THE SMART GRID:

MODERNIZING THE U.S. ELECTRICITY INFRASTRUCTURE

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Introduction

The modern electric system is an incredible technical achievement. Plug something in, turn it on, and it works around 99.97% of the time (“The Smart Grid: An Introduction”). We never even think about the complex and delicate infrastructure of electric generators, transmission lines, and control equipment required to keep the lights on.

Electrical energy, unlike mechanical or thermal energy, must be consumed the moment it is produced. If generators supply more power than the current load on the system, overvoltages will occur, which damage appliances and cause lights to burn out. The opposite condition creates undervoltages, which may cause computers and other sensitive digital electronics to malfunction and large motors to overheat.

Historical factors have created an electricity supply network that responds to demand. Major sources of electrical energy - coal, natural gas, nuclear power plants, and hydroelectric dams - are highly controllable and regular. Electricity demand, however, is highly irregular and largely uncontrollable. Large commercial and industrial customers provide a steady base load on the grid, but residential consumers introduce wide variability into the system. Though demand is somewhat predictable based on past trends and weather forecasts, events such as one-time highly-watched television broadcasts can cause unusually large loading. Electric utilities must have ‘spinning reserve’ capacity - plants that are on and powered up, but not producing electricity - to handle these spikes in demand.

This approach would work forever, if it were not for the fact that fossil fuel resources are limited and their burning has created millions of tons of pollutants and greenhouse gases which are choking the planet and changing the global climate on a wide scale. Future sources of renewable, clean energy, such as solar photovoltaic panels and wind turbines, could supply most to all of the nation’s electricity, but these sources are fundamentally different from those which currently supply the system. The wind doesn’t always blow, and the sun doesn’t always shine, introducing an intermittence which doesn’t exist with traditional fossil fuel or nuclear generation. Integrating these sources into our electricity supply on a large scale will require an ability to manage demand, for appliances to know the state of the grid and to cooperate to reduce load so that reversion to fossil fuel power is minimized.

This and many other challenges have shown that we need an electricity transmission system that is smarter than the current one, with more communication between different parts of the system, an even higher reliability, the ability to reconfigure itself to respond to outages, and which provides much greater support for integration of small generation facilities, such as residential solar panels and wind turbines. Hence the ‘Smart Grid,’ which is a loosely defined umbrella term that represents a future grid that accomplishes those goals.

How Today’s Grid Works

It is important to understand how the current electrical system functions, both in a technical and regulatory sense, to understand the viability of the technologies proposed to change it and the practical difficulty of implementing those changes.

Technical

The process of producing electricity has three distinct phases: generation, transmission, and distribution.

Generation is the process of converting an energy source, such as wind, moving water, or fossil fuels, into electricity. The energy source is used to turn a prime mover, such as a steam turbine, the blades of a wind turbine, or a water wheel. A generator converts the mechanical energy of the prime mover into electrical energy. The prime mover turns the rotor of the generator, which is either a permanent magnet or an electromagnet. This creates a moving magnetic field which induces a sinusoidal current to flow in a coil pair wrapped around the static part of the generator. Often, there are three coil pairs, spaced equally around the generator. This produces what is known as ‘three-phase’ power, or three sinusoidal currents which are equally displaced from each other by 120°, which is 1/3 of a full cycle. Three-phase power is convenient for running electric motors, because it is able to energize different coils in succession to create a rotating magnetic field to rotate the motor shaft (the opposite of generation). In the United

