group examined the current state of technology on the grid and reviewed the evidence on alternative pricing programs both nationally and for the distribution companies' pilot projects on metering.[6] In general, the evidence pointed to some degree of customer responsiveness to time-varying pricing but mixed results in terms of average savings for consumers. The final report to DPU also included a report on stakeholder preferences regarding the regulatory framework, with the distributors generally favoring plans that provided for preapproval of cost recovery. It also included several proposals relating the scope of cost-effectiveness analysis of modernization plans.

On December 23, 2013, DPU presented a "straw proposal" based largely on the final report (DPU, 2013). In that proposal, DPU proposed to require a ten-year grid-modernization plan from each utility, including a comprehensive advanced metering plan (CAMP) that provides for "advanced metering functionality no later than three years from our approval of its [metering plan], assuming that the benefits of doing so justify the costs" (DPU, 2013, p. 3). Recognizing the ambition of the proposal, DPU requested that each CAMP include a request for a mechanism to allow for faster cost recovery for each utility. The reasoning behind this decision was that advanced metering functionality is a basic platform for grid modernization and thus should be a priority for distribution companies.

On January 17, 2014, NSTAR and Western Massachusetts Electric Company filed a comment with DPU that argued against the AMI mandate. The filing suggested that the technology mandate hindered, rather than encouraged, grid modernization by restricting the flexibility of modernization plans and denying targeted cost recovery for technologies that were not related to AMI. Further, in an argument that was widely noted by anti–smart meter bloggers, the filing noted that there is little evidence that AMI is the most cost-effective smart-grid investment for modernization and that the incremental benefits may not justify the costs.[7] Finally, the filing argued that AMI does nothing to address the integration of distributed-generation technologies that are expected to be a major feature of the future electric system.

The straw proposal and grid-modernization process in Massachusetts was still ongoing October 2014. Public documents related to the case are available through Commonwealth of Massachusetts Executive Office of Energy and Environmental Affairs (undated).

Summary of Empirical Evidence

Although pilot and large-scale studies detect varying degrees of consumer demand response to electricity prices, the experiences discussed above suggest that the benefits of RTP might be overstated. Because prices can change frequently, considerable cognitive or other informational burdens on consumers (i.e., transaction costs) might not translate into changed behavior. Even if the overall net benefits of the smart grid to society are positive, consumers who are less responsive to prices may see increased electric bills as a result of new pricing policies. Fur-

[6] Legacy rates for residential and small consumer customers in Massachusetts are flat, and the distribution companies purchase wholesale power using contracts designed to reduce price volatility.

[7] It should be noted that the two utilities had previously installed drive-by metering, which had already lowered metering costs to the utilities.

thermore, anecdotal evidence suggests that utilities may not prioritize the same technologies as regulators do, and some smart-grid investments have been characterized by cost overruns and a lack of recoverability by utilities. In the next chapter, we turn to a more theoretical discussion of the incentive structures inherent in grid modernization. These incentives can often provide barriers to the development of the smart grid.

CHAPTER FIVE

Explaining the Evidence: Barriers to Smart-Grid Technology Adoption

As documented in previous chapters, use of smart-grid technologies have the potential to increase efficiency and reliability of the electricity market through the enabling of peak-load shifting and making it easier for utilities to respond to outages and threats. The information layer of the smart grid would likely enhance the economic efficiency of the electric system, lowering overall operational costs and providing the possibility of additional entrepreneurial activities. Nevertheless, adoption of smart-grid technologies has been relatively slow when utilities (and, ultimately, consumers) bear the costs, and the full potential of the IT layer has not been realized.[1] Utilities are also facing reduced demand through efficiency measures, peak-load demand reductions, and the introduction of distributed supply (such as household solar, PV, and wind) in which consumers produce a portion of their own electricity.[2] Declining demand means declining revenues, which provides less operating capital to upgrade technology without raising rates through lagging rate cases. Dynamically, as rates increase, alternative distributed technologies (e.g., solar panels) become more attractive, and, as they are adopted, the demand for the utilities' electricity declines even further. A shrinking number of customers means increases in average fixed costs for each, resulting in higher average electric bills for those still on the system. This has led to talk of smart-grid solutions leading to a "death spiral" of traditional utilities as the attractiveness of technology-enabled distributed generation grows (see, e.g., Resnick Institute, 2012; Berst, 2014).

In this chapter, we discuss how the economic incentives faced by utilities and electricity consumers under the current regulatory structure pose barriers to smart-grid technology adoption and use.

Regulatory Incentives on the Supply Side

In a (partially) regulated system, such as the electric industry, innovation can be defined as the process of investing in new capital technologies to either (1) decrease operating costs or (2) increase demand for current or new services (Guthrie, 2006). Utilities face decisions on both the quantity and timing of smart-grid technological enhancements to distribution systems, which are subject to risk on the overall costs of investment and the benefits that such technologies will deliver. Customers face similar decisions when making purchases of "smart"

[1] As opposed to technology adoption that is either paid for (or at least subsidized) by such programs as SGIG.

[2] Total quantities of retail sales (in megawatt-hours) declined 1.5 percent for all sectors between 2011 and 2012 (EIA, 2014b). Peak sales for the past decade occurred in 2007.

appliances that can be used to lower the transaction costs of shifting energy demand and responding to dynamic price signals. In turn, uncertainty about these patterns feeds back into the utilities' uncertainty. The sharing of risk between utilities and customers is determined primarily through the regulatory structure, and this structure ultimately affects the incentives for investment in the new technology.

Distributors of electricity have mixed incentives for adopting smart-grid technologies.[3] On the positive side, the enabling ability of technology to shift peak demands (through conscious or unconscious consumer response) can (1) lower current power-acquisition costs by removing the most-expensive generation sources from the mix when demand is high and (2) lower future infrastructure costs by delaying otherwise-necessary infrastructure. In addition, the ability to quickly and easily diagnose outages and fix problems has the effect of both lowering operating costs (through less time and manpower used per outage) and increasing revenues (through increased sale of power).

Firms invest when the net present value of investment is positive, assuming that firms attempt to maximize the expected net present value of cash flows, or market value (Guthrie, 2006). For utilities, this calculation is influenced by the regulatory structure through a variety of channels, including allowable prices or revenues, the allowable rate of return, the valuation of the rate base on which returns to capital are allowable, and the incentives that the regulatory structure creates toward investment decisions (including the risk of disallowing certain capital investments in the rate base). Regulatory mechanisms need to be designed such that utilities expect gains in their own net benefits when making investments, as well as covering their costs (Joskow, 2007).

