Architecting the Smart Grid for Energy Efficiency

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ABSTRACT

An often stated objective of the Smart Grid is to enable building energy demands to be more responsive to utility and grid system loads. By potentially providing utility capability for direct load control, measurement in support for dynamic pricing, and as well the granular data needed for energy use to be more precisely targeted to consumer needs, the Smart Grid may enable significant electric energy savings as well as peak demand savings. However, it is evident that choices made in smart grid deployment strategy and network architecture by utilities, guided by the policies of state and federal regulatory authorities, may significantly impact the outcome of the Smart Grid initiatives.

As utilities begin their planning and implementation for Smart Grid, it remains ambiguous as to whether the elements needed for efficiency and demand response will be included. Will utilities offer dynamic pricing, and/or control customer systems directly? And will utilities provide customers with a more frequent and granular measurement of energy use?

This paper considers these questions, and proposes architectural directions for the Smart Grid that compare *utility-controlled* and *consumer-controlled* energy networks. With *utility control,* the intelligence of devices is derived from a central control point via a private utility network. With *consumer control,* these devices use a control system that is located in the home or business, or on the Internet but ultimately managed by the needs of the consumer. For both of these extremes, as well as intermediate possibilities, we consider how choices impact the aggregate efficiency and demand response, as well as support/limit innovation in supporting a responsive energy future.

Introduction

The potential for information to help us increase the energy efficiency of buildings is certainly large: examinations of building energy systems show that, in today's practice, we frequently fail to align our delivered end-use (especially air conditioning, heat, and lighting) with the time and place that we require them. [1] In homes as well as large facilities, buildings use energy for light and comfort unnecessarily when unoccupied, or to inappropriate levels where occupied. While local controls such as clock thermostats, occupancy sensors, and photocell dimmers exist, they are far from ubiquitous, and at times inoperative or ineffective at reducing energy use waste. For example, Grid-enabled communications and transparency results in mechanisms that uncover faults in buildings often saving 20-30% as compared with the systems we now have. [2] It is therefore critical to consider the potential of systems for optimizing consumers' end-use needs based on information, consumer preferences, weather, schedules, and time differentiated energy costs.

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[1] MacKinsey , July 2009.

[2] Jim Butler, Cimetrics; Stephan Samouhos, MIT, case study presentations at MIT October 2009

One important objective of the Smart Grid is to enable energy demands in residential and commercial buildings to be more responsive to utility and grid system loads. As experience is gained from early deployments, we will determine the extent to which the Smart Grid could increase the responsiveness of building energy use and displace the need for other energy resources. [3] However, it is evident that choices made in smart grid deployment strategy and network architecture by utilities, guided by the policies of state and federal regulatory authorities, may significantly impact the outcome of the Smart Grid initiatives.

This paper presents findings from the ongoing MIT *Energy Innovations Research Project.* [4] Through analysis of literature, consideration of the results of early trials, advisory team interviews, and discussions at a project forum held in July 2009, our research explored the roles for utilities, consumers, third-party providers of services and technology, and policymakers in the build-out of consumer-side smart grid infrastructure.

Information-Driven Efficiency and Demand Response Mechanisms

Distributed information and intelligence-driven energy management have the potential to create disruptive change in society's use of energy. Potentially, the customer side of Smart Grid architecture may address this opportunity with three strategies:

- utility control of peak building energy use,
- time-differentiated dynamic electricity pricing, and
- more frequent and granular energy consumption data to support operational improvements and behavior change.

Load control/demand response: Using utility network communications, the Smart Grid may curtail consumer loads during critical system hours. It is estimated that 5.8% of our peak loads are currently controllable and up to 20% could be controlled.[5] This approach, historically called load management, is now often called *Demand Response (DR)* - connecting system requirements directly to consumer endpoints. For small consumers, utility load management programs have for many years successfully shed loads on utility peaks. With radio and powerline signals, these programs cycle air conditioners, raise thermostat set points, or shut off water heaters as examples. AMI systems provide a lower cost and more ubiquitous system, potentially aiding expansion.

Dynamic pricing: AMI deployments are increasingly focusing on the ability of AMI to support time-differentiated (dynamic) prices, such as critical peak pricing (CPP) rates, which charge their highest rate for a few hours on a handful of days per year when loads are highest. A study comparing 15 recent dynamic pricing experiments found that critical-peak pricing tariffs, under a variety of price structures, induce a drop in peak demand that ranges between 13 to 20 percent. [6]

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[3] Leeds, David, GTM Research, 2009.
[4] This research was carried out as part of the Energy Innovation Project, based at the MIT Industrial Performance Center and led by Prof. Richard Lester. We are grateful for the support for this work provided by the Doris Duke Charitable Foundation.
[5] FERC, DR Assessment 2008 and DR Potential 2009
[6] Faruqui and Sergici, 2009.