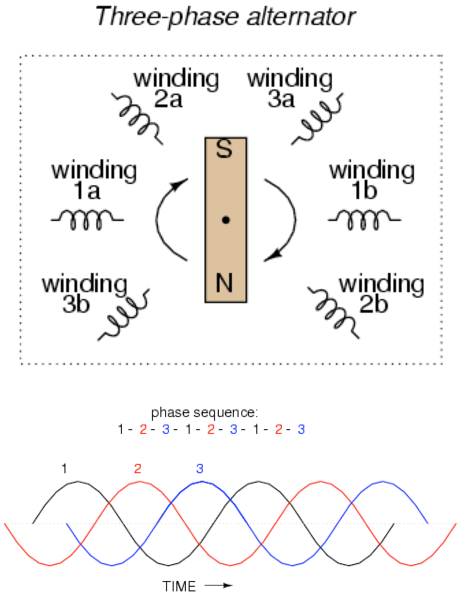
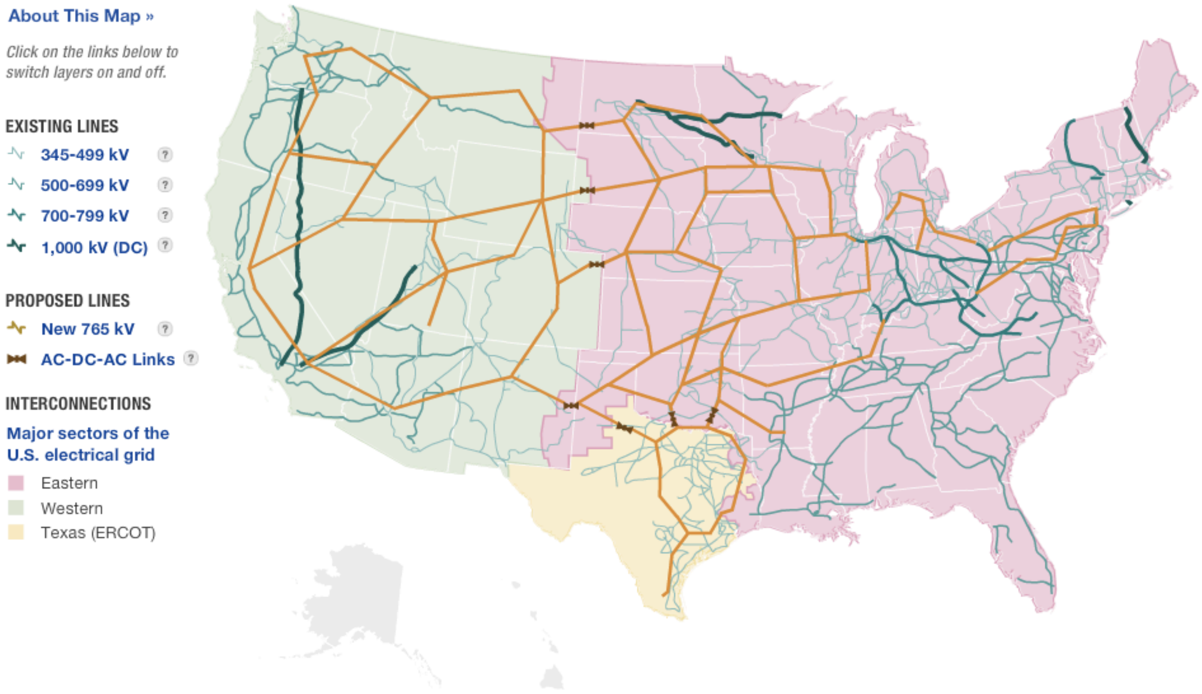


Diagram of three-phase alternator and resulting sinusoidal currents (Kuphaldt).

States and Canada, three-phase power is generated at a frequency of 60Hz, whereas most other countries use a frequency of 50Hz.

Transmission refers to the high-voltage movement of electricity across large distances. After generation, the electric voltage is stepped up using a transformer to anywhere from 230kV to 765kV, and transmitted many miles to serve different population centers around the country. There are over 164,000 miles of high voltage transmission lines in the United States (Talbot 43). Since electric power is the product of current and voltage, stepping up the voltage implies a reduction in current, which reduces heat losses in the wires during transmission.



The U.S. transmission line network. Most lines are concentrated near population centers; relatively few high-voltage lines cross the country. Orange lines are proposed new 765kV connections (NPR "Visualizing the U.S. Electric Grid").

There are three major transmission networks in the United States: the Eastern Interconnected System, the Western Interconnected System, and the Texas Interconnected System. The Eastern and Western networks have limited interconnection, while the Texas network is largely isolated except for a few direct-current (DC) links. The Eastern and Western Systems are linked with most of Canada, and the Western and Texas Systems have connections to Mexico. Almost all of the utilities in the continental U.S. are linked via these grids. The ability for utilities and power producers to sell bulk electricity over transmission lines has given the system higher reliability and lower costs through supply competition ("Electric Power Industry Overview 2007").

The grid's interconnection on a large scale through the transmission network provides benefits which may not be obvious. It keeps the whole country on the same, exactly synchronized power frequency. The newest power plants, which are generally the most efficient, can be used to supply base load anywhere. Even though power must travel further, incurring more line losses, this is still often more efficient than running older, local generating stations. Lastly, spinning reserves, which are generators running up to speed and ready at a moment's notice to produce electric power, need only be maintained at a few plants and their output piped wherever it is needed, reducing source waste (Weedy 45-7).

