Working Smarter, Not Harder: An Introduction to the "Smart Grid"

by Chioke Harris and Jeremy P. Meyers

"A brain is a society of very small, simple modules that cannot be said to be thinking, that are not smart in themselves. But when you have a network of them together, out of that arises a kind of smartness."

—Kevin Kelly, author of *Out of Control: The New Biology of Machines, Social Systems, and the Economic World.*

Consider, for a moment, how communications have changed in the latter half of the 20th century through the first decade of the 21st. In the span of a few decades, we have progressed from rotary-dial telephones and expensive long-distance calling to the Internet, e-mail, cell phones, videoconferencing, IP telephony, and video chats. We are more connected to information and to distant people and places than ever before.

Now consider how our relationship to the electric grid has changed over that same time period. Odds are, you still plug your appliances into an AC outlet, and the way that the power is generated and brought to your home or office doesn't significantly affect how you consume that power.

The development of the electrical grid has been one of the key technical advancements of the 20th century. Both its scale and the scope of its distribution speak volumes about how important it has become to modern life. The modern grid, however, is still largely based on the original design that Westinghouse and Edison debated in the late 1800s, and isn't designed for modern electrical loads, distributed energy sources, or optimal efficiency. Power is generated and distributed by utility companies, without local competition to speak of, and with fairly little communication between utilities and end users in terms of how to get more out of the system. To date, the revolutions that we have seen in communications have very few analogs in the electric grid.

Nearly all the existing electric transmission and distribution infrastructure in the United States was built prior to 1965. Since then, that system has had five major outages. While this may seem like an impressive track record, three of the five outages have occurred in the past decade. Every year, American businesses lose an estimated $100 billion as a result of power quality problems and blackouts. Nonetheless, it took the massive blackout across the northeastern United States and southeastern Canada in 2003, which resulted in a loss of $6 billion in economic productivity, to place in sharp focus the need to reinvest in transmission infrastructure.[1]

By all accounts, however, the slow pace of innovation and change on the electric grid is about to change with the introduction of the smart grid. Precise definitions of what comprises the smart grid can vary, but generally speaking, this term refers to the use of digital information and controls technology to improve the reliability, security, and overall efficiency of the electric grid. Proponents suggest that this will be accomplished by offering consumers and utilities incentives to work together to create a more responsive and less polluting system.

A popular description of the smart grid invokes the idea of an "energy Internet" with a two-way flow of energy, in much the same way that the Internet allowed greater interactivity and selectivity in the flow of information. Just as we have seen television programming move away from broadcast to cable to video-on-demand and DVR technology, proponents of the smart grid imagine that we will see energy flow onto and off the grid as customer and utility exchange information, a marked contrast from today's one-way, utility-to-customer energy system.

What is the Smart Grid?

Broadly speaking, the smart grid is a fusion of the information technology that has enabled mobile telephony and the Internet with our existing electric grid. In addition to improvements in system resiliency and responsiveness to outages, the smart grid will also enable greater system efficiency, increased installation of wind and solar energy and active participation of consumers in managing their electricity use. The Electric Power Research Institute (EPRI) has found that rollout of smart grid technologies could yield a 4% reduction in energy use by 2030.[2] As a point of comparison, that would be roughly equivalent to eliminating the emissions of 750 million cars.[1] Beyond the emissions impact, that translates to a $20.4 billion in annual savings for utility customers nationwide. With a more robust and efficient system, and better knowledge and control of demand, it will be easier for utilities to manage the integration of renewable energy sources that produce intermittent power. That will help states meet targets for renewable power growth and minimize fuel consumption by reducing their dependence on natural gas or diesel reserve generators and use of fossil fuel-based power plants.

While smart grid technologies have been studied and piloted by the Department of Energy (DOE), universities and research organizations, in regards to federal support, the specific functions and features of the smart grid are explicitly defined by Title XIII of the Energy Independence and Security Act (EISA).[3]

As defined by Title XIII, specific features of the smart grid are:

- increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid;
- dynamic optimization of grid operations and resources, with full cyber-security;
- deployment and integration of distributed resources and generation, including renewable resources;
- deployment of "smart" technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation;
- integration of "smart" appliances and consumer devices;
- deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning;
- development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid; and
- identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services.

