

Challenges and Opportunities in Smart Grid: A Position Article

This introductory article gives an overview of the concepts and purpose of the Smart Grid and the important role of communications technology in its development.

By GEORGE W. ARNOLD

ABSTRACT | This introductory article overviews the concepts and purpose of the Smart Grid and the important role of communications technology in its development. It identifies some of the challenges and opportunities that are explored in more detail in the articles that comprise this special issue.

KEYWORDS | Data communication; data management; large scale systems; power systems; smart-grid

The electric grid was cited by the National Academy of Engineering as the supreme engineering achievement of the 20th century [1]. Affordable and reliable electric power is fundamental to modern society and the economy. With the pervasive application of electronics and microprocessors, reliable and high quality electric power is becoming increasingly important. While the grid has benefited from many innovations and improvements over the last century, in some respects its basic design is little changed from the days of Edison and Tesla in the 1880s (see Fig. 1). Fundamentally, the grid is optimized to move electricity generated at large, primarily fossil-fueled centralized generating stations through a one-way transmission and distribution system to consuming devices that have no information about the cost of electricity or whether the grid is overloaded. Modernization of this aging system has become a major national priority for many countries around the world.

Efforts to modernize the grid are motivated by several goals. First, to make the production and delivery of electricity more cost-effective. Second, to provide consumers with electronically available information and automated tools to help them make more informed decisions about



Fig. 1. Thomas Edison's Pearl Street Generating Station, New York, 1882.

their energy consumption and control their costs. Third, to help reduce production of greenhouse gas emissions in generating electricity by permitting greater use of renewable sources. Fourth, to improve the reliability of service. Fifth, to prepare the grid to support a growing fleet of electric vehicles in order to reduce dependence on oil. Fig. 2 illustrates a conceptual model of the envisioned

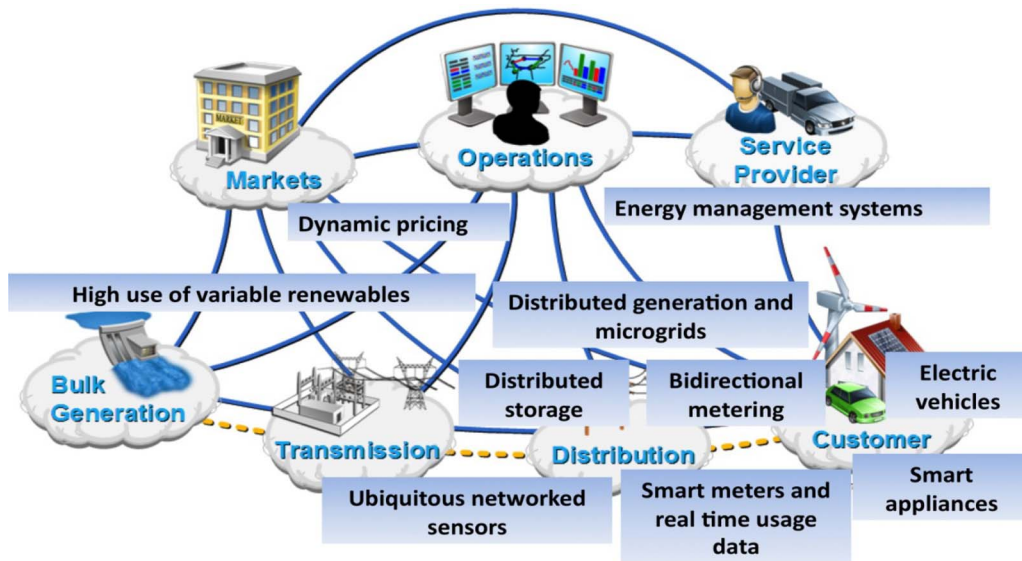


Fig. 2. Conceptual model of the smart grid.

future smart grid intended to achieve these goals. Some of the goals are more important than others in some countries. For example, in Japan, where power outages at the distribution level average only about 16 min per year per customer [2], reliability improvement is much less important than it is in the United States where such outages exceed two hours per year per customer [3].