Assuming that any investment is expected to lower costs and provide benefits in the long run (as argued by smart-grid advocates), the policy levers available to regulators under the current regulatory paradigm are as follows:

1. the share of operating-cost savings passed on to consumers (through retail electricity rates)
2. the share of investment expenditures borne by consumers (through calculation of the rate base)
3. the timing of rate case hearings in which items 1 and 2 are implemented
4. the allowable rate of return on capital (Guthrie, 2006).

In traditional cost-plus regulation, the pass-through of operating-cost savings and investment expenditures is complete (assuming no disallowances by the regulator), while timings of rate cases (and perhaps allowable rates of return on capital) differ across locations and the market determines allowable rates of return. Policymakers can also mandate the adoption of particular technologies through command-and-control regulations, though this lies outside the traditional cost-plus regulatory structure.

In general, all else equal, the larger the share of operating-cost savings passed on to customers in rate cases, the greater the disincentive for smart-grid investment. The reason is that, as the share increases, the net present value of increased profitability from the investments declines as returns are passed from the utility to the consumer in post-hearing time peri-

[3] In this section, we focus on shareholder-owned distributors (regulated utilities) because we are interested in the incentives related to benefits and cost to the firm. Municipally owned utilities may face a different set of incentives.

ods. At the margin, projects that would have been pursued absent the pass-through would no longer be candidates for investment activity. The expected net present value of an investment is clearly greater when the utility is guaranteed that sufficient revenue will be earned to cover the investment.

In practice, at the time of investment, operating-cost savings (benefits) and realized costs are uncertain. In addition, from the utility's and consumers' perspective, the share of each passed to consumers may be uncertain in the absence of credible commitment from regulators. An increase in risk to the utility will generally lead to reduced incentives to adopt smart-grid technologies, given the associated decrease in expected net benefits from such investments.

For example, extrapolating from issues of regulatory capture, we presume that utility regulators have an interest in keeping electricity rates low to please their consumer constituents, an interest that provides an incentive to keep investment costs as low as possible. When engaging in a rate case, a utility thus faces some uncertainty regarding regulator behavior with respect to the allowance of capital costs, especially if there are multiple options available to upgrade a system. If smart-grid technologies are more expensive than a traditional (not-smart) alternative but offer some additional functionality for the greater price, then a cost-conscious regulator may deny the cost recovery of the new technology, especially if it is not easy to document direct benefits to consumers.[4] The costs of such an investment would then be borne by utility shareholders. In the absence of a regulator willing to guarantee cost recovery, the tendency to adopt the least-cost technology (as opposed to technologies that maximize net benefits) provides a disincentive to invest in smart-grid technologies.[5]

The timing of rate cases can also affect the incentives for smart-grid investments. Given the nature of traditional rate-of-return regulation, a utility can benefit from an investment in either of two ways: (1) investing in technologies and generating cost savings in the short run (before prices change) or (2) incorporating the new investment into the new prices following a rate case. In the regulatory case in which there is full pass-through of savings and expenditures, the net benefits of the latter are zero. As a result, for technologies that can generate efficiencies in the relative short run, the longer the period of time between rate cases, the greater the incentive to adopt cost-saving smart-grid technologies. For technologies that do not create cost savings for the system (but perhaps complement external benefits, such as a reduction in fossil-fuel usage), the utility faces a short-run cost until the next rate case.

Finally, there is a positive relationship between the investment incentive and the allowable rate of return on capital because the benefits of investment are directly augmented when the regulator allows the capital to be part of the rate base. A more detailed analysis of the incentives associated with infrastructure investment under regulated monopoly and risk can be found in Guthrie (2006).

The regulatory structure thus allocates the risk of investment between consumers and the utility, with approval of smart-grid investments tending to increase electricity rates to consumers, all else being equal, and disapproval tending to create incentives against further techno-

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4 For example, installing a set of networked sensors that allows for distribution-network monitoring may not be strictly necessary to deliver electricity to consumers but may help the utility identify outages more quickly and ultimately reduce service-call costs. These savings would, in theory, be passed on to consumers. However, a regulator may not believe that the savings would materialize or that the short-run costs exceed the long-run benefits.

5 This is true of all large capital investments in the regulated industry. For example, Fowlie (2010) makes a similar argument with respect to pollution-control equipment in the electricity market.

logical innovation. In addition, if regulators credibly commit to a pass-through of investment expenditures to consumers, all the risk associated with future benefits, including any potential long-run rate decreases from load-shifting and deferred capital investment, is borne by the consumer.[6] Furthermore, the standard pricing practice of allowing only cost recovery plus a profit margin means that the utility itself cannot earn additional long-run profits. This pricing scheme thus protects electricity consumers from monopoly pricing but also creates disincentives for smart-grid investment on both the producer and consumer sides of the market.

Overall, the optimal level (and timing) of smart-grid technological investment is the level that maximizes the sum of consumer and producer surplus from the investment activity plus all external benefits and costs, though this level might be difficult to calculate in practice. Given the restrictions on output, a nonregulated monopoly would both underinvest and wait longer to invest in modernization because the benefits of the investment (but not the costs) must be shared with consumers (Guthrie, 2006). Thus, policy should move a utility toward both greater levels of investment and earlier investment than would be found in the unregulated state.

However, the unregulated monopoly is not the starting point for most incumbent utilities facing smart-grid investments. Instead, utilities operate under different regulatory structures, which vary cost pass-through to consumers, rate-case timing, and effective allowable rates of return. In addition, differences in overall demand structure, the portfolio of capital stocks, and the incumbent level of technological development, among other considerations, can affect the benefits and costs of technological adoption. In short, the question of whether smart-grid investment is proceeding at an optimal level (and, if not, the direction in which it should be pushed) is an empirical question that depends in part on the regulatory structure of the public utility commission in each state.

Nevertheless, there is some evidence that there are nontechnological barriers to smart-grid adoption. Ex ante benefit–cost analyses have found ratios greater than 1, suggesting positive net benefits for society from adoption. If the estimates of benefits and costs are correct, then the lack of adoption absent large government incentives suggests incentive problems created by the allocation of benefits and costs across utilities and consumers.

