GridWise® Architecture Council

Environmental Benefits of Interoperability

The Road to Maximizing Smart Grid's Environmental Benefit

GRIDWISE®

Environmental Benefits of Interoperability

The Road to Maximizing Smart Grid's Environmental Benefit

September 2009

Prepared for
The GridWise® Architecture Council by E Source

This document was prepared under the sponsorship of the GridWise Architecture Council for the purpose of estimating environmental benefits that might accrue as a result of implementing interoperability in a smart electric grid. The focus of this paper was not on original research, but rather with the goal of identifying similar benefits experienced in other industries through a review of the existing literature. By publishing this document, the GridWise Architecture Council hopes to expand the understanding of potential benefits of interoperability in the electric power industry.

RIGHT TO DISTRIBUTE AND CREDIT NOTICE

DISCLAIMER

Contents

Figures

Tables

Section 1: Introduction

Information technologies are driving the evolution of today‘s electric grid into a digitally automated and multidirectional power supply system. Known as the smart grid, this integrated network of supply- and demand-side resources will enable two-way communication between electricity service providers and their customers while supporting distributed generation and storage. Smart grid promises greater reliability, security, and flexibility in the delivery of electricity. It furthermore represents a framework for the development of innovative products and services that can benefit both the economy and the environment.

This vision of a more ―intelligent" grid is largely founded on the concept of *interoperability*, a term that describes ―the capability of two or more networks, systems, devices, applications, or components to share and readily use information securely and effectively without inconvenience to the user."[1] Interoperation is a dynamic measure of communicative capacity and exists on the technical, informational, and organizational level. It can describe the physical interaction of devices (e.g., power plugs and USB ports) or effective data sharing within and among various business entities. When applied to the electricity sector, interoperability calls for the unobstructed connection of hardware and software to coordinate end-to-end energy flows with real-time data and analysis.[2]

An Example of Interoperability in the 21st Century

Because it exists on many levels, interoperability can be quite difficult to understand even though it pervades our everyday existence and is often found right beneath our fingertips. Take Apple's iPhone as an example.

- With regard to content, Apple encourages the development of innovative products and services by third parties. Programmers can design any application for this new mobile device, be it for bowling, Internet radio, or tracking your parked car.
- The iPhone can "plug and play" with both PCs and Macs. Coordination with multiple operating systems in this case promotes applicability across customer segments and increases general usability.
- The iPhone is not restricted by location and can connect to different networks. Using a common language or protocol, the device is able to communicate via multiple pathways for extended service and improved Internet access.
- Finally, interoperability here enables information exchange on the organizational level. Through web-based interfaces, consumers can engage businesses to buy or supply products and services.

The iPhone is a forward step in progress toward interoperability; however, there is still room for improvement. The design of innovative products or applications requires software owned by Apple, who ultimately controls what is made publicly available. Furthermore, consumers wishing to purchase the iPhone are limited by a licensed agreement with AT&T, so that the product itself is available only to subscribers of this particular service.

The focus of this report is to demonstrate the environmental benefits of smart-grid interoperability. Resource optimization, decreased emissions intensity, and carbon productivity are the primary conduits by which environmental benefits can be achieved. Resource optimization refers to the energy savings derived from smart-grid capabilities and includes enhanced efficiency, conservation, demand response, dynamic pricing, and voltage control. Smart grid allows the electricity supply chain to accommodate increasing demand while generating less electricity, resulting in greater efficiency throughout the system. Power that is produced regardless of enhanced efficiency will contribute fewer greenhouse gases (GHGs) as smart grid promotes the integration of distributed generation, renewable resources, and energy storage (or potentially all three in the form of plug-in electric hybrid vehicles [PHEVs]). Finally, carbon productivity describes the move from greater to less carbon-intensive activities and focuses, in this case, on operational and business processes facilitated by a smart grid.

Smart grid has become increasingly paramount in plans to address the electricity needs and environmental concerns of the 21st century. Its implementation depends on interoperability to create competitive economic conditions and expedite the commercialization of new ideas and technologies. Smart grid holds vast implications for the carbon-constrained world, yet much of its benefit and many of its applications are still unrealized in practice and may never be realized without interoperability. In general, existing literature provides initial estimates of potential energy and carbon savings attributable specifically to smart grid and its relevant technologies. This report leverages a growing knowledge base to draw an explicit connection between smart-grid interoperability and said environmental benefits.

Section 2: Resource Optimization

Resource optimization is founded on the principle of –doing more with less,” effectively meeting a customer‘s need with reduced energy use and supply. Smart grid supports this concept and provides environmental benefit through interrelated improvements in the delivery of electricity.

Energy Conservation

Advanced meters and energy displays comprise an integral component of smart grid and are boosting energy conservation through direct feedback. Such devices enable customers to view their energy consumption with near-real-time granularity. Current and historical energy use can be translated into cost projections and GHG emissions to provide alternative incentives for conservation. Electricity providers are showing increasing interest in the potential of direct feedback mechanisms. A 2006 pilot project conducted by Hydro One attributes 6.5 percent energy savings to the deployment of real-time, home energy monitors in Ontario, Canada.[3] An extensive review of feedback-related studies supports an energy-savings potential of 5 to 15 percent.[4]

Sharing of detailed, near-real-time energy usage is of course dependent on the interoperability of a service provider‘s communication network with a customer‘s information portal or interface. Usage data must be transmitted to a recipient display inside the home. Both devices in this case must speak with each other via a common communication pathway and abide by mutual specifications or language protocols. When meter data are first transferred back to the utility or a common server and then displayed via the Internet, interoperability is required for successful integration into various data systems as well as meaningful interpretation within web-based applications.

The Electric Power Research Institute (EPRI) recently released a comprehensive, first-order quantification of energy savings and carbon dioxide (CO_2) emissions reductions attributable to smart-grid implementation. EPRI‘s analysis projects that direct feedback could, in 2030, produce energy savings of 40 to 121 billion kilowatt-hours (kWh) and avoid roughly 22 to 68 million metric tons, or teragrams (Tg), of associated CO_2 emissions.[5] This estimate is based on a range of assumed market penetration with low and high bounds of 25 to 75 percent. Interoperability of feedback devices and communication networks will allow competitive market forces to guide the least-cost adoption of these technologies; such a framework will support higher achievable reductions within the reported range and thus maximize environmental benefits.

Energy Efficiency

Program innovation. The smart grid furthermore represents an opportunity for the expansion of end-use energy efficiency. Service providers can leverage the smart grid‘s interval metering capabilities and communications infrastructure to provide advanced efficiency products and services. On-line information portals and in-home displays not only provide detailed energy usage—they may also facilitate marketing of efficiency programs to customers with a demonstrated need. For instance, given a home‘s square-footage data (perhaps obtained from public property records), the electricity retailer could provide a function comparing the normalized energy use of that customer to the average consumption of his or her peers living in the same service territory. This knowledge would stimulate conservation while allowing service providers to more easily identify opportunities for saving energy. Localized advertisements embedded in energy-information portals (such as pop-up screens and integrated hyperlinks) could boost participation in efficiency programs or promote awareness of related rebates and incentives.