Making the generation and distribution of electricity more efficient and cost-effective is an important goal because significant investments will have to be made in the coming decades to replace aging facilities that are nearing the end of their useful life. In the United States, about half of electricity is generated from coal (see Fig. 2) [4], and half of these generating plants are more than 40 years old. They will need to be retired and replaced or modernized. The Brattle Group has estimated that the investment required in replacement or new generation is about \$560 billion by 2030 [5]. Efficiency improvements can reduce the amount of investment that will be needed. For example, if greater efficiency in the transmission and distribution system and in end use could reduce the need for generation capacity by even a few percent, tens of billions of dollars could be saved.

There are a number of ways to make the transmission and distribution system more efficient. In most cases today, there are no sensors in distribution grids that communicate the actual voltages delivered to customers, so systems must be operated based on estimates of losses along the line. Deployment of automated sensors and controls that permit dynamic optimization of voltage levels and reactive power may permit reduction of voltage levels by a few percent and reduce power consumption [6].

Another source of inefficiency arises from the peaked nature of electricity demand. Generation and transmission capacity is provided to meet peak demand that occurs infrequently, for example on hot summer afternoons in areas where air conditioning represents a significant load. Less than half of the generation capacity in the United States comes from power plants designed to run all the time to meet demand. The rest—which are much more costly to operate—is in reserve to supply electricity during periods of high demand. It is estimated that capacity to meet demand during the top 100 hours in the year account for 10 to 20 percent of electricity costs [7]. One of the goals of the smart grid is to enable signaling between the grid—using either dynamic pricing information or direct control—to reduce consumption during peak hours and shift demand to off-peak periods. The concept is very similar to peak/off-peak pricing plans and flow control protocols that have historically been used to smooth demand in telecommunications networks. Dynamic pricing can take many different forms, ranging from simple schemes such as scheduled time-of-use pricing, to schemes that set higher prices only during critical peak periods, to real-time interval pricing based on wholesale market rates. Evaluating which schemes are most effective is an important area of experimentation and research. Some pilot programs have demonstrated that well-designed schemes can achieve reductions in peak energy use and customer savings across all income levels and are well-received by customers [8].

Reduction in the investment that will be required to replace aging generation and transmission facilities can also be achieved by using electricity more efficiently. Electricity is consumed by three categories of users:

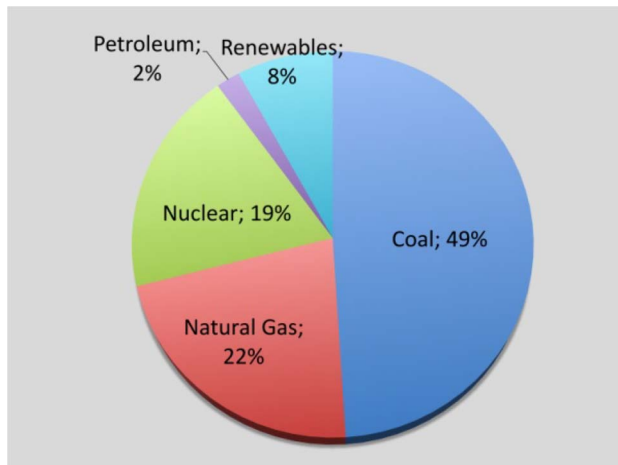


Fig. 3. United States electricity generation by source.

residential, commercial (e.g. office buildings), and industrial (e.g. factories). Each category accounts for roughly one-third of overall consumption [4]. Automation and information technology have been employed for many years to increase efficiency or curtail load when necessary in commercial and industrial environments. However, there has been little attention placed on residential environments beyond demand response programs that allow utilities, by agreement with customers, to control devices such as air conditioners, pool pumps or hot water heaters during periods of peak demand.

Consumers generally pay little attention to how they use electricity because they do not receive any timely or actionable information about their consumption. Smart meters that electronically record interval data can provide near real-time information about electricity usage and cost to an in-home display or software application that allows consumers to make informed choices about energy use and control their cost. “Smart” appliances are being designed by manufacturers to adjust their operation in response to price or other signals, without inconvenience to consumers and reduce usage during peak periods. For example, a refrigerator could avoid going into a defrost cycle during a time when demand and electricity prices are high. A computer-based energy management system in a home could receive dynamic pricing information over the internet and adjust lighting, air conditioning, and appliance operation in accordance with consumer preferences to minimize cost.