Demand–response control can assist utilities when unexpected supply losses occur or during periods of unprecedented demand. Utilities, regional transmission authorities, and independent system operators contract with customers who can support power losses in their operations in exchange for compensation. If a system operator encounters an unexpected need for reserve power, they may temporarily disconnect these contracted customers to restore reserve availability until demand falls or additional generation comes online. Demand response capability is critical to creating a more resilient power delivery system, one of the major goals of the smart grid. This communication between utility and consumer already exists for a subset of customers, but the communication may soon become more pervasive and subtle as new technologies are integrated into the system and device-to-device or device-to-subsystem communications become standardized.

Smart Metering and Variable Pricing

A significant component of the future smart grid is composed of changes within homes and businesses that will provide customers with awareness of their real-time power consumption as well as the ability to control that demand. Time-of-day pricing, determined in such a way as to minimize congestion on the grid and to maximize generation efficiency, will allow customers to make informed decisions about how to lower their electricity costs, even if the total amount of energy used over the course of a day remains the same.

One such innovation that should affect the grid's operation is the introduction of smart electricity meters, which differ from regular meters by providing real-time two-way communication between the meter and the utility. This not only provides the utility real-time awareness of every customer's usage, but also allows the utility to share the information with that customer through online tools. This information can be aggregated to provide various metrics to the customer, giving them the opportunity to set goals to reduce their consumption. These goals can be attained more easily with the introduction of smart appliances. These appliances have Internet connectivity, allowing them to share usage data with the utility, and through the same online tool, the customer. This gives customers the ability to observe not only how much power they use in real time but the specific devices in their home that are using that electricity.

Smart appliances may also mean utilities can use them as additional tools in their demand–response arsenal, allowing them to be remotely shut off during peak demand, reducing costs for the utility and the customer. Smart meters can also enable real-time pricing, which means customers pay a price more representative of the actual cost of generating the electricity they use. Real-time pricing provides a market signal to customers to reduce their use during peak demand, which is the most expensive time of day for the utility and also the most polluting, as it often involves the use of peaking generators, which can respond to rapid demand changes at the expense of efficiency and emissions.

All of these changes have several benefits to utilities and their customers, and are perhaps the most publicly anticipated improvements of the smart grid. Through price signals and real-time consumption data, customers will be given the information they need to reduce their use, and hence, their utility bills. Utilities will have access to the same data, giving them improved prediction of future demand. In addition, they will gain access to significantly greater granularity in demand–response control through the introduction of smart appliances. Furthermore, customers will be incentivized to take power from the grid at times when the utility is most able to supply it. For some applications, customers will be willing to pay the premium for using the power whenever they happen to need it, but for other applications customers might be perfectly willing to delay a high-demand activity such as drying a load of laundry or running the dishwasher until the grid has more excess capacity and the cost per kWh goes down.

By way of example, the authors' local utility, Austin Energy, has already begun implementing some smart grid technology. They have installed monitoring devices on their transmission and distribution infrastructure and, through custom software, can observe their system and rapidly diagnose problems. Additionally, they have begun installing smart meters across their service area.[4] Beyond these improvements, Austin Energy is a partner in the Pecan Street Project, which a public–private partnership that seeks to open up the grid to try out new technologies.[5] These will likely include increased distributed wind and solar generation software allowing customer interaction with smart meter data, smart pricing, user management of smart appliances, and sufficient system resiliency to support the charging infrastructure for plug-in hybrid electric and battery electric vehicles. The project will build on the general concepts inherent in any definition of the smart grid, and implement communication and pricing tools to allow the Energy Internet and clean energy systems being deployed to compare different delivery and business models, including dynamic pricing, demand response, decoupled pricing linked with net metering, and even rooftop solar leasing. An illustration of the distribution system that the Project is seeking to create is shown in Fig. 1. As is shown, considerably more information flows back and forth between the grid and the user, in the form of demand–response, variable pricing, net metering, and distributed resources that are equipped to handle local changes in demand.