Granular energy use information: With the availability of hourly electric reads, early research shows that, in addition to pricing, the information of AMI may by itself be a valuable source of behavior change. With feedback about energy consumption, an interested energy consumer can better manage their energy and money. There have been over 40 studies that have identified how direct and indirect feedback on energy use can reduce energy consumption. Direct, real-time, feedback through in-home energy displays and other enabling-technology can have positive effects on consumer electricity efficiency, reducing average participant usage by up to 15%. [7] Inferential analysis supported by granular data continues to advance; for example:

- *End use disaggregation* analytics separate energy use into meaningful components. A recent California study indicated that disaggregated end use information was, in fact, more impactful than real-time feedback. [8]
- *Benchmarks:* New companies such as O-Power (formerly Positive Energy) focus on providing consumers with benchmarks to understand their relative energy use, and are comparing these consumers with a similar social or demographic group. Early indications are that 5 – 10% energy savings may result from these benchmarks.[9]
- *Collective Action*: With ubiquitous metering, there is the potential opportunity to leverage the benefits of shared information resulting in greater individual behavior change. Anecdotal trials suggest that group dynamics hold a tremendous potential, with several models under consideration, including competitions and group rewards or recognition. [10]

Smart Grid Architecture and Energy Efficiency

Smart Grid is a broad objective, addressing opportunities for enhanced communications and control in transmission and distribution of electricity. Within distribution, a key component under consideration is Advanced Meter Infrastructure (AMI), which is usually defined as measuring energy use at the meter at hour intervals or less and communicating these reads at least daily to the utility. However, it remains ambiguous as to whether the deployments will include the elements needed for efficiency and demand response. For example, will utilities offer dynamic pricing, and/or control customer systems directly? And will utilities provide customers with a more frequent and granular measurement of energy use? The paper reports findings on three architectural dimensions of AMI:

1. *In-facility Local area networks: thermostats, appliances, controls.*
2. *Utility-facility Communication.*
3. *Content Provisioning.*

1. <u>Controlling Appliances</u> with Utility vs. Consumer-Controlled Architectures

AMI provides operating benefits including reduced meter reading costs, outage management, and granular visibility on distribution components including transformers. However, in many cases, energy efficiency, including but not limited to peak demand reduction,

[7] Summarized by Darby,2006 and EPRI, 2009
[8] Herter, K., 2010
[9] OPOWER. (2009). The Home Energy Reporting System Fact Sheet.
[10] EPRI, 2009.

is important to the business case to proceed with Smart Grid. Automated control of appliances and thermostats is one approach to creating a sustainable energy impact. In fact, Home Area Network (HAN) enabling technologies are now viewed as an important element of achieving the highest peak demand savings. In the summer of 2003 the California Statewide Pricing Pilot found that *average peak savings were 34.5% on households with enabling technology* such as communicating thermostats, appliance cycling devices, and in-home displays. [11] This is substantially higher than the 12.5% achieved by pricing-induced behavior alone, and as a result some utilities and regulators have reworked AMI plans to include control strategies to capture these potential benefits.[12]

At the ends of the spectrum, two disparate approaches are under consideration to more intelligently manage devices in the home; utility and consumer controlled architectures.

Utility-controlled architectures create resource benefits, particularly lowering system peak demand, with controls operated by the utility on their customers' air conditioning, water heaters, pool pumps, and other equipment. The infrastructure of AMI/Smart Grid however provides a lower cost, and more ubiquitous capability to achieve utility-controlled demand response as compared with the systems used historically.

The benefits of the utility-controlled approach include:

- A deterministic demand impact, since these are implemented by switching capabilities controlled by the utility, as compared to the potential uncertainties of a consumer decision in response to price.
- Typically, the in-home control equipment in this paradigm is provided by the utility to the consumer at no cost, increasing near-term penetration rates, and does not require the consumer to have any form of Internet access. [13]
- Since the system is utility managed, attribution of the demand impact to the utility infrastructure investment of such control is very clear, simplifying the evaluation of benefits for incentive ratemaking.