In the United States, about 40 percent of the human-caused emission of CO₂ is produced in the generation of electricity [9]. If the power grid were just 5 percent more efficient, the resultant energy and emissions reductions would be equivalent to permanently eliminating the fuel consumption and greenhouse gas emissions from 53 million cars [10]. The need to reduce carbon emissions has become an urgent global priority to mitigate climate

change. Reducing the production of carbon dioxide in electricity generation will require a variety of clean or cleaner energy sources, including coal with carbon capture and sequestration, natural gas, nuclear, hydro, geothermal, biomass, and increased use of wind and solar. Unlike conventional forms of generation, wind and solar are variable in output and cannot be controlled. As distributed forms of renewable generation such as rooftop solar photovoltaic panels become more widely deployed, utilities will need to have real-time information about these systems to maintain reliable grid operation. Since the grid must always maintain a real-time balance of load and generation, a significant increase in the use of wind and solar will require increasing use of storage and a greater ability to modulate demand in order to keep the grid in balance. The operation of the system, which today is generally controllable and deterministic, will become much more dynamic and stochastic in nature.

The reliability of the grid can be enhanced through the deployment of sensors that provide real-time situational awareness. Synchrophasors, now being widely deployed in the United States transmission grid, will allow earlier detection of and response to anomalies and make widespread cascading failures less likely. Sensors in the grid could also, for example, detect when a transformer is deteriorating and allow replacement before a failure occurs. Remotely operated reclosers and sectionalizers can speed service restoration following a failure. These and other smart grid technologies can significantly reduce the frequency and duration of power outages, which are estimated to cost the United States economy about \$80 billion annually [11].

Many nations that rely heavily on imported oil are concerned about the security of their energy supply. While oil represents a very small proportion of the fuel used to generate electricity, transportation is heavily dependent on oil. Electric vehicles represent a promising approach to reduce dependence on oil. A U.S. Department of Energy study found that the idle capacity of today’s electric power grid could supply 70% of the energy needs of today’s cars and light trucks without adding to generation or transmission capacity—if the vehicles charged during off-peak times [12]. The smart grid will provide capabilities to monitor and manage the charging of electric vehicles to avoid overloading the grid and minimize cost for consumers.

In the United States, the transition to the smart grid already is under way, and it is gaining momentum as a result of both public and private sector investments. The American Recovery and Reinvestment Act of 2009 (ARRA) provided \$4.5 billion of funding to help spur development of the smart grid, including a Smart Grid Investment Grant Program (SGIG) which provides \$3.4 billion for cost-shared grants to support manufacturing, purchasing and installation of existing smart grid technologies that can be deployed on a commercial scale. Significant smart grid