Other utilities have also begun introducing smart grid improvements. These implementations have largely been confined to small local pilot projects, such as those in Fayetteville, NC and Boulder, CO.[6] It is likely that in the near term, the most ambitious projects will be in states where electricity prices are high, as those utilities and customers have the most to gain from improved system efficiency and demand management techniques. For example, Pacific Gas & Electric (PG&E), the energy provider for homes and businesses in most of northern California, began introducing smart meters and variable pricing programs in 2006 and plans to have smart meters installed for all of their customers by 2012.[7] It is likely that utilities and balancing authorities will accelerate smart grid implementations as the deadlines for compliance with state renewable portfolio standards approach, as these technologies will ease the integration of intermittent renewable generation at the ambitious target levels many states have set.

Grid-Scale Storage

One of the most interesting and complicated aspects of grid-scale energy storage is that there are many applications that create value on the grid. It is difficult to fully anticipate exactly what opportunities for arbitrage will develop as more communication among devices, consumers, producers, and distributers of electricity become develop. A report by the New York State Energy Research and Development Authority (NYSERDA)[8] covers the range of possible methods to create value with grid-scale energy storage. These applications include power-oriented (high rate, short duration) and energy-oriented (longer duration) options for operators, end-users, and renewable power.

It is an interesting challenge for storage, both in terms of the technology requirements for the energy storage systems, as well as how to treat it. Electrical energy storage will need to be very cheap and very efficient in order to provide a compelling value proposition, but some of the system-level requirements for portable power and for automotive applications can be relaxed. It is worth noting that if storage only exists at the customer location to reduce demand during peak times, it can provide some value, but such implementations will not handle the challenge of putting stored energy back onto the grid. A simple form of storage is thermal energy storage, particularly attractive in warmer climates, where electricity, which is generally cheap in the middle of the night, is used to produce ice, which can then be stored and used to offset air conditioning demand during the daytime.[9,10] This type of storage doesn't allow for utilities, generators, or customers to put energy back on the grid during peak demand times, but it does mitigate the demand on the system during the hottest, and often most energy-intensive, parts of the day.

The requirements for large-scale electrical energy storage systems are quite different from existing battery