Interoperability again plays an important role in the exchange of information among service providers and their customers. Beyond just language and network compatibility, interoperable communication here implies both secure and facilitated data sharing. Automated networking of residential plug loads and appliances could be used to create an Internet-based profile that improves the specificity, reliability, and accessibility of a customer‘s energy consumption. The home area network (HAN) becomes a foundation for connecting devices—simplifying communication inside the home as well as with outside service providers. Xcel Energy is working with vendors to develop a “home energy manager” that links both HAN and smart meter capabilities so that appliance loads can be monitored and controlled in real time.[6] Such capability would enable greater end-use visibility and potentially allow electricity service providers to target a more definite efficiency need—be it an old refrigerator, a personal computer, a set-top box, or a newly purchased plasma-screen TV. Consumers can also “set and forget” their preferences in a web portal that automatically determines how connected loads respond to price or environmental signals. Feedback on the energy-use impact of these decisions can then be displayed through the customer‘s TV.[7] Interoperability is again requisite to the interconnection of devices in the HAN, communication of the HAN with the electricity service provider, and the final provision of feedback to the customer.

Smarter buildings. The concept of attaining improved efficiency through communications between customer and service provider shows applicability to the business sector in the form of continuous commissioning. Smart-grid infrastructure can facilitate the monitoring and maintenance of electrical equipment to ensure optimal performance and improve operational efficiency. Interoperability of a service provider‘s communication network and a customer‘s energy-management system could provide continuous updates on the energy demand of heating and cooling systems, large motors, electric chillers, and other building end uses. Such data could in the long term help service providers target retrofit programs—but even more compelling is the potential for direct and immediate assistance. With enhanced monitoring and detailed meter data, the service provider's diagnostic tools can signal to facility energy managers if and when equipment is not performing up to nameplate specifications.[8]

Recent analysis shows that today's commissioning efforts in large commercial buildings are able to produce overall energy savings of 15 percent and electricity savings of roughly 9 percent.[9] Based on this assumption and varying levels of market penetration in 2030, EPRI projects that continuous commissioning can provide potential energy savings of 2.2 to 8.8 billion kWh and help to avoid 1 to 5 Tg of CO_2 emissions.[10] The Climate Group, a nonprofit environmental consortium, has also performed an extensive study estimating the global carbon impact of information and communication technologies in 2020. The Climate Group identifies an analogous benefit, here dubbed *intelligent commissioning*, which has a projected abatement potential of approximately 100.8 Tg CO_2 equivalent when applied worldwide.[11]

In many ways, interoperability is the catalyst that drives carbon-saving potential to become real emissions reduction. Building energy-management systems require cooperative aggregation of energy-use data from distinct pieces of equipment and unrelated appliances. Automated monitoring throughout the facility must occur via standards that can include many technologies and dictate two-way communication with service providers and their various customers.

Evaluation of efficiency. Smart grid may advance energy efficiency through enhanced measurement and verification (M&V) capabilities. Advanced meters and interconnected systems for energy management, in the home or office, improve the visibility and accountability of energy savings that come as a direct result of improvements in efficiency. An interoperable smart grid would not only provide more granular energy-consumption data; it would also allow greater access to that information so that it does not sit unused in a service provider's billing system. With enhanced data acquisition and analysis, service providers could more closely observe the impact of their efficiency programs—they could fine-tune incentives or marketing and better align human resources to produce greater kWh savings at a lower price. As of now, M&V typically occurs on an annual basis or even longer, but monitoring impact on smaller time scales would make efficiency a more adaptable service. Greater automation of the evaluation process would decrease overall program costs, improve validation of program results, and more generally support increased investment in efficiency. By reducing uncertainty around the impact of efficiency programs, utilities can more readily encourage participation and seek out greater profits in a regulatory environment that rewards energy savings.

A recent study shows that the total achievable potential for energy efficiency in the United States ranges from 7 to 11 percent by 2030, resulting in an overall avoided energy consumption of 355 to 560 billion kWh.[12] Under this assumption, EPRI estimates that smart-grid–enabled M&V would push achievable efficiency potential closer to its maximum value and thus be directly responsible for potential energy savings of 10 to 41 billion kWh and avoiding an associated 6 to 23 Tg CO_2.[13] Interoperability of devices and communication networks within smart grid supports both direct and indirect benefits of energy efficiency: ―[T]he impact of energy efficiency on CO_2 emissions includes not only the load that it directly reduces, but also the new generation that it defers, buying time for incrementally cleaner and more efficient generation to come online."[14]

Demand Response

Demand response describes the ability of customers to shift or reduce their energy consumption in reaction to price signals or emergency conditions on the electric grid. Generally, demand-response programs fall into two categories based on these motivations—the first category is broadly referred to as *economic demand response* and the second is known as *reliability-based demand response*. Research shows that nationwide, the top 4,000 megawatts (MW) of load occurs for just 1 percent of the time annually and 2,000 MW of that load occurs for only 22 hours per year.[15] The ability of demand response to level off these sharp peaks in energy use has major implications for the cost and environmental impact of the electricity provided.

The environmental benefit of demand response is fundamentally achieved by offsetting emissions from peaking generation units and, over the long run, avoiding the construction of further peaking units. Even if employed selectively for short periods, demand reduction in response to signals of price or system stability still accumulates over time to give real energy savings. A recent analysis by the Brattle Group found that an overall 5 percent reduction in peak demand would avoid the need for 47,013 MW of electricity, or the equivalent of 625 natural gas combustion turbines and their associated emissions.[16] A meta-review of 100 demand-response programs supports energy savings of greater than 20 percent to less than 5 percent as measured in overall kWh consumption.[17]

Demand response holds further benefit in reducing pollutants with a time-dependent impact on the environment. Shifting generation and associated emissions from peak time to off-peak time may improve air quality, as certain pollutants are sensitive to sunlight and temperature. Dan Delurey, executive director of the Demand Response and Advanced Metering Coalition, testified that "time-based emissions (e.g., during hot summer afternoons) can lead to ozone non-attainment. In the case of nitrogen oxide (NO_x) and ozone, demand response holds out the potential to be a dynamic emissions tool that can be used to reduce power-plant emissions precisely when they contribute the most to non-attainment."[18] Emissions modeling related to demand response in New England supports this claim and shows potential summer reductions of 41 tons (0.18 percent) for NO_x, 218 tons (0.3 percent) for sulphur dioxide, and 31,800 tons (0.13 percent) for CO_2.[19] An interoperable smart grid has the potential to augment the afore-mentioned energy savings; however, the nature and extent of environmental benefit differs when considering the manner by which customers change or shift their energy consumption.

Dynamic pricing. A California pilot project testing various smart-grid–related technologies shows that greater interoperability improves the MW reduction capacity of dynamic pricing. In this experiment, residential participants were provided with advanced meters and select groups were given enabling technologies. These devices included smart thermostats and what is considered to be the most state-of-the-art technology available—a gateway system capable of controlling not just air-conditioning load but multiple appliances in response to critical peak pricing signals. Results show that baseline participants reduced demand by 13 percent in response to dynamic pricing signals. Customers with smart thermostats reduced their load by 27 percent, and those who had the gateway system reported a 43 percent reduction.[20] Thus, greater energy savings can be obtained when customers are not only informed of dynamic prices but also empowered to react automatically through enabling technology.

Interoperability is here required to coordinate the two-way flow of meter data and pricing signals so that service providers can accurately reward customers for an observed and verifiable response. As seen with the gateway system, greater interoperability provides greater load reduction through the inclusion of many appliances in this network-based conversation with the service provider. In the previous example, communication in response to pricing signals is mediated through a central energy-management system. Manufacturers may one day choose to install this price-responsive functionality in the appliance itself, allowing for energy management that is personalized to attributes of that specific equipment. Interoperability is key in ensuring that appliances of different brands will be able to communicate with the networks of various electricity providers. Speaking a common language in this manner will enable economies of scale and further progress the development of such appliances and relevant technologies.