Distribution is the final step of getting electric power to the consumers who pay for it. Substations interface between the transmission network and the distribution network, usually stepping down the voltages to between 2.4kV and 33kV. The substation is connected to a number of 'feeders' which are medium-voltage lines which carry power to consumers. One feeder may be used to power an entire block of homes or a single manufacturing plant. The feeders are at different voltages, and are either three-phase, for commercial/industrial customers, or single-phase, for residential customers. Homes in the U.S. are supplied with 240V/120V 'split-phase' power, a three-wire single-phase system where one wire is neutral and the other two wires are 120V offset from that in opposite directions. Therefore a connection from either live wire to the neutral will give 120V, while a connection across both live wires will supply 240V. The lower voltage is what usually comes out of wall plugs, while the higher voltage is used for large appliances such as clothes dryers. Distribution networks are meant to carry a one-way flow of power from substation to consumer, and are not currently designed to accept excess power generated by consumers on a large scale.

We can describe the topology of both transmission and distribution networks using formal network theory. Distribution networks are commonly setup as loop or radial networks. A radial network looks like a tree, where power flows outward from a substation and can be subdivided multiple times into different voltages before reaching its final destination. A loop network supplies power to either end of a closed loop, and each house branches off of this. The advantage of a loop is that if part of a line goes out due to a fault or planned service, no interruption in electrical service occurs for end users as long as the rest of the line can take on a slightly increased power flow. Transmission networks, on the other hand, do not have this regular structure. Their topology is that of a mesh, where nodes are interconnected in random fashion, and almost every node has multiple interconnection points (Eaton 13-14).

A few more terms are necessary to know. Peak capacity refers to the maximum amount of electricity a node in the power system can supply, whether it be a utility, independent power producer, or substation. Peak demand is the opposite, referring to the maximum demand that will be placed on the node. Without any way to control demand, utilities must have enough generating capacity to supply the peak demand, meaning that many so-called 'peaker plants,' which exist solely to meet peak demand conditions, go unused a large part of the time.

Regulatory

The regulation of electric utilities began in the New Deal era. Congress passed the Public Utility Holding Company Act of 1935 to break up the few large interstate holding companies which controlled three-quarters of the nation's electric generation capacity. The companies were forced to split apart and take much smaller markets, but in return, the government awarded them with geographically distinct service areas where they would carry a monopoly on electric service. Each utility was required to provide electric service to all customers in the area at a rate which would be regulated by the government.

In 1992, Congress passed the National Energy Policy Act, responding to a growing call to allow competition within the industry. This allowed power producers to compete with each other to supply electricity to utilities. A market sprang up for the sale of wholesale electricity. In 1996, FERC (Federal Electricity Regulatory Commission) issued Order 888, which required utilities to allow competitors to use their transmission lines ("Electricity Deregulation").

This had unintended consequences. Transmission lines were still owned by individual utilities, but none wanted to build new lines to expand capacity since other utilities could benefit at no cost from their capital investments. Thus, large-scale infrastructure development slowed down immensely. Instead, utilities built new power plants, which they alone could realize revenue from. Many utilities also tried to sell power to regions further away than before, since they had access to more transmission lines. Due to those three things, the current transmission network is experiencing a shortage of power-carrying capacity (Talbot 44). To underscore the magnitude of the problem, as demand has continued to grow relatively steadily, only 668 miles of interstate transmission lines have been built since 2000 (“The Smart Grid: An Introduction”).

Electric utilities can be investor-owned, publicly-owned, or cooperatives, meaning they are owned by the customers they serve. There are also federal electric utilities, which operate about 200 power plants, most of which are hydroelectric dams built for the purpose of flood control or irrigation. Investor-owned utilities are the largest group by many metrics, serving over 100 million customers (71%) and owning 38% of generating capacity. Publicly-owned utilities, which are often owned by municipalities or state authorities, are much more numerous, but only control 9% of generating capacity.

There are still many regulations which govern the electric industry, especially when electric power crosses state lines. FERC has the power to regulate interstate transmission and sales of electricity and licenses navigable waterways for hydroelectric generation. The Nuclear Regulatory Commission is responsible for nuclear power plants, including overseeing their construction, operation, and waste disposal. Individual states have the power to regulate retail sales and prices, although sometimes this is left to local municipalities and cooperatives. States also regulate the construction of power plants and transmission lines. Until recently, if a utility wanted to build an interstate transmission line, any state that line crossed could block its construction. This obstacle was lessened by the Energy Policy Act of 2005, which enabled utilities to petition FERC to exercise federal eminent domain rights to force states to accept new transmission lines when it was deemed crucial to the security of the electricity supply (“Electric Power Industry Overview 2007”).

