FUTURE GRID

Public Report on the Future Grid

PSERC

Researchers Explore Re-engineering the Electric Grid to Enable Renewable Energy Systems

ABOUT PSERC

Started in 1996 as a National Science Foundation Industry-University Cooperative Research Center, the Power Systems Engineering Research Center (PSERC) draws on researchers' ingenuity to creatively address key challenges in creating a modern electric energy infrastructure. The multidisciplinary expertise of PSERC's researchers includes power systems, applied mathematics, complex systems, computing, control theory, power electronics, operations research, non-linear systems, economics, industrial organization, and public policy. PSERC partners with private and public organizations that provide integrated energy services, transmission and distribution services, power system planning, control and oversight, market management services, and public policy development. Currently the PSERC collaboration includes 13 universities and 36 industries.

For more information visit the PSERC web site at:
www.pserc.org

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Funded by the U.S. Department of Energy (DOE) "The Future Grid to Enable Sustainable Energy Systems" project focuses on how to integrate higher penetrations of renewable generation and other future technologies into the grid while enhancing grid stability, reliability, and efficiency. It also aims to stimulate discussion among the academic, industry, and government communities on what it will take to shape the future grid for the mid-twenty-first century.

Learn more about the research behind this report by visiting:
http://pserc.org/research/FutureGrid.aspx

"The 450,000-mile U.S. electric grid is widely regarded as one of the greatest engineering accomplishments of the 20th century. The problem is that it's not the 20th century anymore."

Increasingly, electricity is being produced from renewable resources – primarily solar and wind – in an effort to mitigate the consequences of global warming resulting from high concentrations of atmospheric carbon dioxide produced by burning fossil fuels. This new direction in energy production and environmental protection requires an extensive re-engineering of the existing electric grid into a computerized future grid – or smart grid – that accommodates the special characteristics of renewable power-generating technologies.

To advance grid modernization, the U.S. Department of Energy funded the Power Systems Engineering Research Center (PSERC), a multi-university center charged with conducting research with its industry partners on the technical challenges facing the electric power industry. Under the Future Grid Initiative program titled, "The Future Grid to Enable Sustainable Energy Systems," researchers looked at ways to integrate renewable energy generation into the grid on a widespread basis while upgrading the overall network with the latest communications and data-processing technologies.

The more than a dozen participating universities in the Future Grid Initiative acquired collateral benefits from their PSERC involvement through its multi-disciplinary research capabilities in areas such as power systems, applied mathematics, complex systems, computing, control theory, power electronics, operations research, non-linear systems, economics, industrial organization, and public policy. In addition, the universities benefitted from new collaborative relationships established with other PSERC partners in both academia and private industry. The Future Grid Initiative also helped the PSERC universities advance sustainable, quality programs in electric power engineering to produce the next generation of highly educated technical professionals.

What is the Future Grid?

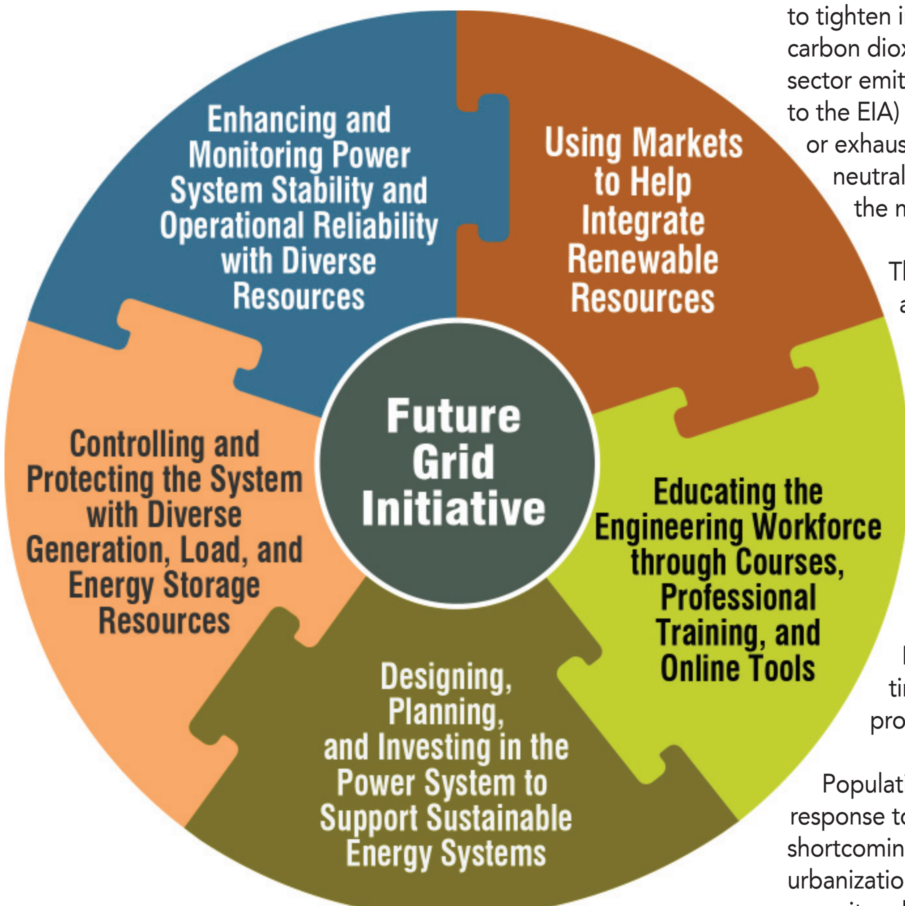
The traditional grid model is fairly straightforward, whereby electricity is generated in bulk at large (primarily coal-burning) plants and then transmitted over long distances via high-voltage cable to substations, and from there fans out in distribution systems to end users. In contrast, the future grid will use a more diverse set of supply and customer-provided resources and will transmit electricity via a computerized smart electric grid, with all the attendant capabilities and functions enabled by digital technology. This is similar in concept to the way a smart phone is at heart a computerized telephone.

The smart grid will be largely automated, which will provide a high level of control over the efficient production, distribution, and consumption of electricity. At the same time, as with any computerized system, new safeguards against disruption to grid operations will be required.

The smart grid will incorporate a host of technologies in measurement and sensing, two-way communications, data processing, and distributed computing. It will accommodate emerging consumer products such as electric vehicles, and even automatically inform the utility instantaneously if a power outage occurs. Perhaps most important of all, the smart grid will address an environmental imperative by facilitating sustainable, renewable energy-production sources on a wide scale.

Making the Case for Renewables

Electricity is critical to the national and world economies, so anything that affects the electric supply industry also carries significant economic effects. The rise in greenhouse gas emissions, adapting the industry to changing global and regional climates, and the availability of water are key factors affecting future electric generation. These issues are complex, with significant interactions among costs and benefits to the industry and its customers, and the reliability of the electric supply.



Existing electricity assets have been designed on the basis of historic climate and weather data.. Climate change affects these assets in many ways, and the industry needs to move quickly to form a long-term plan for adaptation.

In 2014, the electric power sector produced 38 percent of the total carbon dioxide emissions in the U.S., according to the U.S. Energy Information Administration (EIA). The industry also uses sulfur hexafluoride, another greenhouse gas, as an insulator in high-voltage equipment. While the volume of sulfur hexafluoride is minuscule compared to carbon dioxide, and although this material is not usually released to the atmosphere, it has 16,000-22,000 times the global warming effect of carbon dioxide. Regulations on the use and release of sulfur hexafluoride will continue to tighten in the future, but because of the volume of carbon dioxide involved (the U.S. electricity-production sector emitted 2,043 million metric tons in 2014, according to the EIA) and the expense of removing carbon from fuel or exhaust streams, or replacing fossil-fired with carbon-neutral generators, carbon dioxide mitigation will be the most costly.