Although dynamic pricing shows many benefits, its potential to reduce energy consumption is mixed and depends upon pricing specifications within the rate structure. Most dynamic rate structures charge more during peak demand and substantially less during off-peak conditions. Thus, even *if* customers use less energy overall, the net effect of load shifting on the environment depends on the electricity-generation profile of a given region. In one analysis, the more uniform daily load brought about by real-time pricing is seen as decreasing pollutant emissions in only 3 of the 10 Reliability Regions: Florida, Mid-Atlantic, and Mid-American. In these regions, much of peak demand is met by oil-fired capacity. The smoother load profile is seen as increasing emissions in most of the rest of the United States—especially the West, which uses more hydropower for peaking generation.[21]

Most analysts agree, however, that demand response improves environmental quality by minimizing the utilization of natural gas-powered peaking plants. Demand response furthermore promotes a parallel interest in energy efficiency and conservation and can help decrease the need for all generation, as well as transmission and distribution investments.[22]

Automated load control. A smart grid will enable advancement in the implementation, measurement, and reliability of demand response. Historically, demand-response programs have been limited by the behavioral component required to enlist and, in the case of large commercial or industrial customers, manually reduce load when called upon. A smart grid will streamline and automate this process from start to finish so that customer interaction can be minimized. Take for example the programmable communicating thermostat (PCT). This device represents an extension of smart grid into the customer‘s home—users can program their preferences so that their air-conditioning load can respond to information from electricity service providers with little to no inconvenience. Interoperability comes into play when considering the widespread applicability of such devices. PCTs may only prove cost-effective if they are able to communicate with different energy-management technologies and, moreover, different communication networks. Interaction here must exist using a common language or protocol and fundamentally requires an open standard that may govern this conversation.

Automated demand response, implemented on the commercial level, has shown substantial energy-saving potential. Programs assessed in California from 2006 to 2007 give a ratio of 65 kWh of savings per kilowatt (kW) of peak demand reduction. EPRI‘s analysis uses these findings to project, in 2030, potential energy savings of 0.0 to 3.7 billion kWh per year and an associated emissions reduction of 0 to 2 Tg CO_2.[23] This estimate exists in agreement with, or in the range of, existing data using proven technologies. An overview of all U.S. load-control programs in 2005 demonstrates that 1.01 billion kWh savings were achieved through a 10,359-MW reduction in peak demand.[24]

Another benefit of load control is being realized in the form of grid-responsive appliances. Although not yet commercialized, these devices are equipped with smart chips that detect when the grid‘s frequency falls below a specific level (59.95 hertz) indicating a mismatch between generation and load. If a frequency drop is recognized, then appliances automatically shed load, usually by shutting off heating or cooling elements. This concept was tested by the Pacific Northwest National Laboratory, which showed that grid-responsive water heaters and dryers could reduce load by 5 to 35 kW and 3 to 30 kW, respectively. Interoperability is here required on the technical level, where manufacturers must adopt a standard ―plug and play" capability so that appliances of all shapes and sizes can interact with and respond to the electric grid.

System Optimization

Greater efficiency in grid operations has direct environmental benefit in the form of reduced transmission and distribution (T&D) losses. Xcel Energy believes that a smart grid can achieve up to 30 percent reduction in distribution losses from optimal power-factor performance and system balancing.[25] Because T&D losses accounted for 239 megawatt-hours, or 5.9 percent, of net generation in the United States in 2005, even small reductions would allow system operators to reduce generation output and consequently reduce emissions.[26] In the case of Xcel Energy, a 20 percent decrease in T&D losses could cut CO_2 emissions by 500,000 tons annually.[27] Optimization of the electricity supply system thus holds substantial environmental benefit derived through various smart grid capabilities.

Cleaner ancillary services. Interoperability may allow more efficient provision of ancillary services, or the operational management of supply- and demand-side resources to maintain electric reliability.[28] Some of these services are generation resources, known as reserves, that are kept as backup to make sure that production and consumption are kept in balance. As stated by the New England Demand Response Initiative, ―responsive load can be as reliable and robust a resource as generation" for providing reserves.[29] In other words, customers who quickly reduce loads in a dependable manner can perform the same function as a quick-starting power plant, without supplying any electricity and creating emissions.

Interoperability within a smart grid is essential to the real-time coordination of ever fluctuating supply and demand. Information about imbalance must be quickly communicated to customer-sited resources so that service providers can trigger, verify, and regulate curtailments to provide the needed reserves.[30] Overall, enhanced visibility enabled by the communication of ongoing consumption data to both service provider and end user allows both parties to anticipate and accommodate greater load reductions.

Enhanced voltage regulation. To enforce the provision of safe and reliable electricity, distribution operators are currently required to maintain end-use voltage at 120 volts at 5 percent. Because voltage is directly related to power and the magnitude of line loss, distribution operators can save energy by operating within the lower part of this range. The smart grid thus enables automatic voltage adjustment in response to real-time measurement throughout the distribution system. This practice, commonly known as conservation voltage regulation (CVR), shows substantial energy savings potential. Initial studies by Snohomish Public Utility District (PUD) indicate that a 1 percent voltage reduction results in 0.336 to 1.103 percent energy savings, depending on the customer load types.[31] According to the PUD‘s Robert Fletcher, CVR allowed the district to deliver electricity at 117 volts—a 2.5 percent drop, which saved the average customer 350 to 400 kWh per year.[32]

Progress Energy Carolinas is pursuing voltage regulation as a means of decreasing power draw on the distribution system during periods of peak demand. The utility‘s program integrates regulators, sensors, and meters with nearby substations to drop voltage by almost 5 percent when the grid becomes critically overloaded, typically on the hottest summer afternoons.[33] Demand response courtesy of the distribution system itself is a key component of the program‘s smart-grid strategy and is expected to deliver 250 MW of capacity savings—the equivalent of two large peaking power units.[34]

Whatever the application, voltage reduction has the overall effect of decreasing energy consumption. This potential benefit is again dependent on the interoperability of devices that automatically measure and manage voltage across the electric grid. Each on its own is straight-forward; however, matching customer-sited measurements with voltage control at the substation level in real time requires an interoperable communications platform. Assuming that a 0.1 percent reduction in voltage yields a 0.8 percent reduction in load, EPRI projects that smart grid-enabled voltage reduction can reduce line losses and save 3.5 to 28.0 billion kWh per year in 2030, avoiding 2 to 16 Tg of CO_2.[35]

Outage abatement. Through enhanced monitoring and control of T&D systems, smart grid is expected to mitigate congestion and prevent transmission-related outages. By facilitating communication and data exchange within a complex network of supply- and demand-side resources, interoperability can help prevent environmental problems that often result from outages. Most directly, an interoperable smart grid will result in less utilization of highly emissive emergency generation often used during blackouts. Secondary benefits include avoiding environmental harm from blackout-related events in other infrastructures—such as spillage of wastewater from pumping stations that lose power or waste that results when facilities processing food, pharmaceuticals, and other goods lose power and must discard products. Interoperability is required for continuous monitoring of the grid—information from different points throughout the T&D infrastructure must be successfully aggregated and analyzed at a central management system. Enhanced data flow thus provides more accurate insight into the scope and location of outages, resulting in faster restoration and less environmental damage.