Reasons for a Smart Grid

The average consumer may not understand why we need a major overhaul to the electric grid. The power is on 99.97% of the time, and when it goes out, it’s usually due to extreme weather or wayward squirrels and is back on within a few hours. Unfortunately, the current grid is fast wearing out as components reach their intended lifetimes, our power efficiency is not nearly as high as it could be, and the anticipated growth of renewables demands new technology to utilize their full potential. In addition, the electricity markets could be made much more transparent and competitive by giving consumers access to real-time pricing information and allowing them to choose their electricity provider.

The components that make up the current grid are old. The U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability cites that the average substation is 42 years old, but was only designed to have a lifespan of 40 years. In addition, of the 9,200 generating units connected to the grid, the average one was built in the 1960's ("The Smart Grid: An Introduction"). The Pacific Northwest National Laboratory (PNNL) estimates that $450 billion worth of infrastructure investment is needed between 2003 and 2020 to keep up with demand and to replace worn-out systems. It makes sense to replace and add to the grid with smarter components which will save money through fewer outages, lessened demand for peak generating capacity, and increased plant efficiency (Mazza 4).

Environmental concerns are of paramount importance. Half of the electricity produced today comes from burning coal, releasing copious amounts of greenhouse gases and pollutants into the atmosphere ("The Smart Grid: An Introduction"). But the transition to renewables requires technology that can deal with the intermittency of wind, solar, and hydro power. Utilities must be able to exert some level of control on electricity demand. Also, if small-scale distributed generation systems such as residential solar panels are to become a large part of current grids, upgrades must be made. Current distribution systems can only accommodate distributed generation up to around 15% of peak capacity (Brown 3).

The electric grid is a very important asset from a national security standpoint. We are absolutely dependent on modern electricity. Widespread blackouts are devastating in both economic and quality of life terms. During a blackout food spoils, manufacturing and industry grinds to a halt, traffic snarls, and communications are interrupted. As alluded to above, the transmission system is already highly stressed. A well-coordinated terrorist attack that incapacitated just a few large generating stations and high voltage transmission lines would cripple our electricity infrastructure - a scary thought indeed. A grid with redundant transmission capacity, the ability to self-heal, and with generation resources spread across many small facilities instead of a few large ones, would be much more difficult to attack ("Grid 2030").

Lastly, consumers have no input in today's electricity markets. Prices are set by utilities and regulated by states. In 2008, electricity retail markets which offered a choice of supplier were available in only fourteen states ("Electric Power Industry Overview 2007"). Also, if customers were charged based on how energy prices change minute by minute due to fluctuating demand, they would be more likely to adopt efficient and grid-friendly usage patterns.

Smart Grid Technologies

The smart grid has been aptly described as information technology applied to the electric power system. The internet has revolutionized modern society by offering fast two-way data transfer between any two computers that wish to connect to it. The grid can be made smarter by building in analytics, communication, and decision-making at every node.

Advanced Electricity Meters

A key part of the smart grid is the Advanced Metering Initiative (AMI). Right now electric meters are usually located in out-of-the-way places such as basements or outside walls, and they are dumb, one-way devices which simply measure the amount of power that flows through them. Future meters will be placed in much more prominent locations and serve as an electrical control center for the entire house, similar to the way that thermostats are used today.

Advanced meters will be in constant communication with the electric utility, retrieving real-time prices and transmitting real-time demand upstream. Consumers will know how much energy they are using at any point in time and how much it is costing them. But the real value comes from the ability to set usage preferences, using the meter or attached software residing on the internet. By telling certain devices, such as water heaters, clothes dryers, and dishwashers to only operate when prices are low, consumers will save money, demand will be leveled out, and the whole system will be more efficient. Advanced meters will need to be combined with smarter appliances to realize full efficiency potential. For example, a refrigerator's daily defrost cycle uses up to 7% of its energy. A smart fridge could easily schedule this to happen at night, when electricity demand is lowest (Mazza 13).

Standards are emerging for the (wireless) communication that needs to happen between meters and household appliances to enable these types of applications. This communication between smart appliances and a smart meter is collectively referred to as a home area network (HAN). One of the most popular standards is ZigBee, which is based on an IEEE standard for wireless personal area networks. The ZigBee standard specification is available to members of the ZigBee alliance. ZigBee devices are inexpensive and have low power consumption, prompting many companies to build products that are already available which conform to the ZigBee standard.