In addition to the incentive problems created by regulatory structure discussed above, the adoption of smart-grid technologies may be hindered by problems stemming from positive externalities. If all of the net benefits of a firm's innovations are not fully appropriable, the initial incentives to invest in innovation are reduced (Spence, 1984). As a consequence, if knowledge spillovers are strong, as they are likely to be with smart-grid technologies, investment and adoption of cost-reducing innovations may be socially suboptimal. Although this problem is not created by regulatory failure, it results in similar incentives for decreased investment in process innovations that lead to lower production costs in the future (Berg and Tschirhart, 1988; Malkin and Centolella, undated).

We now turn to several specific barriers associated with smart-grid technologies and dynamic pricing.

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[6] In the recent Northeast Utilities/DPU case, the utility stated in a letter to the department that

> the price tag for an AMI roll-out . . . would likely approach, and possibility exceed, $1 billion over the course of the CAMP implementation—all of which is to be borne by customers *who may or may not be interested in interacting with the distribution system at the level implicated by AMI technology.* (emphasis in original, Winter, 2013)

Lack of Technology Standards

The Energy Independence and Security Act of 2007 (EISA) (Pub. L. 110-140) authorized FERC to adopt a set of interoperability standards that the National Institute of Standards and Technology (NIST) would craft based on the recommendations of private-sector counterparts.[7] NIST convened the electric-power, IT, and manufacturing sectors to contribute to the standard-setting process. NIST produced five families of interoperability standards in 2010. The standards span areas that include protocols for data exchange between devices and networks and between control centers, common data formats to facilitate substation automation and communication, and addressing the cybersecurity implications of all proposed standards.[8]

NIST's first set of standards was not adopted by FERC, nor would it have been enforceable were it adopted.[9] EISA did not explicitly provide FERC with the necessary authority to enforce any standards that NIST would produce. This means that the standards will remain voluntary unless a pertinent regulatory hook is instituted.

The lack of enforceable standards (as opposed to the lack of technological feasibility) is a barrier to smart-grid adoption. For instance, in a recent report on the topic of electric-grid cybersecurity, one important aspect related to the smart grid, GAO listed the lack of coordinated effort, jurisdictional issues, a misplaced focus on compliance instead of comprehensive security, the lack of sufficient inbuilt security features, the lack of a proper forum for disseminating knowledge, and the lack of metrics for performance evaluation as a few key challenges to ensuring the cybersecurity of the electric-power grid (Wilshusen and Trimble, 2012). Similarly, standards regarding the interoperability and implementation of AMI are not homogenous and tend to change rapidly.[10]

In addition to limiting the intended functionality of the smart grid, a lack of consolidated, enforceable standards can be a deterrent to investment across all players as they decide whether and how much to invest in new technologies and ideas. A tenuous and changing framework of standards can reduce willingness to take entrepreneurial risks for fear of stranded assets if and when standards *are* finalized.[11] Needing to retrofit assets because of changed standards and requirements can result in prohibitively high costs that are typically not factored into analysis of the benefits and costs of smart-grid development.

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7 EISA directs federal policy for the development of the smart grid and thereby sent a clear signal of the commitment of the U.S. federal government to furthering smart-grid development and deployment. It established the Federal Smart Grid Task Force and the Smart Grid Advisory Committee, further establishing governmental intent in dedicating resources to the smart-grid effort. This aspect of the legislation can be seen as directly promoting advancements in the smart-grid space.

8 A summary of NIST's standards can be found at NIST (2010).

9 This decision was made in the summer of 2011 because of lack of sufficient consensus among state and federal commissioners.

10 See Institute of Electrical and Electronics Engineers (IEEE) Smart Grid (undated) for a sampling of several IEEE standards pertaining to different aspects of the smart grid that are continually evolving.

11 Anecdotally, this appears to be confirmed through experience. For example, both Craig Miller, chief scientist of the National Rural Electric Cooperative Association, and Steven Widergren, principal engineer with the Department of Energy's Pacific Northwest National Laboratory, cited a lack of standards as a large barrier to smart-grid adoption at an IEEE conference (Ravindranath, 2014).

Perceived Costs to Consumers

As described in the previous chapter, past studies that have examined the potential benefits and costs of the smart grid have noted the potential of cost savings to the utility being passed on to consumers because of efficiency gains. This is a long-run phenomenon for consumers under the incumbent rate-of-return regulation (even with RTP) because savings are passed through during rate cases. Utilities can gain only in the short run. The costs, and much (if not all) of the benefit risk, of that investment, however, are borne by consumers following a rate case. Even if the technology saves consumers money relative to an alternative investment path in the long run, the fact that electric bills may increase can increase opposition to the smart grid on the consumer side, especially if utilities create an impression of immediate cost savings that are not realized in the short term.[12]

Changes in pricing structures, the question of who pays for investment, increased costs related to demand management, and concerns about privacy and health may create a perception among consumers that the smart grid's net benefits to them are lower than claimed. We document these barriers in the following subsections.

Real-Time and Time-of-Use Pricing and Transaction Costs

The introduction of time-varying prices has the potential to increase the overall efficiency of the electricity market. From the consumer standpoint, however, overall system efficiency is not necessarily the goal. Consumers would like to maximize their own total net benefits, which is their total willingness to pay for a given quantity of electricity less the cost that they actually have to pay (consumer surplus), including the costs of making any adjustments to their consumption (transaction costs). They also are relatively comfortable with the incumbent pricing regime, likely have a sense of how their electricity bill varies with the seasons, and have, in essence, optimized for the old pricing system.

The introduction of time-varying prices has the potential to affect different customers in different ways. For example, a consumer who normally tends to make liberal use of electricity during peak periods would be faced with a choice: Either pay the high peak prices and have an increased electric bill with RTP or avoid high peak prices but at the cost of enduring the inconvenience or discomfort of curtailing electricity consumption during those times (Boisvert and Neenan, 2003). In choosing the latter, this customer does not benefit from the reduction in consumption but rather has his or her net benefit reduced not only because of the decrease in overall consumer surplus but also because of the costs of monitoring electricity consumption.

On the other hand, a consumer who is flexible and can easily (i.e., with little cost) shift demand from peak to nonpeak hours for the same services could take advantage of off-peak rates, thus increasing his or her net benefit from the pricing change.