The most direct effect of climate change is higher average air and water temperatures. Average global temperature increases of 1 degree to 2 degrees C are projected for 2050, and 1.5 degrees to 5 degrees C by 2100. Because so much electric load is temperature-dependent, this increase will have a direct effect on energy consumption and peak load patterns. The use of air conditioning for cooling is expected to increase significantly, producing higher summer peak loads and greater total electric energy consumption. Higher overnight temperatures reduce cooling times for transformers and other assets and will produce higher failure rates.

Population migration is expected, especially in response to social / political unrest and agricultural shortcomings. These factors may result in increased urbanization, creating additional challenges in generation capacity addition, maintaining reliability, and affordability of energy needs.

Additions to power plant capacity slow after 2016, but accelerate beyond 2023.	By 2035, natural gas will surpass coal as the largest source of U.S. electricity generation.	Nuclear electricity generation varies with license renewals, upgrades and operating costs.	Growth in power-generating capacity parallels rising sales of electricity.	Most new capacity uses natural gas and renewables.	Solar photovoltaics and wind dominate renewable capacity growth.	Total generation from wind, solar and other renewables surpasses hydropower.

POWER TRENDS

"The future grid must accommodate increased demand for electricity, which is expected to grow 29 percent from 2012 levels by 2040, according to EIA's Annual Energy Outlook 2014."

Snow and ice will melt as temperatures rise. This will initially increase runoff and hydroelectric production, but as long-term snow and ice levels are reduced because of warmer winter months, runoff will decrease and reduce hydroelectric generation availability. Research is needed to quantify the scope of increased loads, and decreased generation and delivery capacities due to higher average temperatures.

Demand for Electricity Will Grow

According to PSERC researchers, the central challenge is to accommodate the jump in electricity demand during the next three decades while mitigating damaging environmental effects.

Although nuclear and clean coal are low greenhouse-gas-generation technologies, it's likely that costs, waste storage, and (in the case of nuclear) safety concerns will limit penetration of these technologies. Natural gas plants have carbon dioxide emission rates about half or less than those of coal plants, as the EIA forecasts, and will certainly play a major role in future electricity generation portfolios. Yet the fact that natural gas plants are significant greenhouse gas emitters that may also have limited reserves (reserves range between 40 and 90 years depending on recoverability) suggests that the role of natural gas plants in the nation's generation portfolio, other than perhaps replacing retiring coal plants, may decline over the second half of the 22nd century.

Therefore, renewables, primarily wind and solar, with their promising low greenhouse-gas-emitting technologies, will comprise a large percentage of the overall national generation portfolio.

The Challenges of Adding Renewable Energy Sources

Renewable energy-generating technologies can't simply be plugged into the existing grid. Traditionally, centralized generation systems, such as a coal-burning generator or hydroelectric plant, deliver power at the appropriate voltage and frequency through synchronous generators directly coupled to the network at the U.S. alternating current standard of 60 Hz.

Modern renewable technologies can provide what's called distributed generation; that is, they are much smaller in design and power output, and can be built closer to consumers. In some cases, they may serve individual end-users, which means the grid must have the capacity to receive unused electricity produced by these sources.

Also, renewables connect to the grid indirectly, through DC-to-AC conversion. Their power-generating function is not synchronous, meaning their output varies by the time of day and current environmental conditions — solar cells don't produce at night, for example — which introduces a set of technical challenges related to energy storage, grid management and control, balancing electrical load and demand, and many others factors.

The interconnection of distributed generation with the electric grid can pose safety and reliability challenges for the utility, researchers noted, and may reduce the demand for traditional utility services as well. Distributed generation also potentially poses an economic risk to utilities and their consumers unless appropriate rate structures or cost-recovery mechanisms are put into place.

The design of future grid standards must support the evolution of future physical and cyber architectures. PSERC researchers discussed whether it would be possible to design easy-to-use standards that would enable integration of new generation, transmission and distribution, and demand technologies in a plug-and-play fashion without creating operating problems. They have proposed four basic functionalities for standards that are necessary to support future electric energy systems evolution.

1	Ensure the safety of components, interactions among groups of components and interactions in the system as a whole.
2	The electric energy system must continue to function as an interconnected AC system; further considerations are required to ensure that hybrid AC/DC interconnected systems are compatible and continue to function as a single interconnected system. System standards for interconnecting microgrids, ranging from AC to all-DC, to the bulk-AC power system, must be such that the hybrid AC/DC/AC system remains synchronized.
3	Quality of service as defined by system users must be maintained; in particular, sustained variations in frequency and voltage experienced by system users (both producers and consumers) away from the nominal must be maintained within specified thresholds.
4	Standards must be sufficiently user-friendly, and easy-to-understand and use.

The challenges in creating a future grid that enables sustainable energy-generating systems are wide-ranging and diverse. The PSERC Future Grid Initiative has identified a number of these technical challenges, from which a number of research activities are summarized in the sections that follow.

Developing New Transmission Systems and Technologies

What's commonly referred to as the national electric grid is actually three separate grids called interconnections covering the contiguous U.S.: one east and one west of the Rockies, and one covering most of Texas. The ability to move electric energy inter-regionally is limited by the capacity of the existing transmission system, which was built primarily to support coal, natural gas, and nuclear generation of electricity.

PSERC researchers studied this question: How could the U.S. produce the equivalent of the interstate highway system for electricity transmission?

Their answer is a national transmission overlay, defined as a high-capacity, multi-regional transmission grid spanning all three interconnections and designed as a single integrated system to provide economic and environmental benefits to the nation.

PSERC researchers working on several fronts designed a simulation of a U.S. interregional transmission overlay to facilitate the growth of wind, solar, nuclear, geothermal and clean-coal generation over the next 40 years. Such a national transmission overlay, under a high renewable penetration and low carbon dioxide emissions scenario, could result in a cost reduction of between one-quarter trillion and one-half trillion dollars over a 40-year period, while increasing infrastructure resilience and flexibility.