Advanced Visualization

Utilities are woefully uninformed about the state of their power distribution network. So uninformed, in fact, that the only way they know about small power outages is through the calls of customers whose lights have gone out. They can only forecast demand, and the way they know how well they are meeting it is by monitoring the frequency and voltage on their lines at points far upstream of where the electricity is actually consumed. Adding measurement devices at more points in the system, including advanced meters that transmit current loading conditions, would allow for utilities to know unambiguously whether their current generation matches demand. This would have the side benefit also of making the voltage at the wall outlet less variable. Sophisticated visualization tools could be built to inform engineers of constriction points and impending problems on a large-scale.

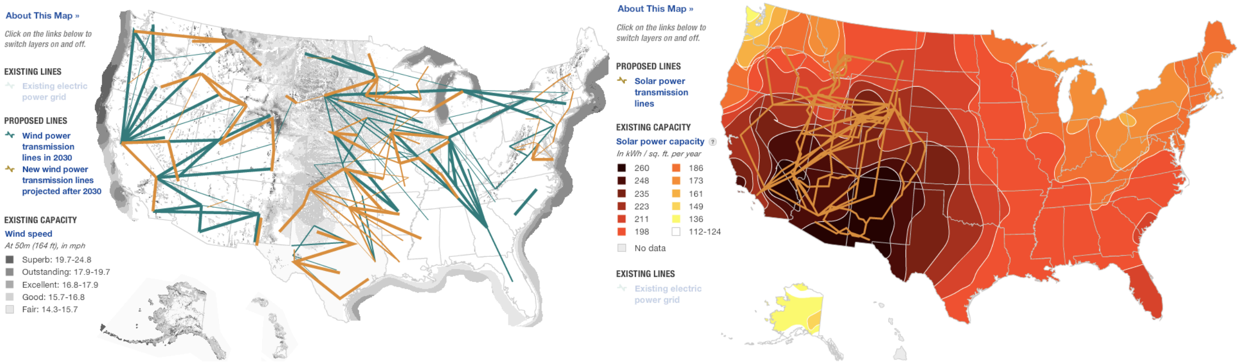
Distribution Automation

Today's distribution networks are limited to cycling circuit breakers to try to automatically recover from a fault. Future systems should be able to automatically reconfigure themselves if recovery is not possible. This will require excess distribution capacity and redundancy in the network. In particular, radial distribution networks will become mesh networks, as feeders are connected to more than one substation and homes are connected to more than one feeder. Sophisticated controls will be needed to make sure that homes are not oversupplied, but the benefit of higher reliability and redundancy will be well worth the costs (Brown 3).

Intelligently-Designed Transmission

The transmission network in the U.S. was built in a very haphazard way. David Talbot remarks, "Over the past century, regional monopolies and government agencies have built power plants—mostly fossil-fueled—as close to population centers as possible. They've also built transmission and distribution networks designed to serve each region's electricity consumers. A patchwork system has developed, and what connections exist between local networks are meant mainly as backstops against power outages" (43). This is not a system designed for high reliability; in fact, it was never designed in the first place.

Proposed large-scale renewable generation facilities will not be possible without new transmission lines. The midwest, which is the windiest area of the country, and the southwest, which receives the most direct sunlight, are areas that are very low-population, and are thus quite isolated from the current transmission network (Talbot 43). In order to use large wind and solar farms to harvest this energy, new high-voltage lines, which require a 5-7 year lead time, must be built starting now (Mazza 3).



Maps of wind and solar generation potential. Darker areas indicate higher solar and wind concentration. Turquoise lines are those intended for construction by 2030, and orange are those proposed for beyond 2030. Note that the wind map includes offshore generation capability. NPR: "Visualizing the U.S. Electric Grid"

Plug-In (Hybrid) Electric Vehicles

Plug-in electric vehicles run on a battery which charges through a wall outlet and is used to drive an electric motor. These are also available in hybrid models which can use gasoline to extend the range the vehicle can go on a full charge. Plug-in hybrid electric vehicles are different from most of today's hybrid vehicles which have much smaller batteries and are not able to be charged through the wall outlet.

The PNNL estimates that the current electricity network, if used during nighttime off-peak hours to charge electric vehicles, could power 73% of our existing light vehicle (car, SUV, van) fleet! Even though the electric grid is not as efficient as it could be with regards to energy sources, it is still cleaner on average than oil and gas, and this would save an astonishing 6.2 million barrels of oil a day. This transition would reduce our foreign oil imports by a half ("The Smart Grid: An Introduction"). With prices of electricity so low, consumers would spend on average 1/4 - 1/3 as much per mile as they do on gasoline (Ipakchi and Albuyeh 55).