Smart appliances, which users can program to automatically adjust energy use, can help reduce the transaction costs associated with adjustment, though they may be more expensive to purchase than the alternative and users may incur additional costs in setup and use. Unfor-

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[12] For example, during GridWeek 2011, Elizabeth B. Fleming, commissioner at the South Carolina Public Service Commission, stated,

> I agree about the transmission and distribution lines and how that can be greatly enhanced with a SmartGrid. As far as a consumer goes, I think the important thing there above all else—I do agree that the [public relations] that was put out there really set up a perception that can't be realized, because the cost of electricity will go up. But it can keep their bill lower than it would be without [the investment in smart-grid technologies]. ("Smart Grid," 2011)

tunately, low-income households that have difficulty affording upgrades to smart appliances will lose out on these savings. Variable pricing will provide incentives for them to adopt the new products (EPRI, 2011), but the lumpy nature and prices of these long-lived capital goods suggest that responses may be relatively slow, thus decreasing the elasticity of demand in the shorter run.

The movement toward RTP could also increase electric-bill volatility for most customers because of higher prices in peak hours of the peak months (Borenstein, 2007a). This is particularly troublesome for lower-income households in which energy costs contribute toward a sizable share of monthly expenses. If these effects are substantial, customers are likely to object to the adoption of RTP in the absence of additional programs to mitigate the negative effects (Borenstein, 2007b).

Because consumers tend to be quite different in terms of their flexibility to make change in electricity demand either directly or indirectly through smart appliances, it has been noted that the potential for "large redistributions across customers is possibly the largest impediment to further adoption of dynamic pricing" (Joskow and Wolfram, 2012, p. 384). In other words, the introduction of dynamic pricing has the potential to create both winners and losers among the consumer population. The less responsive the population is to changes in electricity prices, the larger the barriers to smart-grid technology adoption.

In a similar vein, the ability of smart-grid technologies to support (through more-precise information) differential spatial pricing (termed locational pricing) on the basis of the entire network's status can create winners and losers on the supply side. Although true marginal pricing can lead to overall system efficiencies in the long run (through entry, exit, and relocations) as generators compare their opportunity costs and the willingness to pay for their services, individual suppliers likely to face lower-than-incumbent prices would probably be opposed to the adoption of capital equipment that can hasten this process.

Privacy and Health Risks

Perhaps the most important barrier to innovation derived from newly available smart-grid data is an unresolved understanding on how to treat electricity-data privacy and ensure data security. Amassing large collections of information about all consumers and then applying computing power to mine and analyze this information has become a recognized part of modern life. Data science can be used by researchers for good intentions, such as understanding climate change, identifying genetic markers linked to cancer, or combating hospital infections (Henn, 2014). However, recent disclosures of National Security Agency global surveillance programs and of major breaks of customer credit-card records at major retailers highlight the perils of big data.

To be effective in delivering the potential benefits of the smart grid, smart meters need to collect and transmit household-level data in real or near-real time. However, with this potentially useful information comes risks that (1) activities within the home may be predicted from the data and (2) unauthorized private or public users of the data may gain access through either legal (market) or illegal means (NIST, 2010; Murrill, Liu, and Thompson, 2012). If appliance-level data can provide a company with unprecedented access to formerly private household behaviors, such access opens the door to exploitation by marketers, surveillance networks, and anyone else with access to the data stream. This allows for proximate surveillance of inhabitants in a household. For police and intelligence organizations, the idea of a stakeout might change to simply tapping into electricity data to obtain insight on people's schedules. In theory, smart meters transmit data through wireless, encrypted protocols, but the security of these protocols has not been tested extensively. Furthermore, not only do utility companies lack the skill to work with the data; they have also not developed the skills to keep the data secure.

In addition, several consumer and medical groups have raised concerns about the health risks associated with smart meters, given their emissions of radio-frequency waves. There is mixed evidence of questionable quality, and the American Cancer Society (ACS) rates the risk of cancer and other health effects from smart meters as extremely low (ACS, 2014). However, it suggests that, in some cases, more research is needed.

Regardless of this and similar conclusions from health research, if consumers perceive a health risk or privacy risk (or both) and opt out of demand-management programs as a result, the overall benefits of RTP will be reduced, resulting in higher utility bills and less consumer surplus for households.[13]

Big-Data Technological and Personnel Barriers

One technical barrier for entrepreneurship activities related to smart-grid technology adoption lies in the hardware capabilities of currently installed smart meters. Many smart meters are not equipped to record and transmit aggregate data at the level of frequency required to provide quality disaggregated data. Firmware and hardware upgrades could be required, and compatibility standards may be necessary to ensure interoperability with disaggregation software. This issue of potentially stranded investments in information infrastructure, especially in the absence of technology standards, reduces the incentive to invest in smart-grid technologies.

Second, an accurate, deployable, cost-effective software solution to the disaggregation problem has yet to be found. Further research and development are necessary toward the classification of appliances. Current disaggregation solutions have used data sets in which a specific household's appliances have already been documented. In order to effectively disaggregate data from a house without an appliance inventory, machine-learning techniques should be applied to probabilistic classification of devices. Such a classification would rely on the context and timing of device usage to provide clues to the type of device being observed. In addition, work needs to be done toward developing better calibration methods to validate the accuracy of disaggregation algorithms.

Finally, the management and storage of disaggregated data face issues common to big data. An often-cited challenge that differentiates big data from standard data is dimensionality. Standard databases have been around since the latter half of the 20th century, and the tools to organize standard data often consist of spreadsheets. In contrast, *big data* implies information with many more entries and character fields. The ability to visualize and understand such vast data sets is still immature. Utilities will need to carefully decide how to spend resources storing and curating such large data sets.

Because they lack in-house expertise, the entities that will come to possess raw smart-meter data may be ill equipped to properly make use of the data. Utilities need to find personnel with the statistical expertise to make sense of the flood of new data. Finding talent qualified to work with sophisticated data-analysis tools is one issue, but justifying the cost of building in-house expertise is also an issue. It might not make sense for each utility to have

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[13] The Northeast Utilities/DPU case cited both health and privacy concerns as potential demand-side issues with AMI. Household bills would likely increase in conjunction with the introduction of a peak-load pricing mechanism and assumed nonresponsiveness of demand.

its own data-analysis group, but rather to develop partnerships with companies that have such capabilities. These capabilities include data integration, data visualization, probabilistic modeling, and machine learning. Current tools intended to work with extremely large data sets are insufficiently mature and are not being taught in schools.

Costs of Interstate Transmission Infrastructure

Finally, an additional barrier to smart-grid implementation comes from issue of responsibility for upgrading interstate transmission lines with new technologies. By design, ISOs do not have a profit motive, but their infrastructure crosses traditional public utility commission lines because they connect generators and utilities across large distances. Both suppliers of electricity and consumers thus could benefit from improved transmission infrastructure as a public good, but the issue of the share of expenditures for which each is responsible has not been resolved.