Section 3: Greener Energy

A smart grid not only allows electricity producers to meet demand while generating less electricity; it can also decrease the GHG intensity of the electricity provided. Currently, the electricity industry accounts for roughly 33 percent of total CO_2 emissions in the United States.[36] Intermittent renewable technologies, such as wind turbines and photovoltaics, show huge growth potential but are limited by the inherent variability of their output.[37] A smart grid can provide substantial reduction in emissions by facilitating large-scale integration of renewable and clean distributed technologies.

Enhanced Integration of Renewables

Forecasting and resource management. To provide reliable energy at the lowest possible cost, electric-system operators regulate generator output to match load changes and maintain system reliability. Because renewable generation has a low operating cost but is weather dependent, system operators are encouraged to use this resource when it becomes available and forced to use spinning reserves to protect against any sudden loss of generation.

Emissions resulting from these spinning reserves can be avoided through smart-grid–enabled integration of short-term weather forecasting and power-supply management. Here, interoperability is requisite in the communication of real-time meteorological data to operators who manage generator dispatch and system reliability. The devices and applications required to predict renewable energy output must transmit data from various locations and across different communication networks. Interoperability thus optimizes real-time coordination of renewable energy and its required backup generation. This capability will support a higher proliferation of renewable technologies as service providers can better predict and incorporate variable output and thus displace some backup generation and related infrastructure.

At the most sophisticated level, service providers could match near-real–time consumption data with intra-hourly forecasts of wind or solar resources. The application of time series analysis to low-cost sky image processing has allowed European scientists to forecast solar irradiation with a startling degree of accuracy.[38] If such information from these devices was made readily accessible, system operators could precisely quantify photovoltaic (PV) output across their entire service area on a minute-by-minute basis. In cases where predicted output cannot accommodate the concurrent load, service providers could then engage automated demand response (for example, via interactive thermostats or energy-management systems) or alternatively quick-starting generation units. Wind farms would also benefit from technologies that improve resource predictability and decrease the need for emissive backup generation (Figure 1). The International Energy Agency (IEA) confirms that ―the more precise the forecasting and modeling becomes, the smaller will be the error margin in forecasting [renewable] variability and the lower the requirements can become for operational reserves and balancing energy."[39]

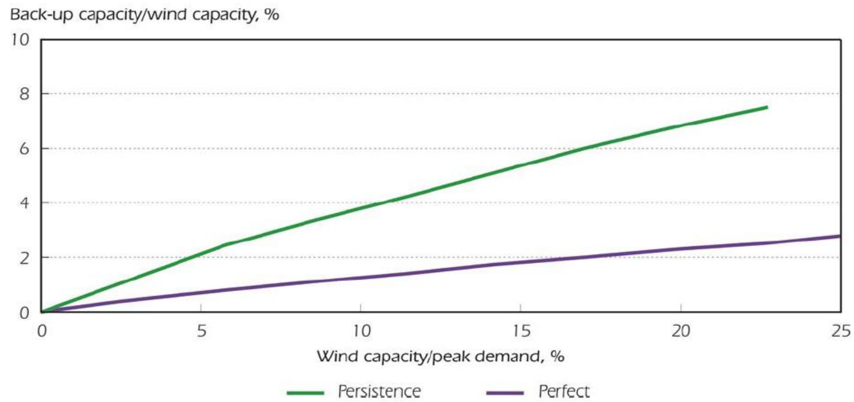

Figure 1. Improved forecasting decreases required operational reserves (Courtesy: NREL; first published in *Windpower Monthly*, December 2003)

As penetration levels increase, intermittent resources such as wind generally require additional backup capacity to maintain system stability. “Persistence” forecasting assumes no change in output over the following hour and “perfect” forecasting assumes an exact prediction of output at subhourly time intervals. Increased precision in forecasting results in lower required operational reserves and decreased backup capacity requirements.[40]

Grid connectivity. The IEA concedes, however, that “much of the value of improved forecasting depends on the flexibility of the electricity system in which an intermittent generator is embedded. Better short-term prediction will only translate into reduced costs if enough flexible technologies, possibly interconnected from another country, are available.”[41] In Europe, the interoperability of “micro” grids is minimizing the intermittence of renewable sources, allowing Denmark to generate 20 percent of its electricity from wind power. Interconnection to Swedish, Norwegian, and German grids allows the Danish to trade wind power on the spot market in times of excessive supply, thus greatly increasing its economic value.[42] If renewable generation cannot be used elsewhere at the time of production, it can be kept as reserve capacity in Norwegian pumped-storage hydro facilities. Storage of renewable output by hydropower, compressed air, or electric battery greatly increases the effective load-carrying capacity of renewable technologies so that they can reliably replace conventional generation and decrease the overall emissions intensity of the grid. In this manner, interoperability of information shared with neighboring grids permits a wider distribution and hence higher proliferation of renewable energy resources while improving the reliability of the greater system.

Dynamic line rating. Smart grid has the potential to optimize the loading of transmission lines and consequently increase their overall capacity. Currently, power lines have a static thermal rating—a limit on how much current can be carried while maintaining a required level of clearance from the ground. Because of resistance in the conductor, an increase in current will heat the line and cause it to elongate and sag. Thus, for purposes of safety and reliability, a rating is calculated to determine how much power a line can handle in worst-case conditions. These conditions naturally apply to external variables affecting the temperature of the conductor—namely solar exposure, wind speed and direction, and ambient temperature. Even though most transmission lines have a static rating that assumes extremely hot temperatures, maximum solar irradiation, and low wind speed, their actual capacity fluctuates in real time and is typically much higher than their rating allows (Figure 2).

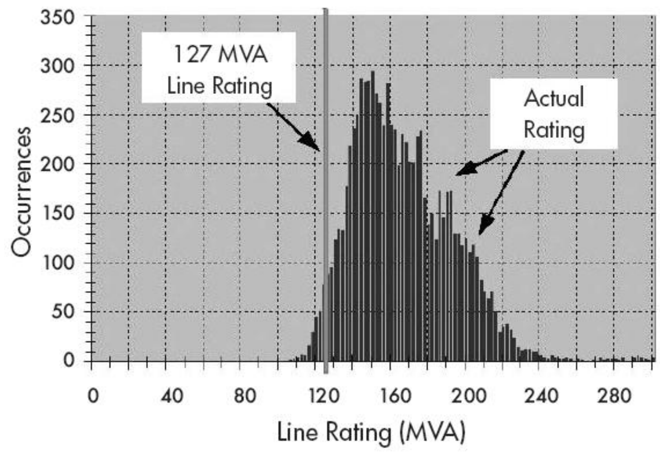

Figure 2. Actual line ratings over a summer month (Courtesy: *North American Windpower*)

Occurrences of real-time line rating show actual values that are higher than their required 127 megavolt-amp limit most of the time. This observation equates to wasted transmission capacity and lower efficiency across the grid.[43]

A smart grid could provide dynamic line ratings with the installation of simple weather-measurement devices at key points throughout the transmission and distribution system. As with the forecasting methods used to predict renewable output, interoperability is here required to successfully exchange this data across different communication systems. Furthermore, these devices must provide information with real-time granularity so that system operators can know exactly how much power to put across a given line. Thus, interoperability applies to the application, communication, and integration of data required to determine the actual capacity of a transmission or distribution line at any point in time. Simplifying the connection of these measurement devices and the integration of this information can bring costs down to justify their installation and deliver benefits to system operators who must balance supply from various resources on a minute-by-minute basis.