These cars will need to be equipped with smart technology as discussed above to communicate with advanced meters to determine when demand is low enough that charging can take place. Even so, they will place a significant new load on an already-stressed grid.

Consider an electric sedan such as the Chevy Volt, which has a 16kWh battery and gets 5 miles/kWh, giving it a range of around 40 miles (the battery cannot be allowed to fully discharge to avoid ruining it). With a 120V/15A wall outlet supplying 1.4kW, full charge time is eight hours. Doubling the current to supply 3.3kW reduces the charging time to three hours. Now consider that the average residential load in Southern California is anywhere from .5kW to 1.4kW depending on the season and time of day. Adding electric vehicles to this load, even during off-peak times, would at least quadruple it. Vehicles with larger batteries will require even more powerful outlets to complete a charge in a reasonable amount of time. This will at least require a large increase in capacity, but an optimal system will take advantage of smart communication to make sure that all these cars aren't charging at the same time (Ipakchi and Albuyeh 56).

Electric vehicles will necessitate huge infrastructure investments outside of upgraded transmission networks. Commercial and industrial facilities and municipalities will all need to install electric charging stations in parking areas, most likely with credit-card readers. Battery technology needs to be improved to create lighter batteries with higher capacity which can charge faster (Grob 4). The potential benefits, though, are huge. Stationary vehicles would no longer waste energy. Imagine streets filled with quiet, nonpolluting electric vehicles rather than today's loud, smelly combustion engines. Cities would be much more peaceful and pleasant places to live.

Distributed Generation and Storage

Utilizing generation or electric storage capacity which is spread across the network makes sense from both reliability and national security perspectives. In order to enable this, the current one-way distribution system will need to be largely rethought.

Plug-in (hybrid) electric vehicles, if adopted en masse by consumers, will represent a massive source of distributed energy storage when plugged in. Electric vehicle batteries are designed to discharge quickly to provide high torque on the motor for acceleration, which makes them ideal to supply power for quick spikes of demand. Since these spikes often represent low total energy outlay, it is conceivable that EVs could someday remove the need to maintain spinning reserve capacity. This technology is sometimes known as Vehicle to Grid, or V2G. However, many of today's vehicles are not designed to provide this service, and careful studies will need to be made to determine what effect this charge cycling has on battery life (Ipakchi and Albuyeh 59).

Distributed generation will most likely come in the form of small rooftop solar installations or micro wind turbines. No fundamentally new technological advances are needed to connect these sources to the grid, but rather generation control needs to move from being centralized at utilities to distributed across the power network to make sure the correct amount of power is being produced to meet demand. As with advanced meters, two-way communication is needed between loads, distributed sources, substations, utilities, and transmission lines. Utilizing parameters such as the current loading of the network, capacity of power lines, weather forecasts, and competitive selling price, distributed generators will be able to coordinate with each other to supply enough electricity to meet the load (Pudjianto, Ramsay, and Strbac 12).

Islanding

When all these technologies are combined – distributed generation and storage, sophisticated distributed control systems, and advanced meters that keep loads and generators in constant communication and police demand – 'microgrids' or 'islands' may emerge that can take over from electric utilities should conventional generation and distribution experience a fault condition. An island will need to be able to physically disconnect and reconnect itself from the larger grid and perform all the functions that central utilities perform now, including voltage and frequency control (Vokony and Dan).

Public Policy and Investment

Three federal agencies are principally involved with smart grid development in the United States. The Department of Energy's Office of Electricity Delivery and Energy Reliability (DOE - OE) is responsible for the security of our electricity infrastructure and its modernization efforts. The National Institute of Standards and Technology (NIST) is responsible for coordinating the interfaces and standards necessary to make sure that different smart grid technologies can operate seamlessly with each other. Lastly, the Federal Energy Regulatory Commission (FERC) will manage the regulatory environment of the new grid.

Energy Independence and Security Act of 2007

The most important piece of legislation to address the Smart Grid was the Energy Independence and Security Act of 2007 (EISA). Its stated purpose was "to move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, and vehicles, to promote research on and deploy greenhouse gas capture and storage options, and to improve the energy performance of the Federal Government" (1). Title XIII of this act describes the characteristics of a smart grid:

1. increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid;
2. dynamic optimization of grid operations and resources, with full cyber-security;
3. deployment and integration of distributed resources and generation, including renewable resources;
4. development and incorporation of demand response, demand-side resources, and energy efficiency resources;
5. 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;
6. integration of "smart" appliances and consumer devices;
7. deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal storage air conditioning;
8. provision to consumers of timely information and control options;
9. development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid; and
10. identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services (293).