Issue with the utility-controlled approach: Speculating forward on the Smart Grid option, the utility controlled approach anticipates in the years ahead that generation, transmission, distribution, and end use equipment will, in effect, collaborate directly as part of a single system, without any direct consumer involvement. Consumers express concerns regarding consumer choice and privacy, with detractors envisioning a scary *Big Brother-like* network as a natural extension of this approach. As a result, in 2008, the California Energy Commission needed to scrap a plan to require programmable communicating thermostats (PCTs) in new construction, following a public outrage at a perceived trend towards utility access to home controls and information.[14] The PCTs were to have radio capabilities to respond to utility signals to increase home temperatures during system peaks, and report home temperatures and compliance back to the utility. To this point, it is unclear as to whether these fears will subside, as society's concerns for other information-related technological changes have over time, or force an end to this paradigm.

[11] Statewide Pricing Pilot Summer 2003 Impact Analysis, Charles River Associates, Table 1-3, 1-4, August 9, 2004.
[12] Pacific Gas and Electric announced reconsideration of its AMI plan with this objective in June 2007.
[13] While the consumer is not charged, the costs are embedded in rates paid by all consumers.
[14] Barringer, F. (2008). California Seeks Thermostat Control. *New York Times* Retrieved from http://www.nytimes.com/2008/01/11/us/11control.html

By comparison, **consumer-controlled architectures** are composed of consumer purchased and configured building (LAN) or home (HAN) network devices that optimize appliances to meet the consumer's objectives for comfort or function, while minimizing energy costs and/or carbon footprint. Often, these devices connect to public networks, and interface with the consumer through Internet applications (often called control panels or dashboards) provided with the devices, or offered by third parties such as Google, Microsoft, or even the utility (but under consumer control). Utility AMI systems that support time-based pricing are beneficial, as they can add value to these systems if properly implemented. Direct interface with the meter network is not absolutely required, as price information can be made available over the Internet or intercepted by an in-home display.

Consumer-controlled benefits: Supporters argue that the consumer-controlled approach has the following benefits as compared with utility-controlled demand:

- Compared with utility control, consumer control has a similar theoretical potential to create demand impacts, but with price as the arbiter there is a boundary providing greater privacy to the consumer.
- Consumer control is more likely to generate energy savings as well as peak demand savings. Since total dollar savings is a common consumer goal, the system is more likely to save significant energy throughout the day, week, and seasons, while utility controlled systems are typically focused on the peak hours of the year.
- With time-based (dynamic) pricing, there is a more obvious connection to hourly meter read capability of AMI than with demand response, justifying the utility's investment.
- It is argued that time-based rates are inherently more fair and inevitable: without them, some consumers, such as those without peak-contributing central air conditioning, are paying too much and are subsidizing AC consumers. [15]
- Home area network (HAN) devices leverage existing networks already in the home such as Internet, mobile, cable, and in-home power lines for communication and control are more likely paid for directly by the consumer, rather than the utility (although all utility costs are indirectly borne by consumers through rate-setting). As a result, the utility total cost of the system may be less.

Issue with the consumer-controlled approach: The consumer approach is more reliant on the market to develop options, and the consumer to both purchase and use them, to get the desired energy and demand impacts. As a result, it is necessary with this approach that the utility provide a system to accelerate adoption, similar to the objective of other efficiency programs. Several, including Commonwealth Edison and Duke Energy have announced significant customer and market partnership programs.[16]

Potential 5-10 year innovations in consumer-control architecture: Just as the capabilities of Internet and electronics have continued to progress for a variety of consumer applications, one would anticipate that a decentralized ecosystem of competitive applications will continue to adapt to the improving understanding of consumer preferences. Some directions that have been already considered or are under development include:

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[15] Faruqui, *The Ethics of Dynamic Pricing,* 2010

[16] Vardell, 2008.

Improved control precision: In time we can anticipate improvements in sophistication of control. For example, in addition to the control of heating, air conditioning, hot water, and pool pumps, we can anticipate that in time refrigerator/freezers could modify their use pattern by linking their internal control logic to a home network signal of high cost, a scenario already being beta-tested in select households. In addition, comfort settings are increasingly more automatic, and mitigation is possible by pre-overcooling of the home, for example, prior to anticipate high cost periods to allow the system to coast.[17]

Thematic control: A trend to establishing default settings in complex electronics is to offer the consumer a few high-level thematic choices. Browser Internet security settings set many parameters based on a consumer's selection of low, medium, or high security. Some automobiles have tunable transmissions that allow power vs. economy settings. Similarly, we can see the trend towards thematic options in home controls, allowing consumers to select their preference for maximum economy, low carbon footprint, or full-but-not wasteful comfort.