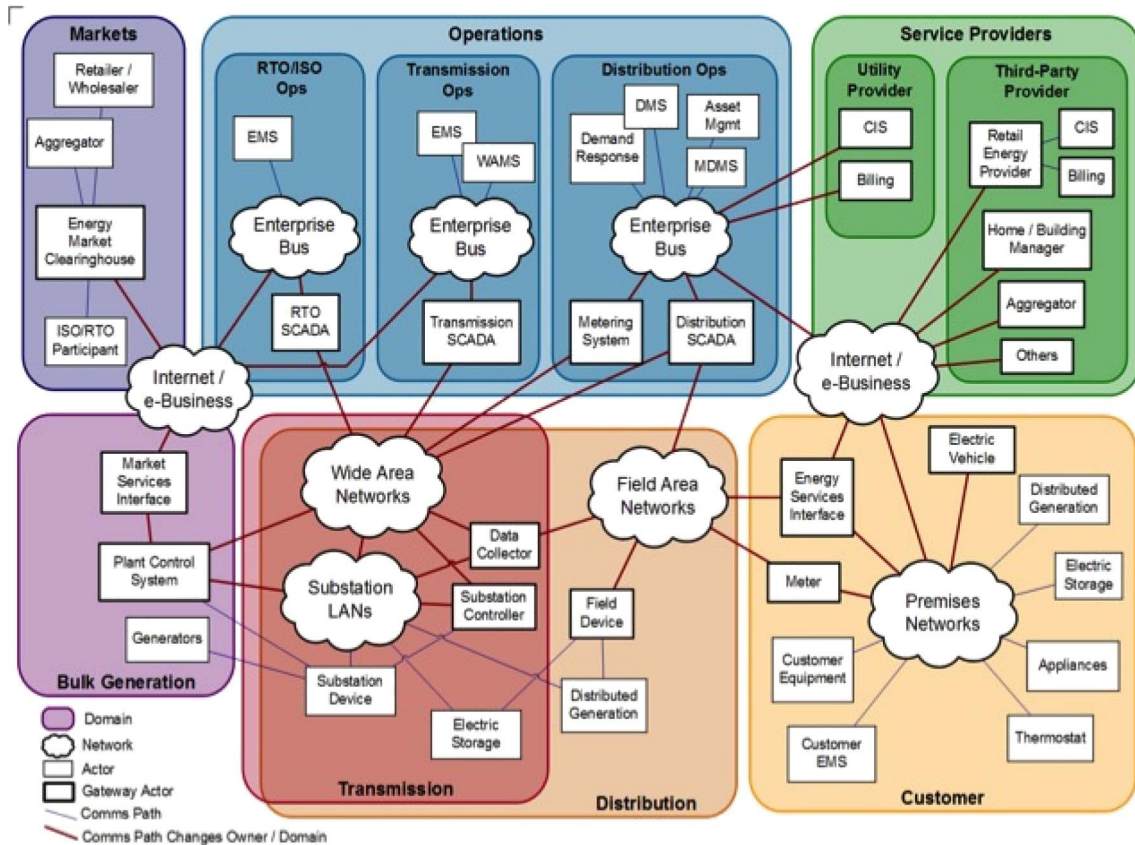


Fig. 4. NIST smart grid reference model.

efforts are also underway in other countries, including China, the EU, Japan, Korea, and Australia, among others.

The essential concept of the smart grid is the integration of advanced information technology, digital communications, sensing, measurement and control technologies into the power system in order to achieve the benefits described above. The smart grid evolves the architecture of the legacy grid which can be characterized as providing a one-way flow of centrally generated power to end users into a more distributed, dynamic system characterized by two-way flow of power (centralized and distributed) and information.

Communications and information technology (IT) play a critical role in the smart grid. The smart grid will ultimately involve networking vast numbers of sensors in transmission and distribution facilities, smart meters, SCADA systems, back-office systems, and devices in the home which will interact with the grid. Large amounts of data will be generated by meters, sensors and synchrophasors. Techniques for managing, analyzing and acting on this data will need to be developed.

The automation being applied to the electric grid is similar in concept to the network management and operations support systems that were applied to the telecom-

munications network in the 1970s and 1980s. However, applying IT and communications technology to the grid is not straightforward because it must account for constraints that did not exist in automating the telecommunications network. Unlike the telecommunications network, which routes packets of information, the electric grid routes power flows that are constrained by the laws of physics. Some smart grid applications, such as SCADA systems that control generators or substations, have latency requirements measured in milliseconds and the consequences of failing to deliver a control packet on time can be catastrophic. Other applications in the smart grid, such as communication of smart meter interval data, have much less stringent requirements. Characterizing the performance requirements for various smart grid applications is critical to understanding which communications technologies should be used for various applications.

Many suppliers from industry sectors that have not historically had to work together, such as electric equipment manufacturers, information and communication technology and service suppliers, and automotive manufacturers provide the equipment and systems that comprise the smart grid. Control systems operated by different electric utilities whose networks interconnect

will need to exchange information. Customer-owned smart appliances, energy management systems, and electric vehicles will need to communicate with the smart grid. Standards defining the meaning, representation, and protocols for transport of data are essential for this complex “system of systems” to interoperate seamlessly and securely.