This concept was tested by San Diego Gas & Electric, which transmitted data regarding conductor tension and environmental factors to its energy-management system over a radio communications network. With real-time ratings, the transmission lines monitored in this study had 40 to 80 percent more power-transfer capacity than their static counterparts.[44] The real environmental benefit of this smart-grid functionality lies in the improved utilization of renewable resources. Often, system operators are forced to curtail output from wind farms at peak generation because of capacity limitations in the connected transmission lines. Of course, high winds not only produce more energy; they also cool the transmission lines serving that electricity. Upon implementation of dynamic transmission monitoring, Xcel Energy realized that actual line rating exceeded the static rating more than 96 percent of the time. Utilizing this previously unrealized capacity allowed Xcel to avoid 10 to 20 instances of wind curtailment per month.[45] Overall, interoperable rating systems allow system operators to accommodate more renewable energy over existing transmission lines. This capability decreases the need for new transmission infrastructure, saves energy that would be produced through traditional generation, and decreases emissions by supporting renewable resources.

Facilitated access to green power. In the same way that information technologies can boost participation in and awareness of programs for energy efficiency and conservation, smart grid may facilitate consumer access to energy from renewable resources. A typical system operator knows how much renewable energy is presently on the grid, but communication systems and web-based applications could make this information available to consumers as well. Interoperability at the organizational level could result in a new renewable energy notification service that may potentially affect customer behavior and reduce emissions. By knowing the current source of electricity—be it primarily coal or wind—customers may choose to adjust their consumption according to their environmental preference. At the most sophisticated level, service providers could calculate their overall emissions factor (pounds of CO_2 equivalent/kWh) in real time and provide that information to end users. The environmental benefit exists here in the possibility that consumers may use less energy during periods of high emissions and use more when the proportion of renewables is higher.

Support of Distributed Generation

Finally, an intelligent grid could provide the informational infrastructure needed to decentralize energy production throughout the United States. The national average for T&D losses is approximately 5.9 percent of total electric generation and can be nearly twice as much during hot, summer peak conditions.[46] Distributed generation integrated into the system with clearly defined, interoperable interfaces can significantly reduce T&D losses by supplying electricity at or near the site of consumption. Local energy supply can displace substantial generation from remote plants if employed during summer peaks when resistive losses and system congestion are greatest. Assuming that a distributed resource produces roughly the same emissions per kW as a large power plant, electrical demand can be satisfied using less fuel—due to less line loss—thus decreasing impact on the environment.

Enhancing renewables through distribution. Emission reductions are greater when the distributed generator is powered by renewable resources such as solar panels, small wind turbines, or biogas combustion. Pacific Gas and Electric found that replacing remote generation with a 500-kW PV array eight miles downstream of its targeted substation resulted in a total loss reduction of 300 kWh/kW over an entire year. Greater end-use proximity minimized losses at the feeder circuit, transformer, and transmission level and thus improved the efficiency of each PV kW by roughly 3.4 percent. Overall, avoided T&D losses compounded to give a

1.12 multiplier for avoided generating capacity. Studies performed by the Los Angeles Department of Water and Power offer a rule of thumb that “[i]n general, for every [one] percent displacement of remote system supply by [distributed] output, there will be roughly a 2-percent drop of losses associated with the load downstream of the interconnection point for the [distributed resource].”[47] Distribution of renewable sources also decreases the variability of output as localized weather conditions do not necessarily affect multiple generators dispersed over a large area (Figure 3). Geographical dispersion in this case levels out extreme fluctuations in generation and allows for higher penetration levels of intermittent renewable technologies.

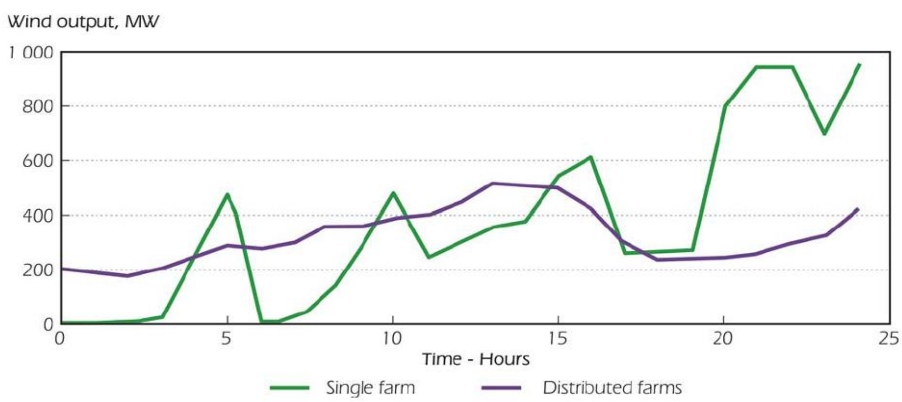

Figure 3. Geographical dispersion of wind farms levels overall output (Source: CEC Brussels, graphic provided courtesy of the International Energy Agency, 2005)

Geographical dispersion has a smoothing effect on overall wind output, as seen in the compared output of a single wind farm and distributed wind farms, both rated at 1,000 megawatts.[48]

Distributed generators that are interoperable with remote system supply offer a highly efficient means of energy production. An intelligent grid will provide the real-time functionality needed to manage many generating units over large service areas and coordinate fluctuating supply and demand. Interoperability can enable the collaborative use of generation, storage, and inter-grid communication technologies to provide reliable energy while protecting the environment.

Peak load reduction. Renewable energy technologies and distributed resources offer even more pronounced environmental benefit if they are able to provide electricity when it is needed most. The generation required to meet peak demand in the United States produces on average 26 percent more carbon per kWh than overall output in a given year.[49] Large-scale integration of intermittent renewables, namely PVs and solar thermal, as well as clean distributed generators, can minimize emissions associated specifically with peak load generation. A Southern California Edison case study shows that peak generation requirements for commercial buildings can be reduced by approximately 31.5 percent with a 50-percent PV penetration level.[50] However, interoperability is again required to accommodate a large PV supply as system operators must have near-real–time information to accurately coordinate the dispatch of spinning reserves when renewable generation falters.

The Future of Green Energy

The emission-reduction capabilities of renewable technologies apply at any time, not just during peak demand. Dependence on such resources is growing, due to efforts aimed at mitigating climate change. The U.S. Energy Information Administration estimates that by 2030 the United States will see the addition of 55 gigawatts (GW) of renewable-generation capacity.[51] EPRI's Prism analysis tops this projection with an estimated addition of 100 GW of renewable capacity by the same date, simply through compliance with existing renewable portfolio standards.[52] These levels of renewable penetration are made possible through the previously discussed attributes of smart grid. Increased interoperability will maximize the smart grid's impact on resolving the issue of renewable intermittency. This effect, when applied to wind energy alone—the fastest growing and largest contributor to additional capacity in 2030—can be attributed with the addition of 33.4 to 66.8 billion kWh from wind resources and an associated emissions reduction of 18.7 to 37.7 Tg of CO_2.[53]

Section 4: Carbon Productivity

Carbon productivity, also dubbed *dematerialization*, refers to the ―substitution of high carbon products and activities with low carbon alternatives, e.g. replacing face-to-face meetings with video conferencing, or paper with e-billing."[54] This concept applies to business processes across various industries, but has environmental benefits specific to the implementation of smart grid and concurrent attainment of interoperability.