Among other things, Title XIII charges NIST with "the development of a framework that includes protocols and model standards for information management to achieve interoperability of smart grid devices and systems," requires utilities to consider smart grid systems before investing in "nonadvanced grid technologies," establishes a federal matching fund to match up to 20% of qualifying smart grid investments, and charges the DOE with producing a report that provides a "quantitative assessment and determination of the existing and potential impacts of the deployment of Smart Grid systems on improving the security of the Nation's electricity infrastructure and operating capability" (293-303).

Smart Grid Economic Stimulus Grants

In 2009, President Obama and DOE director Steven Chu announced the availability of $3.4 billion in grants through the Department of Energy to spur smart-grid investment. The grants were allocated as economic stimulus money under American Reinvestment and Recovery Act. Billed as "the largest single energy grid modernization investment in U.S. history," one hundred grants were awarded on October 27, 2009 (DOE Press Release).

Of the awards, $1 billion was allocated to projects to install smart meters, $2 billion to integration of different components of smart grids, $400 million to automation and monitoring of the current transmission and distribution networks, and $25 million to bolster companies which manufacture the products that will make up the smart grid. The press release touted the future installation of 40 million smart meters in American homes, 700 automated substations, 200,000 smart transformers which can detect their own impending failure, 850 'phasor measurement units' to provide visibility into grid conditions and pave the way for incorporation of large blocks of renewable generation, and a reduction in peak demand of 1400MW.

Smart Grid Pilot Projects

The concept of a smart grid has been discussed for at least a decade, but only now has the convergence of technology, policy, and demand occurred that is spurring investment into pilot projects to realize the goals of a more efficient, reliable, and secure electricity grid. These are mostly multi-year ventures which require a large amount of planning due to the paramount importance of keeping electricity service on at all costs. Most projects are still ongoing and do not yet have results, but their stated plans are promising, and after the recent disbursement of money provided by the stimulus grants, more are certain to come online soon.

The following sections discuss one small-scale study, results of which are already available, and outline the plans of a much larger project which is still ongoing.

GridWise Olympic Peninsula Project

The Pacific Northwest National Laboratory collaborated with IBM on the GridWise Olympic Peninsula project, funded mostly by the U.S. Department of Energy. The Olympic Peninsula in Washington state is an area of high-population growth, and it has already been projected that existing transmission capacity will not meet future demand there. The study set out to determine two things: whether distributed generation resources could take over from central generation to relieve a constrained feeder, and whether advanced metering with real-time pricing could encourage consumers to adjust space and water heating demand. Data was collected in 2006 and 2007 (Hammerstrom).

The assets managed by the project were five 40-horsepower water pumps, representing a 150kW load, two diesel generators, in 175kW and 600kW capacities which could be engaged through an automatic transfer switch to take a building off the grid entirely, a 30kW microturbine which operated in parallel with the grid, and smart meters communicating with electric water and space heaters which were installed in 112 residential homes.

In order to track the effects of utility pricing structure on demand response, the residential customers were divided into three pricing groups: fixed pricing, time-of-use pricing (the day is divided up into off-peak, peak, and critical-peak segments) and real-time pricing, with a granularity of five-minute intervals. There was a fourth control group. Homeowners were given financial incentive in the form of cash back proportional to how much money they saved by changing their energy usage habits to take advantage of the new pricing structure; the control group was simply given a constant cash award over the duration no matter how they used energy.

Using a convenient internet software interface, homeowners were able to choose settings for their devices in six settings from maximum economy to maximum comfort, which corresponded to different levels of variability in the desired temperature range, and thus different levels of tolerance for price control. All 112 subjects were able to set their thermostat preferences, but only those in the real-time pricing group were able to configure their water heaters.

The study found a number of interesting results. Residents in the real-time pricing group were more likely to tolerate variability in their thermostat settings than their water heater settings, although the report acknowledged that this could be due to a control glitch in the initial software that led many residents to choose the maximum comfort setting and not change it once the glitch was fixed. As for actual figures of energy savings, the report states that "the differences in mean energy consumption between the contract groups were small but measurable. Time-of-use contract members consumed less energy, on average. The real-time and fixed price contract groups used successively more energy. The variances of these measurements were large" (88).

Projected energy savings were highest for the time-of-use customers (30%) and close for real-time customers (27%) although the median savings for real-time customers was much higher than that of the time-of-use customers. This is probably due to the real-time customers who selected the most economical settings for their appliances.