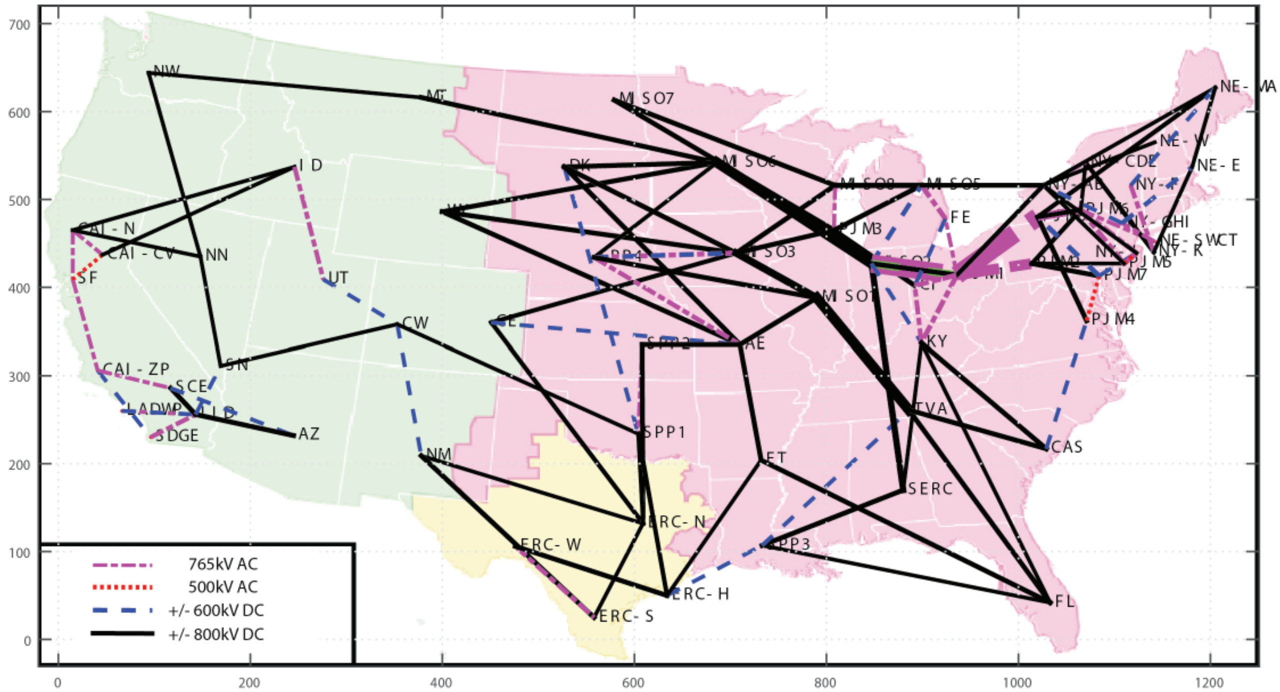
The overlay design co-optimizes generation and transmission, identifying a minimum-cost transmission network and a corresponding generation expansion plan in terms of location, capacity, and technology. Researchers also found that the design and development of a high-capacity interregional transmission overlay requires redeveloping much of the entire generation and transmission expansion process. To perform this redevelopment, a number of essential tools were identified and are now in various stages of development.

While data indicates that a national transmission overlay has the potential to offer significant net benefits to the nation, the political, regulatory, and procedural difficulties associated with initiating it are formidable. The next step could be to convene a group of experts to provide recommendations on the extent to which a national transmission overlay should be pursued.

A separate study in the Future Grid Initiative examined innovative transmission technologies. The three-phase transmission of AC power over electrical lines is fundamental to the operation of the current grid. For a future grid, PSERC researchers analyzed the advantages and disadvantages of selected innovative transmission technologies such as six-phase AC and other high-phase orders; multi-terminal and meshed networks; and high-voltage and high-temperature, low-sag transmission lines.

Innovative technologies proposed for expansion of this work include high-phase-order underground cables, which offer high power transfer with lower phase-to-phase voltage magnitude. Also, electromagnetic interference and impact need to be greatly reduced. Researchers propose to design sample underground cables of different phases and integrate them into appropriate applications.

In addition, researchers have proposed to combine several new technologies into a single, integrated design for bulk power transmission: they include high phase order, phase compaction, high-speed impulse attenuation methods for reduction of the required basic impulse level, and non-sinusoidal waveshape applications. The objective is to maximize the impact and advantages of each of these areas for optimum conductor utilization.



Interregional high capacity backbone transmission grid

The research challenge is the integration of innovative transmission circuits into the existing transmission system, and the maximal use of electromagnetic field theory and analysis tools for the design of the needed transmission components, as well as the extension of the concepts of transposed sections for polyphase systems.

PMU Technology Supports Future-Grid Control

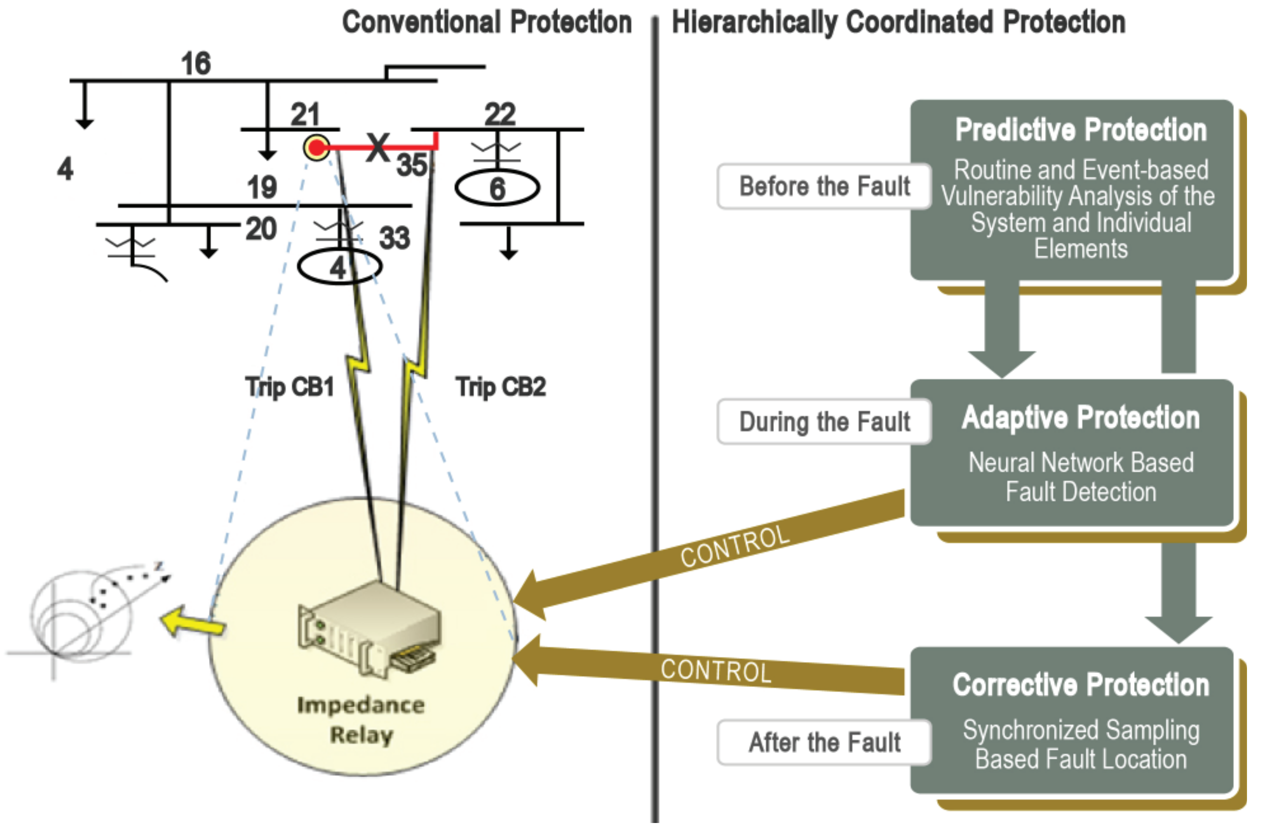
Phasor measurement units (PMUs) will play a central role in monitoring and controlling the future grid. PMUs are devices that measure electricity flow through the grid, synchronized against a common time source. This functionality, which may also be built into other devices such as protective relays, allows synchronized real-time measurements of numerous remote points on the grid, allowing more accurate and responsive control of grid operations. PMU capability is based on Global Positioning System technology (GPS), which uses satellites to accurately synchronize and "time stamp" system measurements from widely separated geographic locations. This technology provides real-time monitoring of the grid network on a regional and national scale, and enables a wide scale awareness of the grid.

From a control standpoint, the beauty of PMU technology is its high sampling / reporting rate and bandwidth. PMUs typically report at 30 or 60 times per second, versus traditional control and data acquisition techniques that report at rates of only one sample every few seconds.

PSERC researchers have developed new methods to design, simulate, and test the IT infrastructure for a given power grid to accommodate PMU data — synchrophasors — at substations and in new smart grid applications. The research results establish a foundation to test grid designs with high penetrations of variable electricity generation from renewables.