Advanced Meters

With deployment of advanced metering infrastructure (AMI), remote monitoring and control of customer meters can replace vehicle trips previously needed for several areas of utility operations. This capability reduces vehicle miles traveled and associated emissions. PECO Energy employed automated meter reading (AMR) to remotely read meters, virtually connect and disconnect new customers to a home's electricity service, examine a customer's daily usage records to settle high-bill complaints over the phone, and address observed outages. Although its system did not support two-way communication with the customer, the resulting improvements in operational efficiency saved the utility more than 400,000 gallons of gasoline and over 7.7 million pounds of CO_2 per year, as seen in Table 1.[55]

Table 1. PECO Energy's reduction in annual vehicle miles traveled and gasoline consumed per year through implementation of automated meter reading.

Utility Operation	Vehicle Miles Saved Per Year	Gallons of Gasoline Saved Per Year	Pounds of CO_2 Saved Per Year[(a)]
Meter reading	5,200,000	273,684	5,309,470
Virtual service connections and disconnects	1,500,000	100,000	1,940,000
High-bill investigation	400,000	26,667	517,340
Outage management	Not known: >0	Not known: >0	Not known: >0
Total	**>7,100,000**	**>400,351**	**>7,766,810**

© E SOURCE; data from PECO Energy.
(a) According to the U.S. Environmental Protection Agency, burning of one gallon of gasoline produces 19.4 pounds of CO_2.

Interoperability is required here to achieve the carbon productivity of system operations enabled by AMR and even more so by smart grid's advanced metering capabilities. By definition, AMI is a ―comprehensive, integrated collection of devices, networks, computer systems, protocols, and organizational processes" intended to provide an unobstructed, two-way flow of information between service provider and customer.[56] To become economically viable, remote monitoring and *control* of said meters depends on the holistic cooperation of back-office systems, such as customer billing and distribution management.[57] For instance, remote connection and disconnection of a customer‘s meter is optimally useful if such information is relayed to a service provider‘s billing, outage management, and field service teams. Environmental benefits are thus maximized by the dissemination of information throughout system operations and processes.

Electronic Billing and Other Forms of Carbon Productivity

A smart grid contributes many capabilities of direct environmental benefit; however, improving the information and communication infrastructure available to this sector has positive side effects as well. For instance, electronic billing—as enabled by interoperability of metering, communication, and billing systems—brings several environmental benefits associated with paper production and mailing. These benefits include saving trees, fuel, and solid waste and reducing emissions of GHGs and wastewater. According to a calculator incorporating assumptions from the U.S. Postal Service, the U.S. Environmental Protection Agency, and environmental groups, a household that switches to electronic billing for two statements per month (such as electricity and gas) can do the following every year:[58]

- Save 0.7 pounds of paper
- Avoid producing 30 pounds of GHG emissions
- Avoid release of 7 gallons of wastewater into the environment
- Avoid use of 1 gallon of gasoline to mail bills, statements, and payments.

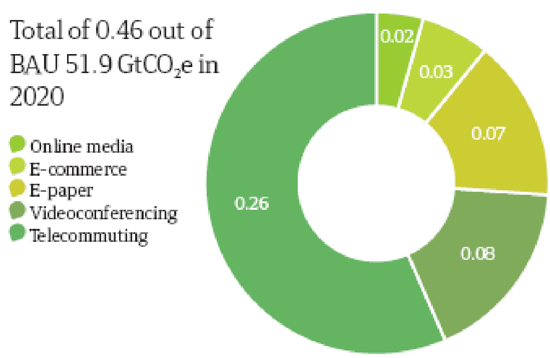

Figure 4. The global impact of carbon productivity (Source: The Climate Group, ―SMART 2020: Enabling the low carbon economy in the information age," 2008)

When multiplied by roughly 116 million U.S. households,[59] electronic billing can save the energy industry 81.2 million pounds of paper, 116 million gallons of gasoline, 812 million gallons of wastewater, and a cumulative 1.6 million metric tons of GHG emissions in a single year. It becomes apparent that the impact of carbon productivity is no trivial matter and contributes to substantial global emission reductions when applied not just to energy but across many industries (Figure 4).[60]

The application of information and communication technologies within the energy sector allows electricity providers to employ less carbon-intensive activities. E-paper accounts for roughly 15 percent of carbon productivity‘s global abatement potential—460 teragrams of CO_2 equivalent in 2020.

Section 5: Plug-in Hybrid Electric Vehicles

PHEVs have the potential to significantly reduce systemwide GHG emissions by relying on grid-provided electricity as opposed to liquid fossil fuels. Depending on the methodology and region under consideration, PHEVs powered by coal-based electricity could result in a 30 to 75 percent emissions reduction when compared to conventional automobiles.[61] The environmental benefit of electrified transportation is, however, skewed as service providers will have to accommodate increased demand with greater capacity (Figure 5).[62] Fleet charging, at a market penetration of approximately 50 percent, will require additional energy supply equal to roughly 10 to 20 percent of current electricity generation.[63] A 30 percent penetration of PHEVs by 2020 could decrease transportation-associated emissions by 22 million metric tons while increasing the carbon impact of the electricity sector by 6 million metric tons.[64]

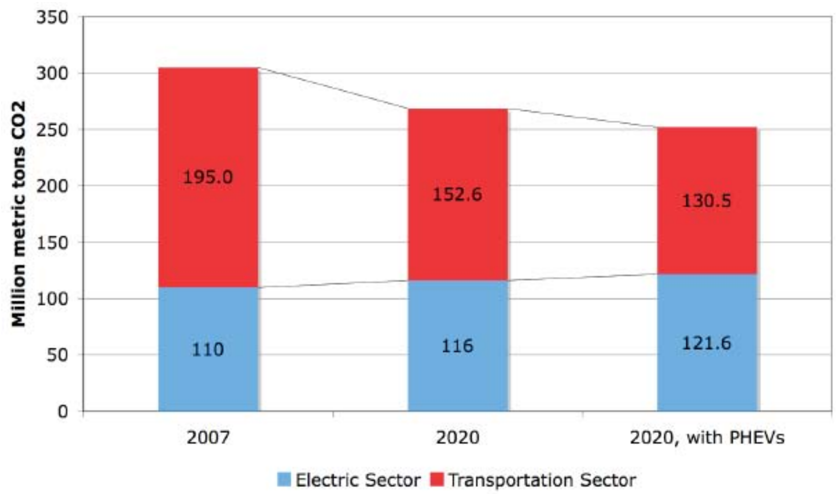

Figure 5. The sector-specific impact of PHEVs on greenhouse gas emissions (Provided courtesy of the Rocky Mountain Institute, 2008)

Demand associated with greater PHEV penetration will require electricity providers to increase their overall capacity and their concurrent carbon emissions. The net effect is positive, however, as total emissions are reduced by 16.5 million metric tons with a 30 percent PHEV market penetration in 2020.

Interoperability is a crucial ingredient in smart grid's ability to support PHEVs and capitalize on their environmental benefit. Vehicle-to-grid (V2G) capabilities promote the bidirectional flow of electricity and information, thus enabling a new source of highly responsive storage and distributed generation. Smart-grid infrastructure will allow service providers to coordinate the charging and discharging of PHEVs relative to concurrent strain on the system. When applied on the scale of millions, an electric fleet could represent a virtual power plant with almost instantaneous startup capabilities. PHEVs viewed in this light can provide ancillary services to the electric grid—withdrawal of electricity can occur automatically to fill gaps in generation-to-load frequency regulation. Besides offering real-time system balancing, electric vehicles can supply electricity in event of a power station or transmission failure and effectively displace emergency backup generation from conventional power plants.[65]

PHEVs utilized in a smart-grid environment may also increase renewable capacity factors and allow for higher penetration levels of these clean technologies. Most of these vehicles will be plugged in at night and supplied by idle, off-peak generation. Nighttime charging could support intermittent wind resources as many regions experience maximum output during these hours.[66] If service providers are able to communicate to electric vehicles so that they charge only when wind energy is available, then PHEVs could minimize the variability of that resource through flexible energy storage. A similar concept applies to photovoltaics in that cars parked in a smart garage could store solar energy and essentially level out its intermittency. Interoperability of electric vehicles with smart buildings would in this case enable enhanced integration of renewable energy technologies and perhaps provide a transportation infrastructure powered entirely by clean energy.