The project was also able to achieve a shift in load shaping. Time-of-use pricing was most effective at reducing global residential load, but resulted in very abrupt usage shifts at the time boundaries when the price of energy changed. The real-time loads had the smoothest curves throughout the day, which could be expected due to the granularity of the pricing structure. However the real-time group also exhibited less change than the time-of-use pricing group. This is due to the fact that the real-time prices accurately reflected peak conditions, which happen sporadically through the day, unlike time-of use which designates the whole day as a peak condition (94, 99).

Overall, the project was successful at reducing congestion on the feeder during times of peak usage, and shifting commercial loads to auxiliary generators. But the results raise more questions than they answer. It is still unclear whether time-of-use or real-time pricing schemes will lead consumers to conserve more energy. Although we must keep in mind that the goal of the study was to see if congestion could be eliminated, not to get consumers to conserve energy across the board. The most important thing to remember about this study is that just because people are given tools to change their habits doesn't mean that they will. Price is a great motivator for behavior change, but a market-based approach to the problem will likely only lead to as much conservation as is necessary to keep the grid running smoothly.

Beach Cities MicroGrid

The Beach Cities MicroGrid Project is a three-year ongoing project sponsored by San Diego Gas and Electric to integrate many of the smart grid technologies discussed in this paper into the distribution network served by the Beach Cities substation, which serves approximately 20,000 residential, 1,200 commercial, and 3 industrial customers. The substation feeds into eight 12kV circuits which deliver a total of 49MW of power. Currently, there are 47 renewable power sources representing 186.4kW of generating capacity attached to the distribution network (Mohn).

One of the stated project goals are to achieve a 15% or higher reduction in feeder peak load. This will be enabled by the distribution of advanced metering devices to customers and a demand response program whereby smart appliances will shut off during periods of peak usage to save the grid from a fault condition. The project hopes also to spur heavy integration of distributed generation and storage through solar panel generators located at residential and business sites. Lastly, to improve the security and reliability of the grid, a technology called FAST (Feeder Automation System Technologies) will be implemented to allow the network to reconfigure itself in response to faults. New monitoring devices will allow outages to be detected by the utility as they happen, and customers on certain circuits may be intentionally islanded from the main supply to continue their service while the system recovers.

Although no equipment has yet been installed, the project has been in development for more than a year and looks extremely promising. In the future, this distribution network could serve as a model for other utilities looking to integrate Smart Grid technologies into their own systems ("The Smart Grid: An Introduction").

Conclusion

The most difficult part of understanding the need for a Smart Grid is realizing the problems and limitations of the current system and their historical context. Once this is accomplished, it becomes fairly obvious how it can and must be fixed. The grid needs more transparency at every level, two-way communication from generation all the way to load, and new methods of control which take the burden off the utility and allow customers to buy their own solar panels, wind-turbines and plug-in electric vehicles and connect them to the grid. Higher efficiency, reliability, and security will be achieved as byproducts of these measures. The internet, with its distributed intelligence and plug-and-play nature (any computer implementing the basic internet protocols can both access and serve websites) serves as the perfect model.

Not to say that the details aren't important. We will need engineers to develop the sophisticated distributed control algorithms which will enable this system, and to design the standards of interconnection and data transfer that will allow all these devices to communicate with one another. Economists will need to figure out how to best award incentives to consumers to moderate demand, and how to deal with both supply-side and demand-side resources which will bid to supply generation capacity. Policymakers will need to determine the regulatory structure of this new network and whether electricity can finally become a fully free-market commodity or whether some oversight is still needed. The technical hurdles, especially, of building such a massive system, are large. But again, consider the internet. It works remarkably well and reliably across the globe, and it sprang up organically, one new computer at a time. Certainly a planned system, with the internet as inspiration, can do at least as well.

Infrastructure development is not something the United States is always very good at, or proactive about. Many other countries are ahead of us in supporting renewables, emissions controls, electric vehicles, and smart grids. But there have been instances in history where we have come together to transform the country in a very short time, such as the development of the Interstate Highway System, or the building of the first national electricity grid.

It is time to stop talking about the smart grid and start implementing it. In that respect, this is a very exciting time to be involved in this industry. The grants which were awarded only months ago will spur development into all facets of the smart grid. I predict that by the end of the next decade, most people who receive electric service in this country will come into contact with at least one part of the smart grid. The benefits will not be immediate, but over time we will have a better electricity system, one that is efficient, clean, secure from attacks, and utterly reliable.

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