Adaptive control: Many software systems improve their functionality for the consumer through automatic response to user experience. For example, voice recognition systems adapt based on the history of corrections, as do many other functions on websites, word processing, and mobile phones. In time the response of household and business energy systems to dynamic pricing can be designed to adapt to user corrections, reflecting preferences more accurately through learning, and over time requiring fewer corrections. As an example, if a more general thematic setting such as "super green" had been selected, but the consumer at regular times adjusted the heating or cooling for increased comfort, the software system can learn and tune the controls to more accurately reflect these preferences in the future.

2. Communications - Utility Meter network vs. Public Network Approaches

Somewhat independent of the question of utility vs. consumer-controlled load is whether utilities should provide proprietary meter network connectivity, or alternatively communicate via Public Internet.

With the meter network approach, the utility provides the meter-to-display and meter-to-control devices, and in most models subsidize them substantially for provision to consumers, with the costs recovered through rates. In early trials of Smart Grid-enabled controls, most systems offered a paradigm of utility-controlled smart thermostats, with on-device displays, firmware, and utility-network connectivity. In-home display pilots have been typically deployed in the kitchen or dining room, providing basic information on metered electricity use and prices in *real time*.

However, if the meter network is going to manage the devices, it needs to have greater bandwidth, two-way capability, and more upgradeability than systems installed to date to service these needs over the next 20 years, a typical meter network system life. As a result, a meter network gateway system may have $50-$200 per home additional costs for these system capabilities, excluding the costs for any utility-provided HAN devices.

With public network approach, the home network components communicate through a market-provided home network wireless router to connect with the home computer or other market-provided processor, which in turn connects with the public Internet, as do other devices like printers and computers on a home network today. Alternatively, home powerline and/or wireless broadband may support the home area network.

[17] Galvin Electricity Initiative, 2007.

Consideration of AMI high bandwidth and two-way communication capability: With the consumer-controlled approach focused on dynamic pricing with Internet-provided communications and information presentment, one-way hourly meters may be sufficient for this purpose, as there is no need for control capabilities to be built into the AMI network itself. Further, bandwidth needs are less, potentially reducing the AMI cost and increasing the number of options available. Also, since the consumer buys the display and control equipment, these costs are less for the utility. As a result, if AMI system costs are substantially higher for high bandwidth two-way capabilities (considering the cost of communication devices and upstream software and control systems), these may not be justifiable costs based on efficiency and DR considerations.

Benefit of containing the requirements for AMI: Certainly, the higher the stakes in terms of initial cost, and the greater the technology expectations placed on the system, the more difficult it will be for AMI to move forward. Not only will the higher costs produce near-term rate impacts that might be politically unacceptable, the breadth of current and near-term future solutions will slow the purchasing process. In addition, the higher requirements expand concerns for upgradability, obsolescence, and standards. Therefore, to achieve the necessary opportunities for AMI-enhanced energy use, *minimizing the technology requirements is an important focus of policy and regulation*.

3. Content: Meter Information and Analysis

A third related architectural issue is provision of information; again the main question is whether the utility is the provider or the market: who will design and deliver information that consumers need to better manage their homes and buildings?

Meter-to-Home Network Communications: In the last section, we discussed Internet options that reduce the necessity of utility-to-meter communication. Nonetheless, it is valuable for the meter systems to provide at a minimum hourly reads directly to the home for use by consumers with their web workspaces. Several AMI systems offer technology in the meter that broadcast short-interval reads directly to the home. These short-interval reads *on demand* (when the consumer can use them) are a key ingredient in measuring differential energy use, supporting the measurement of load, and cost, of any device in the home.

At the low marginal cost of $10 or less often cited, it should be justifiable for AMI systems to have functionality to support high frequency reads *on demand* to home networks. With short-interval meter data available to the home router, and then routed to a Web-based application, diagnostics and inferential analyses can be performed for a variety of functions. For example, applications using this data may be able to determine appliance energy use, determine when heating or air conditioning systems are in need of service, and evaluate options to reduce costs or improve device performance. For interested consumers, a Web audit on a cell phone could support the consumer walking around the home, switching loads on and off, and seeing what the impact of the switched load – costs per hour during peak or off peak periods, carbon footprint, etc.

> *The biggest challenge will be to assure that the electric company meter hanging on the outside wall of buildings will be linked real-time with the consumer-owned building management system inside the wall. The ubiquitous IP-based commonality now becoming standard will make that easy to achieve at the right time. The immediate challenge is to make sure that the utility industry moves away*

from small-scale proprietary systems and embraces broader, interoperable IP-based protocols and approaches. [18]

Should consumers receive their content from the Public Internet, or the utility private network? Many pilots have examined the benefits of in-home displays as part of the AMI network, but it may be more beneficial to tie displays to public networks. With IP connection, the consumer's display of choice can be a home computer, or a log-in from a computer at work, or web-enabled cell phone (i.e. iPhone). Web systems are low cost, flexible, and easily upgraded, promoting open, non-obsolescent consumer connectivity. Compared with the static content and quality of meter network-tied in-home displays, utilities or third parties such as Google or Microsoft can offer a richer, more interesting interface for working with consumers on the public Internet.