Costs of Distributed Generation

At the local level, consumers will ultimately bear the costs of system upgrades under current regulatory policy, which creates political economy disincentives to smart-grid development through likely higher electric bills in the short run. An additional dynamic related to distributed generation can exacerbate this issue: that the incumbent pricing structure is ill equipped to adequately handle prosumers (those customers who install distributed-generation capacity to either reduce consumption from the grid or even sell back produced electricity to utilities). Because current rate-setting results in prices designed to cover generation and investment costs on average, any avoidance of these fees through own-generation essentially passes a greater share of the fixed costs of investment to a smaller share of the consumer base, resulting in increased rates for nonproducing consumers.[14]

Total Potential Costs of the Smart Grid

EPRI (2011) conducted a study of customer costs required to enable a fully functioning smart grid above and beyond the costs to meet electric load growth. Figure 5.1 provides a summary of the costs. Of the $338 billion to $476 billion total investment, costs related to the distribution system account for 69 to 71 percent of the total, while transmission and substation costs account for 19 to 24 percent of the total. Allocating these costs according to overall kilowatt-hour demand, EPRI estimates that residential customers could see bills increase by 8.4 to 11.8 percent, commercial customers could see increased bills of 9.1 to 12.8 percent, and industrial users could see increased bills of 0.01 to 1.6 percent over the period in which the costs are recovered (EPRI, 2011).[15]

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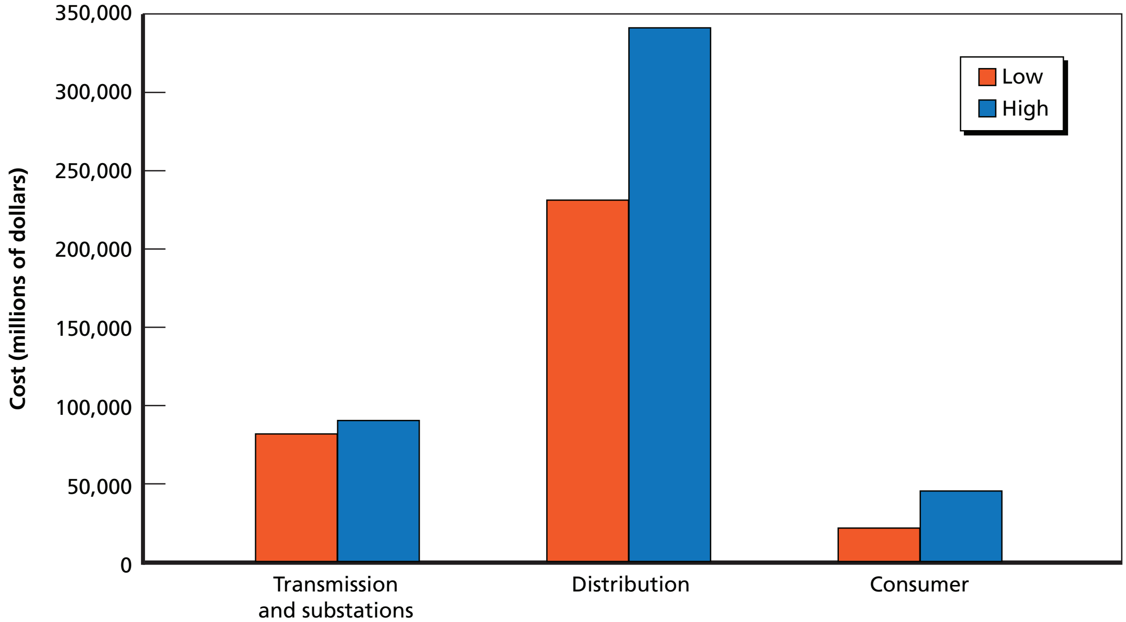
14 *Own generation* is self-generation by consumers not using the grid.

15 This assumes a ten-year amortization with costs split 38 percent residential, 37 percent commercial, and 25 percent industrial. EPRI estimates benefits on the order of $1.3 trillion to 2 trillion.

Figure 5.1
Estimated Investment Costs of a Fully Functioning Smart Grid



SOURCE: EPRI, 2011, Figure 1-3.
RAND *RR717-5.1*

Having documented some of the barriers to smart-grid implementation in the absence of sustained public funding for technology adoption, we now turn to policies that can be used to incent (or discourage) grid modernization within the current regulatory framework.

CHAPTER SIX

Using Public Policy to Encourage Smart-Grid Technology Adoption

This chapter discusses a few policy levers that can be used to incentivize smart-grid technology adoption. We do not necessarily advocate that these policies be used in all circumstances. Rather, we note simply that these policy levels *could* be used to incentivize investment and help overcome the barriers discussed in Chapter Five. After all, innovation cannot happen without adoption (Garber et al., 2011). We also discuss several broad principles, which could be adopted to avoid mistakes in smart-grid development.

Policy Levers to Incentivize Smart-Grid Investment

Traditional cost-plus rate structures pass on operational savings to consumers and thus do not offer the possibility of increasing long-run profits to the utility. This disincentive impedes adoption.

To overcome this barrier, regulators should consider structures that incent the optimal investment level by manipulating the long-run allocation of investment expenditures and cost savings. This could take a variety of forms, each of which entails certain trade-offs. Some examples are provided in the following subsections, focusing on currently available policy levers for regulators.

Mandate Smart-Grid Investments

One strategy to encourage smart-grid investment is to pass laws that require such investment. The Massachusetts case referenced in Chapter Four, in which AMI is a part of the long-term investment plan, is one such example.

Although such command-and-control strategies are likely effective because they carry the weight of law, they may not always be economically efficient. Lawmakers may not have full information about the benefits and costs of a particular requirement, and such policies may limit utilities' flexibility to serve their customers, depending on the type of mandate.

Commit to Inclusion of Smart-Grid Investments in Rate Base

The potential for disallowing certain investments in a regulated utility's rate base increases the risk associated with that investment, thus making it less attractive. Any mechanism in which the regulator can signal to the private utility that the probability of disallowing smart-grid investment expenditures in the rate base has declined will incent such investment.

This could be done, for example, by allowing utilities to capture a share of smart-grid expenditures prior to the completion, often known as capital-expenditure trackers; allowing construction on works in progress; and operating the technology using the concept of a "future test year" based on budget projections rather than historical data (Lowry, Makos, and Johnson, 2011). Such tools have historical precedent. The downside of such a policy (assuming traditional regulatory structures) is that it shifts the benefit risk toward customers as the share of expenditure commitment increases.