PMU data also play a central role in two wide-area controllers developed by PSERC researchers for handling complex, uncertain operating conditions of future power systems. An example is a hierarchical wide-area voltage controller that includes independent local substation controllers and a central voltage coordinator that make automatic control decisions based on widespread availability of synchrophasor measurements. Another example is a model prediction-based, transient stability control that has been updated to make control decisions. These control decisions are based on real-time system PMU measurements.

Operations can also be improved on the distribution side of the grid at local substation controllers and a central voltage coordinator that makes automatic control decisions based on real-time PMU data. In a future



Cascading Event Detection and Mitigation

power system with a high penetration of renewables, substation voltage control is expected to be a major reliability concern because of significant variable demands from power electronic converters and controllers at the substation interfaces with the transmission grid.

PSERC researchers have developed algorithms for analyzing small-signal oscillation problems associated with power electronic converters in wind generators. With improved data collection from PMUs, the goal is to develop power system monitoring tools that are adaptive to certain operating and network changes.

Another key step in meeting the challenges of renewable energy is the development of real-time, lightweight and adaptive algorithms for certain core functions: measurement and monitoring, and communication. These functions must be responsive to grid dynamics and support various applications with diverse requirements. The power grid and PMU-based communication system depend on one another to function properly. This interdependence has motivated researchers to study the cascading phenomena between the two systems; that is, a cascade of power failures that may follow cyber or physical attacks on the grid, which could be devastating and collapse the entire system. Many questions remain open about how best to design cyber-physical systems within these networks.

In a Future Grid Initiative project dealing with hierarchical coordinated control, researchers looked at ways PMU technology could enhance the grid's electromechanical stability in a system with wind energy production and electrical storage. They developed novel control designs to make best possible use of the characteristics of power-electronically-coupled wind energy and electrical storage resources.

Their designs take advantage of synchronized phasor measurements and low-latency communication of wide-area signals whenever available. However, to ensure the high reliability and robustness required of grid controls, these designs employed a mix of hierarchical and distributed state estimation to inform the control, with the practical impact that "graceful degradation" was explicitly incorporated into the design.

The tools developed in this work will enable wind generation resources to be more effective contributors to grid frequency control. More broadly, these tools will enable renewable resources to contribute to grid reliability on a timeframe comparable to that of governor and power-system-stabilizer controls in traditional synchronous energy-generating machines. The research team believes its designs could be adapted for other classes of equipment, such as photovoltaic generation and responsive load.

Challenges of Renewable Energy Integration

In a project exploring ways to mitigate the intermittency of renewable energy sources, researchers studied methods to coordinate aggregations of thermostatically-controlled loads, such as air conditioners and refrigerators, to manage frequency and energy imbalances in power systems.

Their work produced aggregation models and state-estimation strategies that can make demand response a viable strategy for short-term energy balancing. The significance of this strategy is that it can rely on infrastructure that currently exists in many applications, which facilitates deployment of the strategy at a very low cost. The work also provides an important end-use for smart meters beyond automated meter reading by employing them as receivers (but not transmitters) in demand-response control, thereby enabling renewable integration.

Another research project in the Future Grid Initiative focused on system operations and cost by using the Super Optimal Power Flow (Super OPF) planning tool and a test network. The central goal of the analyses was to learn how different components interact with each other on a network, particularly how stochastic wind inputs, storage capacity, and deferrable demand interact with each other to reduce total system costs. The analytical framework developed in this project will provide additional evidence that relying more on distributed energy resources and demand response can be more efficient than using supply-side solutions exclusively. In addition, regulators should understand why it is essential to re-design rate structures so that they reflect the true system costs accurately. If customers and aggregators receive the correct economic signals, it will be economically attractive for them to invest in new capabilities such as deferrable demand. Overall, a genuine two-sided market composed of supply and customer demand resources will lower system costs and lower customers' bills.

A team of PSERC faculty was involved in the development of a set of models and a simulation methodology for analyzing the effects of intermittency / variability of time-dependent resources and electricity storage integration on transmission-constrained electricity markets over longer-term periods. Their practical simulation approach will help power system operators and planners address the challenges posed by the deepening penetration of variable energy resources.

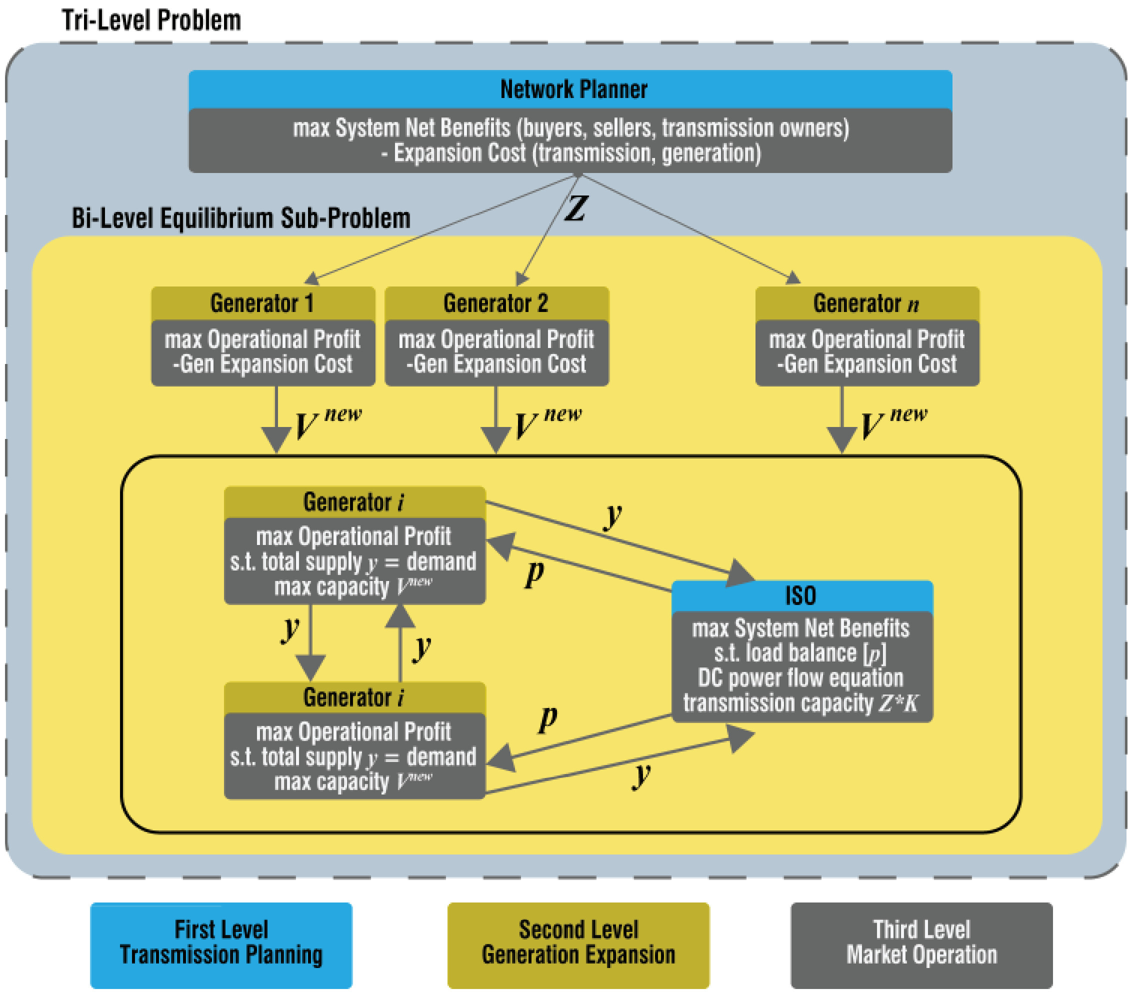
In addition, the team worked on the incorporation of utility-scale storage resources into the simulation approach. Storage units were scheduled in such a way as to maximize the total social surplus for a given scheduling period.