A research project by the Natural Resources Defense Council and EPRI developed several models that assess the projected impact of PHEVs in the year 2050. Three scenarios were reported assuming low, medium, and high adoption rates for PHEVs as well as decreasing levels of carbon-intensity associated with electricity generation (due to differences in the resource mix across the United States). These scenarios resulted in nine potential CO_2 impact results from PHEV adoption, depicted in Table 2.[67] An interoperable smart grid would allow for a higher penetration level of PHEVs as well as renewable energy technologies. This integration would decrease the carbon intensity of the electric grid and would thus permit a best-case emissions reduction of 612 million metric tons.

Table 2. Projected annual greenhouse gas emissions reductions from plug-in hybrid electric vehicles in the year 2050 (Provided courtesy of the Electric Power Research Institue, July 2007.)

2050 Annual GHG Reduction (million metric tons)		Electric Sector CO_2 Intensity		
		High	Medium	Low
PHEV Fleet Penetration	Low	163	177	193
	Medium	394	468	478
	High	474	517	612

Interoperability is an underlying necessity in achieving V2G capability. The need for unobstructed communication stems, in this case, from the PHEV's inherent mobility and diverse functionality. On the technical level, the vehicle itself must be able to be integrated into the electric system in different territories and states to appeal to the increasingly itinerant consumer. On the informational level, PHEVs of different manufactured origin must speak a common language with electricity providers regardless of the communication platform they chose to employ. Thus, regardless of location, electricity providers could interact with these vehicles to engage potential ancillary services or store renewable energy during instances of surplus output. Coordinating a fleet of millions in this manner is only possible with a fully automated and integrated electric infrastructure. Organizational interoperability will be required to support new products and transactions as well as innovative business models. With interoperability, electric vehicles can become more than just cars—they can store renewable energy, support grid stability, and ultimately provide mobility without damaging the environment.

Section 6: Interoperability in a Carbon Constrained World

Interoperability may facilitate the automatic communication of real-time consumption (and production) data to organizations regulating GHG emissions. Enhanced information flow coupled with greater visibility of supply and demand processes could support the establishment of economic regimes that discourage contributions to climate change, such as carbon trading and white tags. An interconnected, intelligent grid could give corporations operating in multiple service areas a more precise and dynamic view of their energy consumption and associated carbon footprint. As of now, companies wanting to inventory their GHGs must collect electric bill data for each individual facility and multiply reported energy use by the average emissions factor for that state. This process can often take months and must be verified by a third party to ensure accuracy. Intelligent-grid technologies, however, would provide businesses with consumption data at near-real-time intervals and could calculate the associated GHGs using an exact emissions factor for that specific electricity service provider.

With greater interoperability and more sophisticated information resources, a regulatory body could more accurately assign carbon credits or permits. Smart grid could set the stage for a dynamic carbon market in which trading is based on the actual and automatically verifiable performance, or GHG reduction, of various companies. Power producers could access data demonstrating the overall effectiveness and environmental benefits of projects pertaining to energy efficiency and demand response. Interoperability would in this case not only allow service providers to target and develop better efficiency programs, but it would also provide the data needed to verify emissions reductions and reward incentives as determined by the regulatory market. Improved precision and flexibility of market mechanisms within the energy industry would provide substantial environmental benefits by incentivizing more efficient corporations and industrial processes.

Smart grid has compelling potential to change the very way we buy, sell, and use energy. Interoperability plays a role in every step of this equation and, if adopted in full, it will guide the development of more interactive and adaptive products and services. Enhanced communication on the technical, informational, and organizational level sets the stage for new opportunities in energy efficiency and green energy. Within a smart grid, customers may no longer be enlisted in programs limited by administrative and verification processes. Instead, they may choose efficiency services advertised according to their identified needs. With full automation of backend processes, consumers can request an air-conditioning tune-up as easily as they can buy a song on iTunes. Interoperability may enhance information flow to create a true connection between customer preferences and a power provider‘s generation portfolio. The environmental benefits of smart grid begin with the simple interaction of devices, they are multiplied through operation across communication networks, and they reach their full potential in the interconnection of entire grid systems. These interactions and the services they may entail are governed by both economic and environmental considerations. Interoperability represents a road, a path of development, through which these two forces can be aligned to bring greater benefit to society.

Section 7: Notes

1. GridWise Architectural Council, ―EICTA Interoperability White Paper" (European Industry Association, Information Systems Communication Technologies Consumer Electronics, June 21, 2004).
2. Gridwise Architecture Council Policy Team, ―Introduction to Interoperability and Decision-Maker's Interoperability Checklist v 1.0" (Gridwise, April 2007).
3. ―The Impact of Real-Time Feedback on Residential Electricity Consumption: The Hydro One Pilot," http://tinyurl.com/5q4w3u; www.reducemyenergy.com/PDF/Summary%20Results%20Hydro%20One%20Pilot%20-%20Real-Time%20Feedback.pdf (accessed April 2009).
4. Sarah Darby, ―The Effectiveness of Feedback on Energy Consumption: A Review of DEFRA of the Literature on Metering, Billing, and Direct Displays" (Environmental Change Institute, University of Oxford, UK: April 2006).
5. EPRI, ―The Green Grid: Energy Savings and Carbon Emissions Reductions Enabled by a Smart Grid," EPRI 1016905 (2008).
6. Thor Bjork, Paul Nagel, and John Laun, ―Even Couch Potatoes Can Save Energy with Dreamy Advanced Meters," presentation at the Association of Energy Service Professionals 19th National Energy Services Conference & Expo (2009).
7. Thor Bjork et al. [6].
8. EPRI [5].
9. Evan Mills, Hannah Friedman, Tehesia Powell, Norman Bourassa, David Claridge, Tudi Haasl, and Mary Ann Piette, *The Cost-Effectiveness of Commercial-Buildings Commissioning: A Meta-Analysis of Energy and Non-Energy Impacts in Existing Buildings and New Construction in the United States* (Lawrence Berkeley National Laboratory, December 2004).
10. EPRI [5].
11. The Climate Group, ―SMART 2020: Enabling the Low Carbon Economy in the Information Age" (The Climate Group, 2008).
12. EPRI and Edison Electric Institute, ―Energy Efficiency: How Much Can We Count On?" presented at Edison Foundation Conference, ―Keeping the Lights On, Our National Challenge" (April 21, 2008), www.edisonfoundation.net/events/2008-04-21/EPRIPresentation.pdf.
13. EPRI [5].
14. David Nemtzow, Nemtzow & Associates, and Omar Siddiqui, EPRI, ―Giving Credit Where Credit Is Due: Energy Efficiency in CO_2 Emissions Trading," 2008 ACEEE Summer Study on Energy Efficiency in Buildings (2008).
15. Robert Pike, Demand Response Product Manager, ―Market Based Opportunities for Demand Response," *NYISO Proceedings of ―The Future Is Now: Energy Efficiency, Demand Response and Advanced Metering NYISO Symposium"* (June 27, 2007), www.nyiso.com/public/webdocs/products/demand_response/general_info/nyiso_symposium06272007_final.pdf.
16. The Brattle Group, ―The Power of Five Percent: How Dynamic Pricing Can Save $35 Billion in Electricity Costs" (May 16, 2007).
17. David Nemtzow, Dan Delurey, and Chris King, ―The Green Effect: How Demand Response Programs Contribute to Energy Efficiency and Environmental Quality," *Public Utilities Fortnightly* (March 2007).