Establishing standards for this critical national infrastructure is a large and complex challenge.

Development of standards for the Smart Grid requires efforts at national, regional and international levels. While electric utilities typically operate within national boundaries, there are interconnections across borders, such as between the United States, Canada, and Mexico in North America, and among member states of the European Union. In addition, many of the suppliers of equipment and systems used in the smart grid are global companies that seek to address markets around the world. Unnecessary variations in equipment and systems to meet differing national standards add cost, which eventually gets passed on to consumers. International standards promote supplier competition and expand the range of options available to utilities, resulting ultimately in lower costs for consumers.

In the United States, Congress recognized the important role of standards and assigned the responsibility for coordinating the development of interoperability standards for the U.S. Smart Grid to the National Institute of Standards and Technology (NIST) through the Energy Independence and Security Act of 2007 [13]. NIST, a nonregulatory science agency within the U.S. Department of Commerce, has a long history of working collaboratively with industry, other government agencies, and national and international standards bodies in creating technical standards underpinning industry and commerce.

Technical standards for the smart grid are under development by over 20 standards development organizations (SDOs), most of them international in scope, including IEC, IEEE, ISO, ITU-T, and IETF, among others. Since the standards need to work together to support an overall system, coordination of the standards work by the SDOs is critically important. During 2009, NIST engaged over 1500 stakeholders representing hundreds of organizations in a series of public workshops over a nine-month period to create a high-level architectural model for the smart grid (see Fig. 4), analyze use cases, identify applicable standards, gaps in currently available standards, and priorities for new standardization activities. The result of this work, “Release 1.0 NIST Framework and Roadmap for Smart Grid Interoperability” was published in January 2010 [14]. To evolve the initial framework, late in 2009 NIST established a new public/private partnership, the Smart Grid Interoperability Panel (SGIP), which has international participation. Over 640 companies and organizations are participating in the SGIP. This body is also guiding the

establishment of a testing and certification framework for the smart grid [15].

NIST and the SGIP are also establishing cooperative relationships with corresponding Smart Grid standardization initiatives that are underway in other parts of the world. In Europe, a European Joint Working Group for Standardization of Smart Grids has been established in which CEN, CENELEC, ETSI and the European Commission are participating. Japan has developed an initial standards roadmap for the smart grid and has also formed a Smart Community Alliance, which has extended the concept of the smart grid beyond the electric system to encompass energy efficiency and intelligent management of other resources such as water, gas and transportation. The government of South Korea has announced a plan to build a national smart grid network and is beginning work on a standards roadmap. In China, the State Grid Corporation has developed a draft Framework and Roadmap for Strong and Smart Grid Standards. International collaboration among these efforts is underway through a recently-established International Smart Grid Action Network (ISGAN) under the auspices of the Clean Energy Ministerial [16].

Ensuring cyber security of the Smart Grid is a critical priority. Security must be designed in at the architectural level, not added on later. A NIST-led Cyber Security Working Group (CSWG) under the SGIP, consisting of more than 450 participants from the private and public sectors, has been leading the development of cyber security guidelines for the Smart Grid. Release 1.0 of the Guidelines for Smart Grid Cyber Security (NIST IR 7628) was published in August 2010 [17]. Ongoing research is needed to help ensure security of the grid. New threats will continually surface, and ongoing development of new technologies and methodologies to detect and mitigate threats and vulnerabilities will continue to be a top priority for smart grid efforts.

Government regulators are playing an important role in these efforts to modernize the grid. Traditionally, regulators have been charged with overseeing electric utilities to ensure that electric service is affordable, reliable and universal. Increasingly, regulators also need to ensure that in meeting these goals, appropriate incentives exist to deploy the new technologies and innovations required to realize the smart grid. In the United States, the Energy Independence and Security Act charges the Federal Regulatory Energy Commission with adopting standards “as may be necessary to insure smart grid functionality and interoperability” when NIST’s work has reached sufficient consensus [13].