In another area, PSERC researchers developed new policies addressing reserve requirements — the amount of generating capacity kept in reserve for emergencies or other contingencies — that are better equipped to manage renewable energy sources and identify the critical locational reserve needs in order to improve market efficiency and reliability.

This research is the first to examine and develop a theoretical foundation to co-optimize reserve zones with reserve levels through the use of mathematical programming problems that determine the optimal network partitions — the cluster of generators and reserve levels needed to ensure reliable and economically efficient operations. The techniques are capable of capturing operational conditions better than static reserve policies since they incorporate the impacts of variable renewable resources. Research results show an improvement in market surplus and a reduction in costly out-of-market corrections, translating to an improvement in the ability to manage the variability and uncertainty of renewable resources.

The new techniques complement stochastic optimization procedures; coupling dynamic reserve requirement policies with stochastic unit commitment reduces the required uncertainty modeling within the stochastic program and, hence, reduces the computational burden. This research provides a unique practical solution to the ever-pressing concern regarding the management of high levels of variable generation, and it opens a new realm of research techniques to further address the problem of resource uncertainty in unit commitment and optimal power-flow problems.

An important aspect of the challenges of renewable energy integration is the centralized versus decentralized generation paradigms. PSERC researchers have examined a comparison of these two basic concepts with an aim of designing the infrastructure for the future electric grid system. This research involves the development of indices for an economical scale study of distributed generation (DG) relative to central generation (CG) and consideration of the more cost effectiveness of the two to accommodate new markets. In order to assess the robustness of DG and CG under different load conditions, different indices for measuring the combination of CG / DG with respect to their capability and resilience to threats, vulnerabilities



Coordinated Transmission and Generation Expansion Planning Under Uncertainty Using Stochastic OPF

and handling unforeseen events were studied. New computational tools comprising decision support tools are part of the research agenda for the development of co-optimization in a CG and DG based network for the future electric grid.

Communications Will Facilitate Better Functionality for Utilities and Customers

Data communications will link the various components of the future grid, from generator to transmission line to substation to distribution network to consumer smart meters, and even extend to equipment and appliances within homes and businesses. However, these channels will also have to be safeguarded in terms of cyber security and information privacy.

Flexible communication networks need to be defined and developed so that all applications can be accommodated with room for growth and expansion. PSERC researchers have shown that properly networked communications using high-bandwidth fiber can allow for complete coverage with PMUs, but the architecture has to be carefully designed to handle the fast controls. There is a great need to develop the architecture that can support the next-generation communications and its applications.

New communications technology built into the physical grid system that utilizes a fault-tolerant control framework can help increase grid resiliency, according to PSERC researchers. With the increasing deployment of PMUs, more wide-area measurements will be available. Controls based on these measured signals are more likely to be adopted. Controls that maintain system stability will become more fault-tolerant to failures in the communication networks.

In a related project, PSERC researchers have developed a method to design, simulate, and test the IT infrastructure for a given power grid to accommodate PMU data at substations and for new smart grid applications, including applications for wide-area protection and control. This methodology could be used to test designs for grids connected to a large number of renewable energy sources.

Advanced metering infrastructure (AMI) with "smart meters" not only measures how much electricity has been consumed, but when it was consumed. This communications technology will be an integral part of the future grid, say researchers.

Unlike standard meters, which measure total energy consumption over the monthly billing cycle, AMI provides two-way communication between smart meters and the utility as well as between the meter and customer. It records energy consumption data in intervals of an hour or less and transmits the information to a central location as well as to a consumer device such as a smartphone or to a digital display on the meter itself. This allows utilities to establish variable pricing for peak and off-peak hours, while enabling consumers to schedule certain electricity-consuming tasks at times when prices are lowest or manage their energy use. AMI also allows the utility to monitor power quality remotely and be notified instantly in the event of an outage.

Residential "prosumers" are a new class of consumers who can both consume and produce, store or transport energy from the home to the grid. PSERC researchers have been working to develop scheduling algorithms to enable prosumers to optimally schedule their energy use in a dynamic pricing environment. Also, in a win-win for both the consumer and power provider, PSERC researchers developed a method to optimally design electricity price signals for retail markets so that when residential consumers maximize their benefit individually, they adopt an energy schedule that also maximizes the electricity provider's benefits.

Additional research could suggest new business models and foster collaboration on future grid research into innovations at the customer end of the grid. Ultimately, customer response to incentives, such as through pricing, will need to be incorporated in future business models and technology decisions.

The smart grid also extends to the development of more robust smart homes, energy appliances and electric vehicles. PSERC researchers are addressing the requirements of an infrastructure that enables optimal use of distributed resources (both utility and customer-owned) through real-time hierarchical monitoring and control. Tools were developed to coordinate the operation of non-dispatchable resources (e.g., renewables) and other resources including storage, smart appliances, and plug-in hybrid electric vehicles. This centralized approach relies on a sophisticated infrastructure of metering, communications, analytics, and controls, as well as on participation of customers.

This integrated approach to power system operations maximizes the value from the use of renewable generation technologies. Fundamental changes will be needed at the distribution level in how the diversity of new resources will be controlled, such as by market mechanisms, centralized controls, or autonomous controls. These controls can rely on new optimization tools that directly account for uncertainty.

New Tools and Techniques

Long-term resource and transmission planning goals will need to be established under the uncertainty of future demand and fuel prices. Better transmission plans must be able to expand the use of renewable resources, equalize locational prices and prevent undue market influences, resulting in lower prices for consumers and viable profits for producers.

PSERC researchers customized and tested a method to efficiently reduce the number of planning scenarios that must be considered, thereby reducing the computation time for planning analyses. Optimization problems were expanded to a tri-level model of transmission and generation expansion in a centrally coordinated wholesale market, thereby capturing both technology choices and market influences. The top level represents a centralized transmission planner. The second level depicts the expansion-planning decisions of multiple generation companies. The third level is an equilibrium model of operational decisions by the generation companies and the system operators to meet demands of load-serving entities in a wholesale electricity market. The lower computational burden of planning under uncertainty will allow more operational details and planning choices in analyses. The tri-level solution algorithm quickly identifies combinations of transmission projects that promise higher net benefits.

In another PSERC research project in the Future Grid Initiative, a comprehensive simulation approach for power systems with renewable and storage resources operating in a competitive market environment was developed. The approach has explicit representation of uncertainty in conventional variable-energy resources and loads; time-varying loads and renewable energy storage resources; and time-dependent transmission usage. The approach is particularly suitable for longer-term studies of power system operations, planning, economics, investment, and policy-analysis formulation.