18. Dan Delurey, ―Testimony of Dan Delurey Executive Director Demand Response and Advanced Metering Coalition (DRAM) Before the Senate Finance Committee—Energy, Natural Resources and Infrastructure Subcommittee" (May 2007).
19. ―Modeling Demand Response and Air Emissions in New England," prepared for the U.S. Environmental Protection Agency by Geoff Keith, Bruce Biewald, David White, and Mike Drunsic, Synapse Energy Economics (revised September 4, 2003).
20. The Brattle Group [16].
21. Stephen P. Holland and Erin T. Mansur, ―Is Real-Time Pricing Green? The Environmental Impacts of Electricity Demand Variance" (National Bureau of Economic Research, Working Paper 13508, October 2007), www.nber.org/papers/w13508.
22. David Nemtzow, Dan Delurey, and Chris King, ―The Green Effect: How Demand Response Programs Contribute to Energy Efficiency and Environmental Quality," *Public Utilities Fortnightly* (March 2007).
23. EPRI [5].
24. U.S. Department of Energy, Energy Information Administration, ―Table 9.4: Demand-Side Management Program Annual Effects by Sector, 1994 through 2005," *Electric Power Annual 2005* (2006).
25. Xcel Energy, ―Xcel Energy Smart Grid—A White Paper" (2008).
26. EPRI [5].
27. ―Xcel Energy SmartGridCity—Benefits Hypothesis Summary," *Utility Innovations* (2008).
28. Eric Hirst and Brendan Kirby, ―Ancillary Services" (Oak Ridge National Laboratory).
29. Brendan Kirby and Eric Hirst (February 10, 2002), ―Technical Issues Related to Retail-Load Provision of Ancillary Services," www.raponline.org/Pubs/NEDRI/AncillaryBackground.pdf.
30. Brendan Kirby and Eric Hirst [29].
31. T.L. Wilson, ―Energy Conservation with Voltage Reduction—Fact or Fantasy," presented at the IEEE Rural Electric Power Conference (2002).
32. Wendy Kaufman, ―Utility‘s ‗Voltage Reduction‘ Plan Saves Energy," *NPR Morning Edition* (February 28, 2006).
33. South Carolina Energy Office, ―S.C. Utility Demand-Side Management and System Overview 2006," www.progress-energy.com/aboutus/news/article.asp?id=18462 (accessed April 2009).
34. Progress Energy, ―Progress Energy Carolinas Files Programs to Reduce and Shift Peak Demand," Press Release (April 29 2008), www.progress-energy.com/aboutus/news/article.asp?id=18462.
35. EPRI [5].
36. P.R. Barnes, J.W. Vandyke, F.M. Tesche, and H.W. Zaininger, *The Integration of Renewable Energy Sources into Electric Power Distribution Systems: National Assessment* (Oak Ridge National Laboratory, 1994).
37. U.S. Energy Information Administration, *Annual Energy Outlook 2008 with Projections to 2030,* www.eia.doe.gov/oiaf/aeo/electricity.html (accessed April 2009).
38. J.C. Nova, J.B. Cunha, and P.B. Moura Oliveira, ―Solar Irradiation Forecast Model Using Time Series Analysis and Sky Images," *EFITA/WCCA* (2005).
39. Timur Gul and Till Stenzel, ―The Variability of Wind Power and Other Renewables" (The International Energy Agency, 2005).

40. David Milborrow, ―Forecasting for Scheduled Delivery,” *Windpower Monthly* (December 2003).
41. Gul and Stenzel [39].
42. Gul and Stenzel [39].
43. Dan Lawry and Burnie Fitzgerald, ―Finding Hidden Capacity in Transmission Lines,” *North American Windpower* (April 2007).
44. William Torre, ―Dynamic Circuit Thermal Line Rating” (California Energy Commission-PIER Strategic Energy Research, October 1999).
45. Pam Oreschnick, ―Dynamic Rating Allows More Wind Generation,” *Transmission & Distribution World* (November 2007).
46. Amory Lovins, ―Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size” (Rocky Mountain Institute, 2002).
47. Lovins [45].
48. J.S. Holt, D.J. Milborrow, and A. Thorpe, ―1990 Assessment of the Impact of Wind Energy on the CEGB system” (CEC Brussels).
49. U.S. Environmental Protection Agency, ―eGrid2006 NERC Region Emission Rates,” www.epa.gov/cleanenergy/documents/egridzips/eGRID2006V2_1_Summary_Tables.pdf (accessed April 2009).
50. H.W. Zaininger, P.R. Ellis, and J.C. Schaefer, *The Integration of Renewable Energy Sources into Electric Power Distribution Systems: Utility Case Studies* (Oak Ridge National Laboratory, 1994).
51. U.S. Energy Information Administration (EIA), ―Annual Energy Outlook” (EIA, 2008).
52. EPRI, ―The Power to Reduce CO_2 Emissions: The Full Portfolio,” EPRI (2008).
53. EPRI [5].
54. The Climate Group [11].
55. Dave Glenwright (September 2008), Manager, Meter Reading Operations & Strategy, PECO Energy, 215-841-6174, david.glenwright@exeloncorp.com.
56. Open Smart Grid Users Group (August 4, 2006), ―Utility AMI: High-Level Requirements,” www.utilityami.org/docs/UtilityAMI%20High-Level%20Requirements%20v2-7%20Approved.pdf.
57. Collaborative Two-Part AMI Programs for Demand Response and Energy Efficiency (22).
58. PayItGreen, ―Alliance Green Calculator,” www.payitgreen.org/green-calculator.html (accessed April 2009).
59. U.S. Census Bureau, ―Families and Living Arrangements,” www.census.gov/population/www/socdemo/hh-fam.html (accessed April 2009).
60. The Climate Group [11].
61. Cameron M. Burns, ―Guiding the Next Big Energy Solution: Vehicle to Grid,” *RMI Solutions Journal* (2008).
62. J. Swisher, L. Hansen, N. Mims, and Z. Taylor, ―Plug-In Hybrid Electric Vehicles and Environmentally Beneficial Load Building: Implications on California‘s Revenue Adjustment Mechanism” (Rocky Mountain Institute, 2008).
63. P. Denholm and W. Short, *An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-In Hybrid Electric Vehicles*, Technical Report NREL/TP-620-40293 (National Renewable Energy Laboratory, 2006).

64. M. Duvall, *Environmental and Electric-Sector Assessment of Plug-In Hybrid Electric Vehicles: Greenhouse Gas Emissions* (Electric Power Research Institute, 2006).
65. Swisher et al. [61].
66. Burns [60].
67. EPRI, ―Environmental Assessment of Plug-In Hybrid Electric Vehicles. Volume 1: Nationwide Greenhouse Gas Emissions," EPRI 1015325 (2007).