Increase the Allowable Rate of Return on Capital

Especially early on in a modernization program, a utility and its shareholders might view smart-grid technologies as riskier than standard investments. Because investments in technologies occur only if decisionmakers perceive them as profitable, it may be necessary to increase the allowable rate of return on capital to incentivize smart-grid investments. Risks of doing so are the increasing probability that excessive rents could be generated for the utility, with higher-than-necessary capital costs being passed on to consumers. In order to avoid perverse incentives on other types of capital, regulators could split the rate base into categories of capital with differential allowable rates of return by capital type.

Change the Distribution of Investment Expenditure and Cost Savings Pass-Through to Consumers

Guthrie (2006) shows that, for investments whose only benefit is to lower operating costs for the utility (i.e., no additional costs or benefits associated with the investment), a utility has incentives that are aligned with society's if the share of capital investment added to the rate base (and thus passed through to consumers) is equal to the share of system-wide cost savings passed through. In the presence of positive externalities from the investment, however, this will lead to underinvestment in smart-grid technologies. It would thus be socially optimal to allow the utility to keep a greater share of the savings or, alternatively, to pass on a greater share of the expenditures, in order to properly incentivize investment. The reverse would be true if, say, consumer surplus decreased because of RTP enabled by the technology or there were negative (e.g., security or privacy) externalities associated with the technology. In this case, a larger relative share of system-wide cost savings should be passed through to consumers (or, equivalently, a smaller share of the expenditures should be passed through).

Decouple Revenue from Sales

In some cases, utilities may be concerned that technologies that enable RTP or distributed generation will result in decreased overall sales because of demand response. Anticipation of lower future sales due to smart-grid investments makes the decision less profitable and thus less attractive. A decoupling of revenue from sales via incentive regulation can help overcome this disincentive, especially when revenue commitments can be made for multiple years. However, doing so can lead to quality degradation as the decoupling eliminates the utility's costs of providing lower-quality services.

Typically, this is accomplished by the regulator through the design of a revenue-decoupling mechanism (i.e., defining the customer base to which the limits apply, defining any exceptions due to weather) and an adjustment mechanism that allows for less-frequent rate cases (Lowry, Makos, and Johnson, 2011). Similarly, lost-revenue adjustment mechanisms, in which utilities are compensated for lost sales due to demand management, can be used to compensate a distributor for lost variable revenues that arise because of shifts in overall demand that end up reducing the overall costs of supply (Lowry, Makos, and Johnson, 2011). Rather than being based on actual cost savings, these must be calculated on the basis of a counterfactual. Finally, formula rates can be used in conjunction with future test cases to reimburse the utility for failure to reach a particular rate of return on its investments and lower variances across years (Lowry, Makos, and Johnson, 2011). Of course, formula rate policies tend to weaken the incentives for prudent investment without additional mechanisms.

Change Procedures for Rate Cases

Longer periods of time between rate cases incentivize investment of technologies that provide cost savings through utilities' ability to appropriate more of the benefits (Guthrie, 2006). Under traditional regulation, however, this is done at the (short-run) expense of consumers, who do not immediately get any operational savings passed through to them. This is a zero-sum trade-off between investors and consumers. Nevertheless, if the regulator believes that the pace of smart-grid investment is not sufficient, a commitment to fixed-date rate cases with reasonably long periods of time between cases will create an investment incentive.

If, however, smart-grid investments do not provide immediate cost savings to the utility but provide benefits (such as a reduction in emissions), then longer periods between rate cases provide a disincentive for investment in the technologies, because the firm can benefit only if the investment is added to the rate base.

Broad Principles for Smart-Grid Regulation

Shift Regulatory Focus from Costs of Investment to Net Benefits of Investment

Traditional rate-of-return regulation and associated rate cases have historically been focused on the allowance or disallowance of capital costs in the rate base of utilities, primarily as a check on the incentives of a (vertically integrated) utility to oversupply capacity when investment costs are completely passed through to consumers. Under a system in which the objective was to reliably serve electric customers at lowest cost, the focus on allowable costs is understandable.

Regulators and policymakers should be aware that a system that is changing because of grid modernization will require additional, costly investments that will likely be passed through to consumers in the short run but should benefit them—at least collectively—in the long run. Furthermore, in a complicated environment in which new technologies are developing and multiple regulatory objectives exist (for example, the mandatory incorporation of costlier renewable energy sources), incentives may be created to adopt systems that do not directly benefit consumers in terms of lower electric bills but rather in terms of other types of benefits (e.g., reduced greenhouse gases). That is, investments related to the smart grid, as currently envisioned, are not designed to replace depreciated legacy capital but rather to create a joint electricity and communication system that provides for (and, in some cases, is necessary for) future opportunities to increase system efficiency subject to additional regulatory goals (e.g., incorporation of renewable technologies and distributed generation).

Public utility commissions should thus focus on the overall social net benefits (consumer plus producer surplus plus any external benefits and costs) of an investment plan in rate cases rather than on the minimization of infrastructure costs. Because these technologies are expected to enable the reduction of a variety of negative externalities from the existing system and generate positive learning by doing and other positive externalities, yet may also be associated with additional negative effects, such as losses of consumer surplus and risk of privacy breaches, all of these benefits and costs should be taken into consideration when approving rates.

Examples include monetizing avoided costs from improved reliability, emission savings from renewable incorporation and fewer vehicle-miles traveled for repairs, the learning-by-doing benefits of adopting novel technologies, the option values associated with investment decision, and resiliency benefits (Rothstein, Besser, and Jenkins, 2014; World Economic Forum, 2009). In some cases, monetary values may be well established in the economics and supporting literature; in other cases, regulators could make informed judgments if the external (i.e., societal) benefits were sufficient to overcome any shortfall in the private net benefits of an investment.

In short, the desirability of smart-grid investments should take into account a complete accounting of the expected benefits and costs of the technology, above and beyond the impact on consumers' electric bills. If the total social benefits exceed total social costs, then the regulator should adopt policies that incentivize the adoption of those technologies, keeping in mind that the utility has an incentive to invest only if expected profitability increases. For some investments for which cost savings are not immediately forthcoming, this may result in higher short-term retail electricity rates.

