Technology Challenges in Designing the Future Grid to Enable Sustainable Energy Systems

Future Grid Thrust Area Synthesis White Paper

Power Systems Engineering Research Center

Empowering Minds to Engineer
the Future Electric Energy System

Technology Challenges in Designing the Future Grid to Enable Sustainable Energy Systems

Prepared for the Project
"The Future Grid to Enable Sustainable Energy Systems"
Funded by the U.S. DOE

Vijay Vittal
Director, Power Systems Engineering Research Center
Professor, Arizona State University

PSERC Publication 12-17

June 2012

Information about this white paper, contact

Vijay Vittal
Director, Power Systems Engineering Research Center
Ira A. Fulton Chair Professor
Department of Electrical Engineering
Arizona State University
PO Box 875706
Tempe, AZ 85287-5706
Tel: 480-965-1879
Fax: 480-965-0745
Email: vijay.vittal@asu.edu

Power Systems Engineering Research Center

The Power Systems Engineering Research Center (PSERC) is a multi-university Center conducting research on challenges facing the electric power industry and educating the next generation of power engineers. More information about PSERC can be found at the Center's website: http://www.pserc.org.

For additional information, contact:

Power Systems Engineering Research Center
Arizona State University
527 Engineering Research Center
Tempe, Arizona 85287-5706
Phone: 480-965-1643
Fax: 480-965-0745

Notice Concerning Copyright Material

Acknowledgements

This paper was developed as part of "The Future Grid to Enable Sustainable Energy Systems: An Initiative of the Power Systems Engineering Research Center (PSERC)." This project is funded by the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability. More information about the Future Grid Initiative is available at the PSERC website. www.pserc.org.

Final research results are scheduled for publication in 2013. Interim publications will be available on the PSERC website. The site already includes

- materials from a public discussion of the Initiative at a workshop on December 7, 2011
- presentation slides and links to archived webinars from a webinar series held from January-June, 2012
- the thrust area white papers on which this paper is based
- a collection of broad analysis white papers on the information architecture of the future grid and on grid enablers of sustainable energy systems.

Work in each thrust area and each broad analysis area has been the result of collaboration among researchers, industry and government. Acknowledgement of the contributors are provided in each project publication.

Executive Summary

This white paper synthesizes technology challenges for reaching a vision of the future grid that, in part, includes a high penetration of renewable generation technologies. The challenges are identified in six technical thrust areas in the PSERC Future Grid Initiative, a DOE-funded research effort entitled "The Future Grid to Enable Sustainable Energy Systems.

A brief overview of each of the six thrust areas is provided first. Then, the technology challenges in each thrust area are presented.

An important and key requirement of the research in each thrust area is the need to provide a seamless transition in the legacy grid while implementing the newly identified technologies. This is necessitated by the enormous capital investment in the legacy grid and its tremendous geographical breadth. With this basic premise, several key technology challenges associated with the various technical tasks in each thrust area are identified and discussed.

The identified technology challenges in each thrust area can serve as a springboard for wider discussions of those and related challenges, and of how the challenges are being or can be addressed. The challenges also serve as a broad foundation on which to systematically identify potential paths leading to implementation of technology solutions to the challenges, and to a grid that enables attainment of national energy and environmental objectives.

Table of Contents

1 Introduction 1
2 Context of the Challenges in Designing the Future Grid 3
2.1 Thrust Area 1: Electric Energy Challenges of the Future 3
2.2 Thrust Area 2: Control and Protection Paradigms of the Future 4
2.3 Thrust Area 3: Renewable Energy Integration and the Impact of Carbon Regulation on the Electric Grid 5
2.4 Thrust Area 4: Workforce Development 8
2.5 Thrust Area 5: Computational Challenges and Analysis Under Increasingly Dynamic and Uncertain Electric Power System Conditions 9
2.6 Thrust Area 6: Engineering Resilient Cyber-Physical Systems 10
3 Challenges and Opportunities in Meeting the Envisioned Objectives 12
3.1 Thrust Area 1: Electric Energy Challenges of the Future 12
3.2 Thrust Area 2: Control and Protection Paradigms of the Future 13
3.3 Thrust Area 3: Renewable Energy Integration and the Impact of Carbon Regulation on the Electric Grid 13
3.4 Thrust Area 4: Workforce Development 14
3.5 Thrust Area 5: Computational Challenges and Analysis under Increasingly Dynamic and Uncertain Electric Power System Conditions 15
3.6 Thrust Area 6: Engineering Resilient Cyber-Physical Systems 16
4 Conclusion 17
References 18

1 Introduction

A wide-spread transformation in the electric grid is underway. The grid is evolving away from a networked architecture with relatively few large, hierarchically-connected, tightly synchronized energy resources supplying large, medium, and many small passive consumers. It is evolving toward a network driven by highly variable distributed energy resources. These resources will be mixed with large central generation sources and energy storage. There will also be responsive users equipped with embedded intelligence and automation to meet their unique energy needs while co-existing and interacting within a complex dynamic network system.

This transformation is driven by critical national energy challenges such as:

- Energy independence and affordability
- Energy reliability, security and efficiency
- Economic development and job security
- Environmental concerns and impact of climate change
- Aging infrastructure, technology change and workforce needs.

In order to address these national energy challenges, a range of energy solution options are being considered by government, industry, and customers, including:

- Renewable resource technologies
- Energy efficiency
- Demand resource management
- Electricity market solutions
- Nuclear energy technologies
- Development of domestic resources
- Improved asset utilization
- Electric transportation
- Carbon capture and storage
- Energy storage.