*Should Utility content architectures support data exchange with other public Websites***?** The open HAN direction discussed above will support a growing set of energy Web content choices in time. This will include portal content providers such as Google (Powermeter) and Microsoft (Hohm), as well as the Web control panels for the thermostat and other devices in the home. In this model, the utility Website provides meter data and potentially collaborative Web content site with models and functionality that can be drawn upon by the portal or control panel sites, ideally with a standard data exchange format. The consumer would need a security password to allow the public portal or control panel Website to connect to his data. This model is similar in architecture to the download of consumer-intimate financial data from bank websites to Intuit's Quicken and TurboTax applications.

Some question exists about whether the utility can refuse to make the consumer energy data available to other Websites, or be able to charge for the access. To date, most rulings by state regulators have determined that billing data availability by utilities is consumer-owned and within their purview to regulate, although the costs to create and support data access can be passed on to the consumer with a shared rate-based approach or event-specific charge. This argument is grounded in the view that the consumer information gathered and managed by utilities is done as a publicly mandated and ratepayer-funded activity. And further, the public interest in energy efficiency seems that regulators should encourage easy access to the consumer's data for the objective of maximizing energy benefits and market innovation.

Conclusions

This paper examined utility vs. public/consumer approaches to various aspects of consumer-side Smart Grid architecture. And our conclusion is that utilities, regulators, and policymakers should focus on the *consumer-centric architectures* for appliance control, *public architecture* for AMI communication, and *collaborative architecture* for content. Some of the elements are summarized on the following table[19]:

	Consumer Control	**Utility Control**

[18] Galvin. (2007). Galvin Electricity Initiative, The Path to Perfect Power: New Technologies Advance Consumer Control.
[19] Terry Vardell and Michelle Davis, Duke Energy, *Analysis of Smart Energy Now pilot*, July 2008.

Control	Consumer decisions/control	HAN optimized by utility - Consumer opt in/out
Pricing	Time-based - dynamic pricing.	Incentive for participating.
HAN	Owned/purchased by consumer. Possible utility incentives	Provided by utility/ recovered as part of regulated filing.
Gateway	HAN via internet, mobile phone, cable	Meter via proprietary system.
Data	To consumer via internet To utility via proprietary system hourly reads once/day; low bandwidth.	To consumer and utility via proprietary system Two way and high bandwidth – Large amounts of data.
Utility Cost	*Less Expensive*	*More Expensive*
Impacts	Creates *efficiency and DR.*	Primary impact *is DR.*

Regarding innovation, our findings to date are that our objectives are best met by an ecosystem where the *utility creates and seeds an effective ecosystem* for innovation, *which the marketplace then fulfills*. In this model, the marketplace will be the innovator that will find the strategies that appeal most to the consumer's motivation. This is accomplished through leverage of the utility's metering infrastructure, with appropriate open access and information sharing. And clearly, the regulatory standards placed and incentives offered to the utility industry will be the drivers of effective change and advancement.

- *We need to focus on consumer-controlled architectures for device control:* The market and consumer-led opportunities for innovation are exciting and substantial. We can see glimpses of ever-improving diagnostic and control methods that will dramatically reduce our energy requirements. Achieving our energy and greenhouse gas goals may require that we focus on market-led innovation in how we manage our homes and buildings.

- *We need to focus on open and public network approaches to communication:* Public network-connected devices are likely to produce more effective energy management, while utility-specific standards for communication protocols may reduce choice and innovation.

- *We need to encourage a broad ecosystem of content providers, including utilities.* The ability of Web software systems to interact with all of the consumer's technologies and information may create an ecosystem that supports the intelligent management of appliances and systems in our buildings, increasingly effective at saving energy and demand, and adaptive to consumer preferences. The consumer-managed approach and IP-based communication options recommended above support this direction. For example, in-home displays if provided by utilities should receive their content from the Public Internet, not the utility private network. And in time, one would expect consumers to rely on their own displays, including computers and phones. However, utility AMI systems that broadcast short-interval reads directly into the home for use by consumers and their web workspaces will support innovation. These short-interval reads *on demand* are a key ingredient in measuring differential energy use, supporting the measurement of load, and cost, of any switchable device in the home.

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