Adapt Pricing Structures to New Technologies

Smart-grid technologies will eventually allow utilities to distinguish (and potentially price-discriminate) not only between times of use but also between different appliance usages within a household. Regulators should consider this expanded set of pricing structures when setting rates. For example, utilities could charge a lower price for essential heating, cooling, and lighting than for nonessential appliances, such as dishwashers, hot tubs, and clothes dryers. This would serve to encourage energy conservation in a targeted manner, focusing on nonessential appliance usage. In addition, certain programs, such as the California Alternative Rates for Energy program, offer monthly discounts on energy bills for low-income households. The discounts have traditionally been applied across all types of electricity use. One way to sustain social safety-net programs while also encouraging reductions in nonessential electricity use would be to explore price structures from a consumption pricing point of view.[1]

Develop Efficient Pricing Policies for Distributed Generation

Existing regulatory structures were based on a one-way flow of power from generator to transmission to distribution to customer, with regulations recognizing the natural monopoly of the transmission and distribution systems. The advent of many decentralized prosumers creates potentially valuable substitutes for the utilities' product but also a large collection of potential free-riders who use distribution infrastructure to potentially sell power back to the utility while partially avoiding their full share of past investment costs by avoiding paying prevailing electric rates designed to capture those costs. In essence, the incumbent electric grid is viewed as a public good.

Smart-grid technologies can be leveraged to help incorporate and properly price such distributed activity, providing benefits to consumers in the form of resilience and the ability to sell electricity back to the distribution operators, which may benefit from additional opportunities

[1] From an economic standpoint, this recommendation implies an additional externality arising from high-priced "essential" electricity.

to balance supply and demand. Prices should be set, wherever possible, according to real-time locational pricing, with negative prices to the prosumer representing a credit reflecting the marginal value of electricity sold back to the network plus an appropriate charge (or refund) reflecting the prosumer's use of (savings to) the distribution network. Because of the two-way nature of the relationship with the network, however, the issue of sharing the burden of sunk-cost capital is rather complex (DOE, 2007).

Create and Enforce Smart-Grid Standards

The lack of standard-enforcement capability for crucial aspects of the smart grid (such as cybersecurity and interoperability) can pose a threat to potential investments in innovation by manufacturers and utilities alike. In fact, in a survey of project managers of smart-grid projects in Europe, the lack of interoperability between system elements was the most common obstacle reported (Giordano et al., 2013). The prospect of assets rendered obsolete due to a changed landscape of standards can significantly limit investment and risk-taking—both necessary ingredients of innovation. As the vision for the smart grid continues to be refined through a deepened understanding of the available technologies and collected data, so too should the framework of standards and regulations evolve to accommodate development and nurture innovation.

State public utility commissions need to make informed changes to rules that currently make investments in microgrid technologies and accompanying controls and automation seem like a risky proposition.

Recognize Differences in Local Electric Systems

Although technical performance standards can help increase the integration efficiency of the smart grid, a standardized policy regime across all service territories will likely not be optimal. There are likely to be significant differences the technologies already installed on local distribution systems, thus changing the relative net benefits of installing identical technologies on system components. Furthermore, differences in the consumer mix, their propensities to engage in demand-side response and adopt new technologies, and weather and climate differences (especially in relation to wind and solar generation) will similarly change the calculus of optimal investment.

Across different utilities, regulators and policymakers should be mindful of the different contexts and path dependencies inherent in electricity regulation and tailor both regulatory systems and grid-modernization plans accordingly. A one-size-fits-all approach will likely not maximize system value because the benefits and costs will differ across utility service regions.

Manage Consumer Expectations

An early assumption with respect to demand-side management pilots and programs was that enabling consumers to monitor their electric consumption would effectively increase the price elasticity of demand, resulting in reduced peak loads *and* lower electricity bills. In fact, in many cases, smart meters were marketed to consumers as a means of reducing their electric bills, and the overall benefits of the smart grid were touted. Although quantity response has been observed in many, if not most, cases, the response is not uniform. Furthermore, many inflexible consumers realized increased bills because of TOU pricing or RTP.

The resultant credibility gap between utilities and consumers potentially raises the costs of further innovation and ultimately may take a concerted public-relations effort to overcome.

One lesson is that overpromising on the benefits of the smart grid should be avoided, and both the potential benefits and potential costs of any change in electricity policy should be clearly articulated to consumers (who ultimately bear most of the costs). Although an inconvenient political reality, most rate and other policy changes are associated with trade-offs.

Require Transparency in Data Collection and Usage

Numerous technological and logistical barriers exist in dealing with data issues that arise from the information layer of the smart grid, but perhaps the most relevant barrier for policymakers is that of data privacy. Many of the business opportunities require access to household consumer electricity data. Policymakers and the utility industry need to understand the trade-off between all the potential benefits of smart-grid data and the privacy concerns that come with them. This is not a binary choice between saving energy and respecting privacy. Policy solutions need to be developed, such as electricity database auditing procedures (just like financial documents are audited), ways to anonymize data, encryption-technology standards, and the use of more-benign proxies for raw data.

A promising avenue in composing such policies is drawing lessons from existing privacy frameworks aimed at protecting consumer financial data or online browsing data. For example, the privacy policy of a major Internet search company explains what information is collected, how the information is collected, and how the information is used. There is a brief explanation of the technologies used in collecting Internet data (e.g., device information, log information, location information, local storage, cookies). Transparency also involves the ability to review information tied to one's account and control how the information is shared. If we were to apply such principles to the electricity industry, utilities would dedicate specific effort into educating customers about information collected from disaggregation of smart-grid data.

Move to a Forward-Looking Test Case

Research has shown that operational efficiency can be enhanced and cost savings achieved if a regulated firm is allowed to diversify into a new market (Palmer, 1991). Expanding into a related line of business can increase the utility's incentive to innovate and can lead to higher gains in consumer welfare over time. For example, this argument was used in telecommunications to justify allowing the Regional Bell Operating Companies to also manufacture communication equipment (Kahn, 1990). Similarly, the entry of utilities into the market for consumer information represents a new business opportunity.

Entry into new markets, of course, will not be reflected in the historical data. Regulators and utilities should thus move to a model in which future planning via multiyear test cases is an integral part of the regulatory process, with regulators developing utility-specific regulations and policies that allow utilities to move into new markets without undue regulatory burden or the risk of generation of monopoly rents.