Deferrable demand, whereby demand for electricity is shifted from on-peak to off-peak times, could be a useful tool for maintaining the future grid's balance between demand and load, according to PSERC researchers. Their initial analyses for a test network at a wind farm in the Northeast demonstrated how deferrable demand can:

- ***Flatten the daily dispatch pattern of conventional generators.***
- ***Mitigate the variability of wind generation.***
- ***Reduce ramping costs and maintain reliability.***
- ***Lower costs to customers.***
- ***Improve environmental quality.***

In another project related to deferrable demand, a model was created to help represent the operation energy forecasting of day-ahead and real-time electricity markets. Coupling contracts that coordinate the consumption schedules of deferrable loads with renewable resources were analyzed. When calibrated against one year of wind-power production data from the National Renewable Energy Lab for a reduced system of the California Independent System Operator, which operates the bulk of the state's electric grid, daily cost savings of 2 percent to 3 percent were demonstrated. The work shows the value of contracted renewable resources, supplemented by spot electricity purchased from the grid, to serve flexible loads. Business models will need to be further explored for serving such flexible loads or for aggregating load flexibility to provide wholesale balancing energy and reserves.

PSERC researchers also developed short-term power system scheduling tools that run in serial or in the cloud. These tools may be used by system operators, policy analysts, academics, financial institutions, and researchers in order to operate the grid, analyze investment opportunities, analyze policies that target renewable integration and demand-response integration, and study the impact of renewable supply-and-demand response integration in power system operations.

Ultimately, the research will lead to educational software for short-term power system scheduling, industrial scale software for power system operations that can enable the large-scale integration of renewable resources, demand response algorithms that can be used by deferrable loads (e.g. electric vehicles) in smart grids, and policy analysis tools.

Challenges and Analysis under Increasing Dynamic System Conditions

Another Future Grid Initiative project developed improved computational methods for long-term resource planning under uncertainty. Efforts focused on two complementary thrusts:

- ***Further develop, implement, and test a method to reduce the number of scenarios considered in stochastic programming when implemented with a rolling time horizon.***

- ***Solve multiple variations of a bi-level optimization problem with uncertainty in the lower-level market equilibrium sub-problem.***

The project's scenario-reduction heuristic reduces the computational burden of long-term planning under uncertainty. Savings in scenario reduction and solution times could allow planners to include more operational detail and identify plans that avoid the potential risks and pitfalls of either under- or over-expanding. The multi-level decision models will promote understanding of how decision-makers may respond to planning decisions. Better transmission plans will expand the use of renewable resources, equalize locational prices, and prevent undue market influences, resulting in lower prices for consumers and viable profits for producers.

In other work, PSERC researchers focused on defining the requirements of an infrastructure that enables the optimal utilization of the distributed resources (utility and customer owned) and has the additional advantage of providing the available demand response capacity in real-time.

The central issue in this study was the utilization of a real-time model for a hierarchical optimization procedure that computes the controls for the overall optimization of the system. This capability will allow utilities to plan their operations more economically and dramatically improve the system's reliability.

The proposed infrastructure and associated optimization procedures and control make the distributed renewable energy resources in the distribution system economically and technically attractive for the utilities, and will enable higher penetration of these technologies. It transforms the grid into an active and controllable resource with favorable attributes such as high efficiency, minimal environmental impact, and increased utilization of renewables. In addition, the proposal offers:

- *Improved operation and economics resulting from peak load reduction and loss minimization.*
- *Improved environmental impact from using environmentally-friendly sources with less greenhouse gas emissions.*
- *Improved operational security from ancillary services and controls provided by the power electronic interfaced devices.*
- *Improved system reliability from the reduction of the grid peak load, the reduction of the cycling of dispatchable generating units, and the enhanced situation awareness of the real-time information of outages.*

Researchers have developed techniques for monitoring operational reliability using real-time, PMU-based tools. They envision their work to be integrated into the following three existing monitoring tools at utilities and independent system operators:

- *Online contingency analysis — to perform online contingency analysis that relies solely on up-to-date measurements obtained throughout the system.*
- *Congestion relief — to determine optimal re-dispatch policy to clear congestion without the use of predefined system models.*
- *Online model validation — to assess the validity of system models by comparing measurement-based distribution factors to those obtained by solving model-based nonlinear power flow equations.*

The proposed tool would improve the situational awareness available to power system operators. With the distribution factors obtained in real-time using PMU measurements without the use of a predefined system model, operators would be able to assess system security and dispatch corrective actions more effectively and accurately since the sensitivity factors would reflect the current state of the system.

PSERC Research Priorities: Security and Resiliency

Cyber security of the power grid — encompassing attack prevention, detection, mitigation and resilience — is among the most important R&D needs for the emerging smart grid, say PSERC researchers. One of the overarching goals of future research is to develop a comprehensive cyber security risk modeling framework that integrates the dynamics of the physical system as well as the operational aspects of the cyber-based control network. These models should quantify the potential consequences of a cyber attack on the power grid in terms of load loss, stability violations, equipment damage, and economic loss.

Following the risk assessment, the next important research challenge is to develop an integrated set of security algorithms that will protect the grid against various forms of cyber attacks including denial-of-service attacks, intrusion-based attacks, malware-based attacks, isolated attacks and coordinated attacks. The countermeasures must address both outsider and insider attacks as well as operator error.

The grid also must be resilient against disruption by natural events, such as transmission lines damaged by severe weather, or human error.

In the event of a fault, circuit breakers and other types of switches disconnect and de-energize parts of the system. Once the fault is repaired, that segment of the system can be brought back online. To safeguard operation of the future grid, PSERC researchers have developed a framework called Hierarchical Coordinated Protection (HCP) that consists of corrective layers as well as predictive and adaptive ones. HCP provides the flexibility necessary in an electrical grid that includes the variable output of renewable energy sources. Protection under this framework avoids unnecessary tripping of overloaded lines and mitigates cascading events, among other system conditions in the future grid.

In a project examining the requirements for HCP, researchers first defined the concept in terms of the smart grid's unique attributes and concluded that a flexible infrastructure for communication and computation needs to be developed in light of the fact that controls will encompass wide areas as well as several voltage levels. Their research showed that properly networked communications using high-bandwidth fiber can manage the communication latencies even for complete coverage with PMUs, but the architecture has to be carefully designed to handle the fast controls.

Using the simulation package NS2, researchers tested an IT infrastructure, defining the possible communication paths between the substation gateways and the control center, and a special protection scheme. The data traffic was defined with specific, realistic applications in mind. This method showed promise as a way to develop the next-generation architecture that can support future energy management systems.

In another HCP-related project, researchers proposed a grid framework that consists of predictive, inherently adaptive and corrective layers. The framework includes a monitoring and control tool that performs routine vulnerability analysis of the operating conditions of the entire system and its individual elements and is deployed at the control center level, while alert signals are sent to the substation level to closely monitor relays placed at the most vulnerable components. At the substation level, a neural network-based fault detection and classification algorithm is employed. As a corrective, fast and accurate synchronized sampling-based fault location and event-tree analysis to detect incorrect line tripping sequence and incorrect relay logic operation, respectively, are deployed. When the transmission line trips, the fault location algorithm will validate correctness of the relay operation. In case of an unconfirmed fault condition, the system component (e.g., transmission line) will be quickly restored.

The key to the HCP concept is that it co-exists with the legacy protection solution and only supplements its normal operation to achieve more selective outcome, when legacy protection may otherwise malfunction or create adverse impacts. The proposed three-layer philosophy may also be extended for protection of the other power system elements.

Certain rare natural phenomena have the potential to cause long-term catastrophic damage to the power system. Among them are geomagnetic disturbances (GMD), in which intense solar activity causes rapid changes the Earth's magnetic field, thereby inducing into the grid quasi-DC currents known as geomagnetically-induced currents (GICs). The GICs in turn can cause saturation in the high-voltage transformers, leading to increased transformer heating and greatly increased reactive power consumption, resulting in the potential for a large-scale voltage collapse.