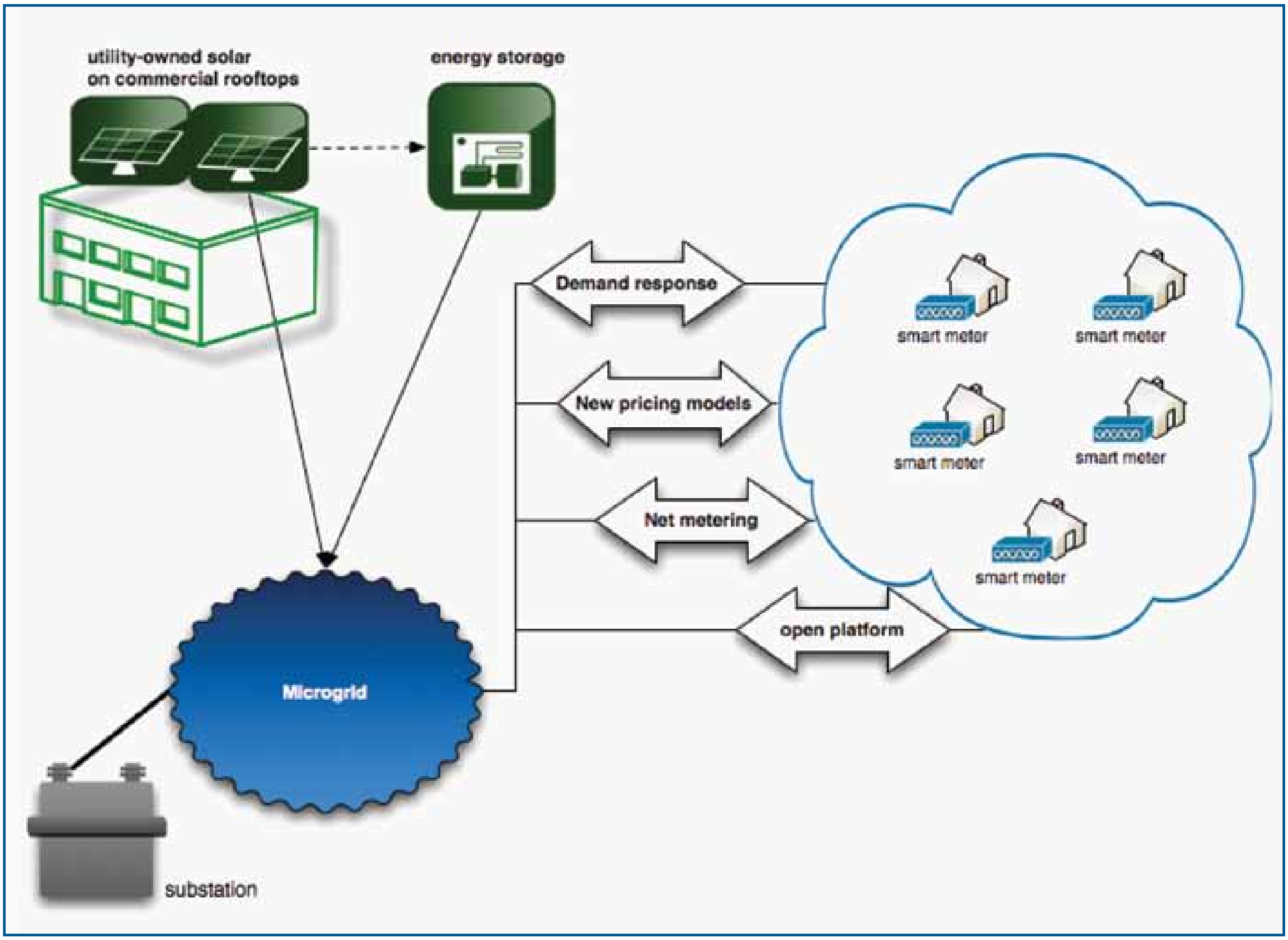

Fig. 1. *Proposed configuration of a smart grid electricity distribution system. Image courtesy of the Pecan Street Project.*

systems. While batteries for portable and transportation applications place a premium on weight and volume, stationary energy storage systems have considerably less stringent weight and volume requirements. Backup power systems and uninterruptible power supplies are used to support telecommunications and data centers already, but are generally not expected to survive large numbers of charge/discharge cycles. Time-of-day pricing on the grid, mandates for renewable power sources, and the accompanying intermittency of those sources are creating demand for electrical energy storage. Batteries and capacitors can serve to complement one another on smart grid. Capacitors can smooth short-term disruptions and ensure power quality, but batteries will be required for long-term load-leveling and peak shaving. We will need energy to be stored efficiently and to accommodate several hours of continuous energy accumulation and release to the grid.

Sandia National Laboratory has recently released a report on the benefits and market potential analysis of energy storage.[11] They correctly note that cost figures for energy storage systems cannot be expressed as a function of power rating alone—the materials and construction of the electrochemical cell, as well as the mechanical and electrical balance of plant scale with the power requirement (kW), but the total quantity of active material that determines the discharge duration and the total quantity of energy stored (kWh) contributes significantly to the cost. Costs are better understood as a function of both the power rating and the discharge duration.

The Sandia report identifies a market benefit of ~$700-900/kW for renewables capacity firming for discharges of 2-4 hours and a total U.S. installed capacity of approximately 36 GW.[11] This provides an ultimate cost target for this application of roughly $200 per kWh of storage capacity. While there are other applications where energy storage might offer operating cost incentives at higher price points, thereby allowing market penetration as economies of scale are established, it is important to ensure that these ultimate cost targets can be met if the goal is to foster the adoption of renewable power sources on the grid.

A possible solution to the cost and implementation problems facing energy storage in the smart grid is the use of batteries in plug-in hybrid electric vehicles (PHEVs). Utilities have envisioned that PHEV owners will plug their vehicles in at night to charge and, with the installation of public charging stations, will also likely be plugged in during the day while at work. In this scenario, since PHEV batteries will be available to the grid for most non-commute hours during the weekdays, PHEVs can essentially be viewed as energy storage for the cost of public charging points. Encouraging or requiring PHEV owners to participate in a program that uses the batteries in their car in this way, however, will require a significant shift in the way they interact with their utility.