Modernization of the electric grid is a significant long-term undertaking that will span decades. It is quite possible that future generations will look upon the work now underway to develop the smart grid as the first great engineering achievement of the 21st century. ■

REFERENCES

- [1] W. A. Wulf, "Great Achievements and Grand Challenges," *The Bridge*, pp. 5–10, Fall/Winter, 2000.
- [2] H. Nakanishi, "Japan's approaches to smart community," presented at the First IEEE Conference on Smart Grid Communications, Oct. 4–6, 2010. [Online]. Available: <http://www.ieee-smartgridcomm.org/2010/downloads/Keynotes/nist.pdf>
- [3] Distribution Reliability Working Group, "IEEE benchmarking 2009 results," presented at the IEEE Working Group on Distribution Reliability (15.06.02), Aug. 3, 2010. [Online]. Available: <http://grouper.ieee.org/groups/td/dist/sd/doc/2010-07-Benchmarking-Results-2009.pdf>
- [4] *Electric Power Annual 2009*, Energy Information Administration, U.S. Department of Energy, Nov. 2009. [Online]. Available: <http://www.eia.gov/FTP/ROOT/electricity/034809.pdf>
- [5] P. S. Fox-Penner, M. W. Chupka, and R. L. Earle, "Transforming America's power industry: The investment challenge preliminary findings," in *Edison Foundation Conference*, Apr. 21, 2008. [Online]. Available: http://www.brattle.com/_documents/UploadLibrary/Upload678.pdf
- [6] Volt-VAR Control Task Force, "Volt-VAR control survey in United States and Canada," presented at the IEEE Smart Distribution Working Group (15.06.08), Jul. 26, 2010. [Online]. Available: <http://grouper.ieee.org/groups/td/dist/da/doc/Herve%20Delmas%20-%20Survey%20on%20VVC%20V3.pdf>
- [7] *Electricity Markets—Consumers Could Benefit From Demand Programs, But Challenges Remain*, Government Accountability Office Washington, DC, 2004.
- [8] *PowerCentsDC Program Final Report*, Smart Meter Pilot Program, Inc eMeter Corporation, Washington, DC, 2010.
- [9] *U.S. Carbon Dioxide Emissions From Energy Sources, 2008 Flash Estimate*, Energy Information Administration, U.S. Department of Energy, 2009. [Online]. Available: <http://www.eia.doe.gov/oiaf/1605/flash/pdf/flash.pdf>
- [10] *The Smart Grid: An Introduction*, U.S. Department of Energy, 2008. [Online]. Available: <http://www.oe.energy.gov/SmartGridIntroduction.htm>
- [11] K. LaCommare and K. J. Eto, "Understanding the cost of power interruptions to U.S. electricity customers," Lawrence Berkeley National Laboratory, Berkeley, CA, LBNL-55718, 2004.
- [12] M. Kintner-Meyer, K. Pratt, and R. Schneider, "Impacts assessment of plug-in hybrid vehicles on electric utilities and regional U.S. power grids Part 1: Technical analysis," Pacific Northwest National Laboratory, U.S. Department of Energy, Richland, WA, 2006.
- [13] *Energy Independence and Security Act of 2007* (Public Law No: 110–140), U.S. Government Printing Office, U.S. Congress, 2007. [Online]. Available: http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_public_laws&docid=f:publ140.110.pdf
- [14] *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0* (Special Publication 1108), National Institute of Standards and Technology, U.S. National Institute of Standards and Technology, Gaithersburg, MD, 2010.
- [15] *Smart Grid Interoperability Panel*, Smart Grid Interoperability Panel, Nov. 2009. [Online]. Available: <http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/SGIP>
- [16] *Fact Sheet: International Smart Grid Action Network*, Clean Energy Ministerial, U.S. Department of Energy, Jul. 2009. [Online]. Available: <http://www.energy.gov/news/doGAN-Fact-Sheet.pdf>
- [17] *Introduction to NISTIR 7628 Guidelines for Smart Grid Cyber Security*, National Institute of Standards and Technology, U.S. National Institute of Standards and Technology, Gaithersburg, MD, 2010.

ABOUT THE AUTHOR

George W. Arnold, photograph and biography not available at the time of publication.