PSERC researchers developed a modeling methodology that integrates the calculation of GMD impacts into power flow and transient stability applications, allowing for estimations of the likelihood that a GMD could result in power-system voltage instability. In addition, code was developed for assessing the sensitivities of geomagnetically induced currents on particular transformers to the geomagnetically induced electric fields on individual transmission lines. The work paves the way for implementation of strategies to reduce GMD vulnerability.

PMU data helped PSERC faculty researchers develop a method to quantify and predict cascading line-outage risk using one year of standard utility data to monitor overall stress at the border of an area. Although subject to further testing, the system-stress metric could provide real-time monitoring of severe line outages with an understandable and easily computed combination of PMU measurements. Better situation awareness also will facilitate integration of variable generation sources such as wind. Direct monitoring of cascading risk could help guide its mitigation and potentially avoid blackouts.

Interactive system control provides another advance in grid resiliency, say PSERC researchers. To address increased penetration of renewable resources into the power grid and the resulting uncertainty due to these resources, researchers have developed a hierarchical set of wide-area synchronized measurements. These measurements take into account the performance of the associated communication networks to effectively deploy corrective control and increase grid resiliency, which is built into the physical system by utilizing a fault-tolerant control framework.

Since communication errors can be easily distinguished from the associated signals in the case of power system faults, poor control performance due to communication failure can be avoided. A large set of wide area measurements can be used as a backup for faulty signals; therefore, it is highly probable that a healthy signal through an alternate communication route could be found to replace the original signal. Thus, the control which adopts the new input is able to damp the system oscillations much faster than when the control is directly abandoned without using a new one.

With the use of the approach proposed in this project, controls that maintain system stability will become more fault-tolerant to failures in the communication networks.

Uncertainty of Policies and Regulations

One of the uncertainties faced by planners is the extent to which regulations and policies influence the relative costs and benefits of renewables, according to PSERC researchers. There is currently no stable, consistent, long-term policy, particularly with regard to subsidization of various technologies and fuels, renewable portfolio standards, and environmental requirements, including implementation of economic penalties for carbon dioxide emissions through taxation or a cap-and-trade system. On the other hand, many states have adopted a renewable portfolio or electricity goals that effectively drive policy on renewables and carbon dioxide mitigation.

On the market side, despite federal initiatives to stimulate competitive wholesale regional markets for electricity, most consequential resource decisions are made on a local level. This has always been a concern with the organization of the U.S. electricity industry, but the shortcomings have become more acute as the industry has grown and demands on large regional interconnections of electrical generation have grown. The fact remains that a large share of the planning, funding and, particularly, siting activity still occurs at the state level.

One other area where local decision-making has a strong interaction with transmission network needs and planning is in the implementation of state-level utility and environmental policies, particularly renewable portfolio standards. There is a diversity of approaches, with some states allowing compliance through generic tradable renewable energy credits while others, such as California, requiring the bulk of the resources be physically connected with its local network.

In the end, there may be increased state-to-state competition for a growing, renewable, energy-based green economy. Because the source of renewable energy generation capacity varies significantly across the country, some states will experience increased generation facilities and the associated economic development that comes from the construction, maintenance, and operation of those facilities. Other states lacking this capacity will not see this benefit. Or worse, they may see reduced usage or even closure of some high-cost generation facilities, effectively transferring jobs to the renewable-rich states, leading to less cooperation to develop a more interconnected grid.

Preparing the Engineering Workforce

In keeping with the education side of its mission, PSERC's faculty has developed software tools, courses, a virtual library and training materials to ensure the basis of a workforce well-versed in implementing the future grid.

Specific projects include a new textbook, titled "Smart Grid Applications Using Synchrophasor and Synchronized Sampling." The book, produced for educators, students, practicing engineers, managers and others electric-industry professionals, is designed to provide a practical foundation in applications and theory for the implementation of synchrophasor technology in the grid. Invented more than 30 years ago, very little is known about this technology in the mainstream academic and engineering communities. The book sheds additional light on how to utilize this promising technology to make the transmission grid more reliable and robust. The text also is expected to stimulate further research in the academic community, and advance more elaborate engineering solutions in the industrial environment and more strategic approaches in the deployment of synchrophasor technology.

A second example of a PSERC textbook for the next generation of power systems education is the book "Energy Processing and Smart Grid." This book is divided into three broad sections: energy conversion (including renewables), measurements and controls of the smart grid, and test beds for the smart grid. The IEEE / John Wiley Press publication version will be made available in hardcopy, e-book, and power point format when completed.

In separate PSERC projects, researchers developed university courses addressing energy economics and grid security.

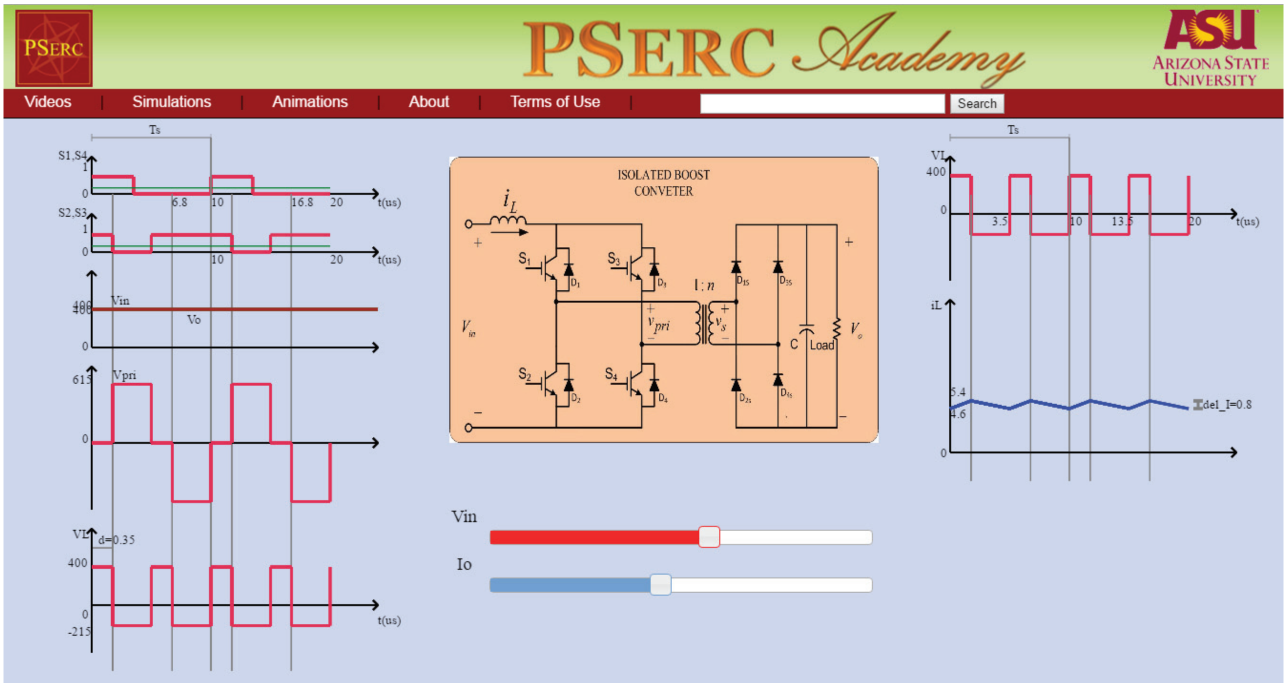
For the former, the team created extensive reading-lists, syllabi, exercises, and exam material covering the economic fundamentals of both electricity and energy markets. The coursework, available at both the master's and doctoral levels, can be applied at a variety of technical levels to a broad set of prospective students. In addition, some of the material has been adapted to a short-course format for industry professionals.