CHAPTER SEVEN

Conclusion

This research report analyzes the state of smart-grid development and identifies the potential barriers of smart-grid technology adoption, as well as identifying policy levers, recommendations, and entrepreneurial opportunities related to grid modernization. Potential benefits of a fully functional smart grid come from increased reliability, the ability to more readily incorporate renewable energy sources into the electric grid, lower long-run prices due to shifts in peak demand, and increased information to consumers enabling more-informed choices related to electricity consumption. In the case of the latter two categories, benefits (in terms of the flattening of peak loads) accrue because of changes in consumer behavior on the demand side. However, this change in behavior is most likely to occur because of a change in the incumbent pricing regime, with prices that more closely match the true marginal cost of electricity delivery to consumers.

Our findings suggest that, although the net benefits of the smart grid are likely, though not necessarily, positive from a societal standpoint, considerable real-world issues constrain the transition from the legacy grid to a fully functioning, integrated communication and electricity-delivery system. These barriers slow the adoption of smart-grid technologies and arise in large part because of the traditional regulatory structures used to protect consumers from natural monopolies, as well as perceived risks from the standpoint of both utilities and electricity consumers.

First, it seems likely that full adoption of smart-grid technologies, coupled with a move to RTP or TOU pricing, will create both winners and losers over the range of consumers and in the short versus long run, even though the overall net benefits to society may be positive. In addition, the extent of the gains is subject to risk, which is borne primarily by consumers. These two factors represent barriers to smart-grid development from the demand side.

Second, the cost-plus-fair-rate-of-return pricing structure, inherited from the existing electric grid, can discourage investment in innovative and possibly more-expensive technologies. The risk is that cost-conscious regulators will not approve the expenditures because an older, cheaper technology might perform many (though certainly not all) of the same functions for less cost. Because regulators tend to function as protectors of consumer interests given the natural monopoly of most utilities, costs that are deemed unnecessary will ultimately be passed to shareholders rather than consumers. This risk, coupled with additional forms of regulation (such as those related to environmental quality) that may take precedence over smart-grid development, creates a disincentive to invest in smart-grid technologies.

Third, the lack of technology standards also increases uncertainty to utilities that are concerned about investing in capital equipment that may not be compatible with other system components or will be made obsolete in the future. Adopting a technology that proves incompatible or of little use or is quickly out of date also increases investment costs to a utility ex post, which again are ultimately borne by consumers. This risk is rarely factored into the benefit–cost analysis associated with the smart grid.

Fourth, faced with budget constraints and multiple sources of non–rate-based regulations (e.g., RPSs and other environmental legislation), utilities and regulators may prioritize investments differently, increasing tensions and risk between the regulators and the utility. External federal mandates to reach nationwide policy goals (such as distributed generation or energy efficiency) may conflict with state-level policy, increase uncertainty about the future regulatory environment, or incentivize behaviors that may ultimately result in a decrease in energy sales from the utility to customers. Indeed, the possibility of creating consumers who sell electricity back to the grid (essentially substituting away from grid-based electricity) or cut back on energy usage because of dynamic pricing may be viewed as a net positive for society but threatens the business model of traditional utilities.

Finally, for parts of the transmission system that cross political jurisdictions, smart-grid investments face the same problem as traditional infrastructure improvements—namely, given the externalities involved, there are typically disputes over who pays for which upgrades. Essentially, then, the economic and regulatory structure of the incumbent distribution and transmission systems inhibits innovation on both the producer and consumer sides of the market.

In order to help overcome some of these barriers, regulators and policymakers should keep in mind several principles:

- Regulators should consider maximization of net benefits to the system, rather than cost minimization, as an organizing principle. For example, a willingness to allow utilities to capture a greater share of the returns to risk-bearing inherent in investment decisions can provide an incentive for innovation in the smart grid. Similarly, forward-looking test cases can help place a focus on forward-looking benefits of a new, upgraded system.
- Pricing policies should both reflect the marginal benefit or cost of a service and recognize the need to recover sunk costs. In addition, the ability to price-discriminate given new technologies may provide an ability to insulate vulnerable populations from large price swings should regulators prioritize this as an objective.
- Because of differences in investment paths and customer bases, the same technologies deployed across different systems may result in different net benefits. That is, a one-size-fits-all approach may not be appropriate across all distribution systems.
- The development and adoption of technological standards at the federal level can help reduce investment uncertainty and facilitate the development of technologies in auxiliary markets.
- Both regulators and utilities should be mindful that smart-grid technologies and their effects may increase overall system net benefits but that experiences may vary across individuals and incentives will ultimately play the key role in their realization. To avoid credibility gaps, overpromising individual-level benefits should be avoided.

Should the barriers of smart-grid innovation be fully or partially overcome, one potentially interesting area of innovation is in the realm of big data. The ability to sort the data collected from the grid into useful, actionable information is perhaps one of the biggest value propositions of new smart-grid technologies, but applications are just beginning to come online. Disaggregated, individual-level information can create benefits, including aiding consumers' ability to optimize electricity consumption and appliance decisions, improving distributors and transmission operators' forecasting ability, and allowing for flexibility in pricing structures and the ability to evaluate pilot and other programs. Utilities may be able to diversify beyond just providing a stable power source toward a more robust power and information model, adding value through tailored marketing campaigns aimed at individual-level objectives, such as bill reduction. Additional opportunities could accrue to entrepreneurs in sectors looking to take advantage of this new flow of information, such as building designers, appliance makers, and even the police.

As with the adoption of smart-grid technologies in general, these potential benefits are not cost free. Privacy concerns among individuals may temper enthusiasm for these big-data applications, and utilities and others either may not have the in-house technical expertise to take full advantage (requiring costly personnel investments) or may have made past investments that inhibit a full realization of the benefits.

Because the era of big data is just beginning and the transformation of the electric grid continues, there are opportunities and risks, benefits and costs. Technological innovation can help enable new services and promote technical efficiencies, but the regulatory and organizational structures of the legacy grid coupled with privacy concerns about information disclosure can create impediments to adoption patterns. Future research into regulatory design and incentive structures meant to manage the tension between overall societal benefits of the smart grid and associated solutions with the micro-level costs of innovation would help overcome many of the barriers to adoption and enable the growth of additional entrepreneurial activity. Evaluation of the distributional effects of smart-grid incentive structures should be a key feature of future research. This deals with how the benefits and costs from smart-grid rollout should be allocated among incumbent firms, new investors, and a diverse customer base. Future policy research and regulatory design should recognize that different groups of individuals and firms may face new and different incentives and attempt to minimize increased costs for any particular group. In addition, a deep understanding of the impacts of privacy regulation and enhanced smart-grid data security is critical to balancing economic innovation in the electricity sector with concern for customer welfare.

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