Information regarding the utility's and owner's plans for how the car's batteries are used must be coordinated if each is to get what they want out of the car. Further, the utility will have to provide some incentive for PHEV owners to participate in such a program, as the utility's use of the battery will probably shorten its life and occasionally make it unavailable to the owner. Since there are few battery electric vehicles (BEVs) and PHEVs on the road today, it is difficult to predict their popularity and how owners will use them, however, the logistics issues associated with utilities

(continued from previous page)

sharing battery use with vehicle owners will present a significant challenge for utility system planning.[12] In such an early stage of deployment, it is not clear that the automotive manufacturers will be comfortable taking on the additional role of grid support as they are still attempting to launch a new vehicle technology in the marketplace. It will be interesting to see to what degree vehicle batteries will allow for greater exchange between the electricity and transportation infrastructures.

Using storage for arbitrage will flatten the effective demand curve, that is, reduce the difference in the amount of power generation during peak demand relative to the minimum demand. Reductions in effective peak demand will mean fewer expensive power plants will have to be dispatched, reducing the cost of peak power and minimizing customer incentive to change behavior. While this use of storage may reduce customer interest in reducing their peak use, utilities operational goal of more stable demand would still be achieved. This may appear a far more expensive way to reduce variations in demand, however, if placed appropriately within the T&D system, using storage for arbitrage also ensures that all renewable energy generated will eventually be dispatched. Even so, grid storage units have yet to achieve economies of scale, and so the capital costs of storage facilities might be hard to justify. Technologists who work on developing batteries for these applications will have to pay special attention to capital and operating costs, as well as to round-trip efficiency and battery lifetimes.

Elsewhere in this issue of *Interface*, authors explore some of the specific electrical energy storage technologies that are being considered for working with the smart grid. The advancement of renewable technologies and the instantaneous exchange of information among managers and customers on the grid may well create entirely new markets for new energy storage and conversion technologies. Members of the ECS community are well-poised to take advantage of, and to contribute to, the development of these new opportunities.

About the Authors

Chioke Harris is a graduate student in mechanical engineering at the University of Texas at Austin. He is a winner of the National Science Foundation Graduate Research Fellowship. A native of Seattle, Washington, he received his BS degree with a concentration in mechanical engineering from Brown University in May 2008.

Jeremy Meyers is an assistant professor in mechanical engineering at The University of Texas at Austin. He is a winner of the UTC George Mead Medal for Engineering Achievement and the DuPont Young Faculty Award. He currently serves as Secretary of the Energy Technology Division of ECS.

References

1. Litos Strategic Communication, "Smart Grid: An Introduction," DOE report, (2008).
2. DOE, "President Obama Announces $3.4 Billion Investment to Spur Transition to Smart Grid," http://www.energy.gov/news2009/8216.htm.
3. Energy Independence and Security Act of 2007, Sec. 1301. "Statement of Policy on Modernization of Electricity Grid," http://www.oe.energy.gov/EISA_Title_XIII_Smart_Grid.pdf.
4. Reuters, "Austin Energy Launches One of the First Smart Grid Deployments in the Nation," http://www.reuters.com/article/pressRelease/idUS140319+23-Sep-2008+BW20080923.
5. Pecan Street Project, Phase I, http://pecanstreetproject.org/?page_id=30.
6. XCel Energy, "SmartGridCity," http://smartgridcity.xcelenergy.com/learn/frequently-asked-questions.asp.
7. Pacific Gas and Electric Company, "PG&E Leads the Nation in Smart Grid Deployment" (2009), http://www.pge.com/about/news/mediarelations/newsreleases/q2_2009/090414.shtml.
8. NYSERDA, "Guide to Estimating Benefits and Market Potential for Electricity Storage in New York," Report 07-06 (2007).
9. I. Dincer and M. A. Rosen, *Thermal Energy Storage Systems and Applications*, John Wiley & Sons, Ltd., West Sussex, England (2002).
10. J. K. Kaldellis and D. Zafirakis, *Energy*, **32**, 2295 (2007).
11. J. Eyer and G. Corey, Sandia National Laboratories, "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide, A Study for the DOE Energy Storage Systems Program," Livermore, CA and Albuquerque, NM (2010).
12. DOE, "Bottling Electricity: Storage as a Strategic Tool for Managing Variability and Capacity Concerns in the Modern Grid" (2008).