The multi-disciplinary grid security course addresses areas such as data communication, computing, control, and cyber security as applied to the electric power grid. It is designed for undergraduate seniors and graduate students, along with an on-line version for industry.

Additional college-level courses developed by PSERC faculty pertain exclusively to power grid-related topics as well as to more general academic disciplines as they relate to the emerging renewables-compatible smart grid and the complex technical challenges surrounding it. Instructional materials for these courses, both graduate and undergraduate, online and in-classroom, are available to institutions outside of PSERC and the individual universities that developed them.

A short sampling of course topics includes:

- *Modeling and analysis*
- *Local- and wide-area control*
- *Probability theory and stochastic processes*
- *Quantitative reliability analysis*
- *Computational framework for real-time measurements*
- *Standards, guidelines, controls and protocols for integrating renewable energy sources into smart grid*



Education (psercacademy.asu.edu)
PSERC Academy provides workforce training in the areas of power electronics, power engineering, and sustainable energy systems. The online library includes a large number of short videos, simulations, animations, and quizzes. The materials can be used as a complete self-learning e-resource, as a complement to class lectures, or as a reference material for practicing engineers.

In another educational project, PSERC faculty created an extensive online library of 15-to-20-minute videos on various topics of sustainable energy systems, smart grid and power engineering, and on important background topics required to understand these concepts. Delivered using a range of methods from simple lectures to multi-media delivery, the PSERC Academy is more flexible and adaptive by design, both in terms of contents and format, and is meant to evolve over time based on user and expert feedback.

The material for the "PSERC Academy" has been posted on the website PSERCAcademy.asu.edu and many videos will be available on YouTube as well. Simulation files and animations will be hosted directly on the PSERC Academy website.

Balancing Costs with Long-Term Benefits

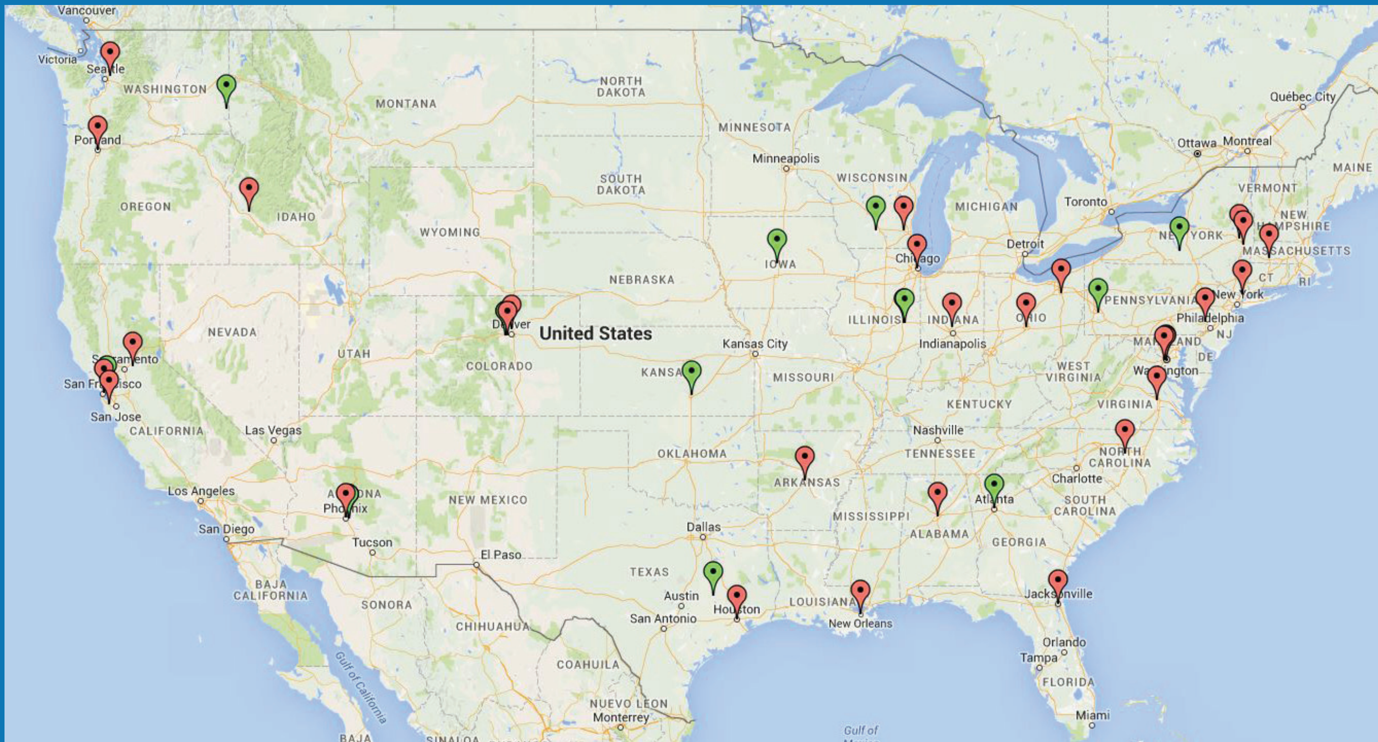
Over the past four years, the PSERC Future Grid Initiative has focused on research supporting the creation of a grid that enables renewable energy systems. The PSERC Future Grid Initiative has served as a comprehensive response to the need to upgrade aging energy infrastructure along with the growing importance of critical environmental concerns. It is hoped that this effort spawns other initiatives that pursue solutions that best meet national energy needs in the decades to come.

The environmental issues, technologies, and regulations all interact, and at times conflict, affecting the cost of producing and delivering electricity. Since electricity and its cost are critical to the U.S. and world economies, potential costs must be balanced against the benefits of improving — or the costs of not improving — the environment.

PSERC Public Webinars

PSERC offers free webinars open to the public. About ten webinars are made available every year. They are presented by PSERC researchers and discuss the results of recent projects. Webinar attendance makes engineers, working with industries that are PSERC members, eligible for professional development credits.

A listing of upcoming webinars as well as recordings of past ones are available on the PSERC website at:
http://pserc.org/education/webinars.aspx



The Power Systems Electrical Research Center (PSERC) is a collaboration between 13 universities and 36 industries.

University Members

1 Arizona State University
2 Carnegie Mellon University
3 Colorado School of Mines
4 Cornell University
5 Georgia Institute of Technology
6 Howard University
7 Iowa State University
8 Texas A&M University
9 University of California, Berkeley
10 University of Illinois, Urbana-Champaign
11 University of Wisconsin, Madison
12 Washington State University
13 Wichita State University

Industry Members

USA
1 ABB Inc.
2 American Electric Power
3 American Transmission Co.
4 Arizona Public Service Co.
5 Bonneville Power Admin.
6 California Independent Systems Operator (CAISO)
7 CenterPoint Energy
8 Dominion Virginia Power
9 Entergy
10 EPRI
11 Exelon
12 FirstEnergy Corporation
13 First Solar
14 GE Energy Consulting
15 GE Grid Software Solutions
16 Idaho Power Company
17 ISO New England
18 Midcontinent ISO
19 National Renewable Energy Laboratory
20 Natl Rural Elec Coop Assn (NRECA)
21 New York ISO
22 New York Power Authority
23 Pacific Gas and Electric
24 PJM Interconnection
25 PowerWorld Corporation
26 Salt River Project
27 Southern Company Services
28 Southwest Power Pool
29 The Energy Authority
30 Tri-State G&T
31 U.S. Department of Energy
32 Western Area Power Admin

International (not shown in the map above):
1 ENGIE (France)
2 Guangdong Power Grid (China)
3 IREQ (Canada)
4 RTE-DMA (France)