Rather than relying on any one of these solutions, an approach that includes a combination of solutions is likely. Such an approach will require an electric grid infrastructure that evolves to enable new solutions as they are adopted. The critical elements of this evolution, and the drivers associated with each of these elements, are outlined in Tables 1-4.

Table 1: Changing generation supply mix

Needed evolution to support this element	Drivers of the evolution/changes
T&D additions and changes Energy storage Enhanced control/communications Handling increased uncertainty	Renewable resources Retirement of aging conventional plants Questions regarding nuclear additions Carbon regulation

Table 2: Demand transformation

Needed evolution to support this element	Drivers of the evolution/changes
Expanding digital economy Power quality and reliability needs Demand flexibility Electric vehicles	Economic constraints Changing customer needs Green awareness and demand Need for higher reliability and efficiency

Table 3: Complexity of the electric grid

Needed evolution to support this element	Drivers of the evolution/changes
Expanding footprint Impacts of market Tighter operating limits Greater reliance on communication and control Need for advanced analytical tools	Spatio-temporal constraints Computational complexity Stochastic nature of variables Need to contain cost

Table 4: Infrastructure vulnerability

Needed evolution to support this element	Drivers of the evolution/changes
Reduce footprints of disruptions Reliability of communication and control Reduce duration of disruptions Guard against malicious attacks	Shortage of skilled workforce Inadequate analytical tools Interdependence of cyber-physical systems

Having identified the possible range of energy solutions, critical elements of the evolution of the electric grid, and the drivers of these evolutionary changes, technical challenges will need to be addressed to transform the legacy grid. Addressing the challenges is driven by the large capital investment made in constructing the legacy grid and its immense geographical footprint. In addition, there is the implied assumption that the future grid will not be built from scratch. Realistically, it would evolve, starting with the existing grid as the foundation. Identifying the technical challenges identified by the thrust areas in the Future Grid Initiative in pursuing this goal is the objective of this white paper.

2 Context of the Challenges in Designing the Future Grid

This white paper synthesizes technology challenges identified in the following six technical areas associated with the Future Grid Initiative:

1. Electric energy challenges of the future
2. Control and protection paradigms of the future
3. Renewable energy integration and the impact of carbon regulation on the electric grid
4. Workforce development
5. Computational challenges and analysis under increasingly dynamic and uncertain electric power system conditions
6. Engineering resilient cyber-physical systems

These areas will be referred to as "thrust areas" in that they are focus areas in PSERC's research on a future grid that enables the energy solutions while incorporating emerging new grid technologies. Within each thrust area there are specific "tasks" that address one or more particular challenges.

This white paper principally identifies the technology challenges being addressed in the Future Grid Initiative's research program, although broader challenges are also identified. Admittedly, these six thrust areas are not the only way to categorize the technology challenges in designing the future grid, but they do serve to provide a context for investigation of key challenges. After all, the grid is only a part of an overall energy system designed to serve societal energy needs. However, the grid serves a critical enabling function. That context will be explored next in a discussion of the six areas. Then, technological challenges identified by PSERC researchers will be presented.

2.1 Thrust Area 1: Electric Energy Challenges of the Future

Electric power engineering is often viewed as a mature topic since the inception of this field dates back nearly 100 years. However, distinct milestones in the field have become 'game changers' in the sense that these critical milestones have caused a radical change in design and operation of the electric grid. As an example, the concept of networking the transmission system was deemed impossible at first because it was thought that synchronizing AC generation over long distances was not feasible. However, large-scale networking has become a design hallmark of contemporary transmission systems. Another example of a transmission design milestone is the use of digital computers to evaluate alternative designs (as well as alternative system operating scenarios). Examples of the game-changing features that face contemporary electric energy engineering are (1) utilization of renewable energy resources (including both design and operation issues), and (2) maximizing the automated features of the system so that operation makes maximal use of the assets available. Also, the expanded use of electric energy in the transportation sector will reduce dependence on foreign oil. The added electric energy demand and its impact on the grid is another game-changing eventuality.

In this thrust area's research, several key electric energy engineering challenges are addressed by bringing innovative engineering technologies [1] to bear on (1) integration of renewable resources into the system; (2) direct digital control of the system; (3) maximization of the use of sensory information to use the assets that we have; and (4) integration of plug-in electric vehicles. The research intent is to use newly available information in mathematics and statistics, instrumentation and control, communications and computing, and advanced concepts of transmission engineering to achieve multiple objectives:

- renewable resource integration
- maximal system operability and reliability
- making use of digital technology where it is warranted and human operator skills where they are needed.

The elements of this thrust area focus on electric energy challenges of the future through four critical areas:

- transmission system design
- substantive changes in power distribution system design
- dynamic balancing of load and generation
- wide area controls, including integrative controls in transmission and distribution systems [2].

These basic elements are unified by an integrative task in the thrust area to identify the likely future technologies that need to be analyzed and to research the identified critical areas. The integrative task is intended to focus on the next thirty years, inclusive of innovative concepts that may be marginally practical today.

2.2 Thrust Area 2: Control and Protection Paradigms of the Future

It is well accepted that new information technology solutions will enable the smart grid with new control and protection schemes that will increase the reliability and the efficiency of the power grid. Moreover, the operation and control of a grid with high penetrations of renewable generation resources will be very dependent on the availability and implementation of these schemes. Research and development of such schemes to solve specific problems are now quite common and some schemes, such as Special Protection Schemes (SPS) and System Integrity Protection Systems (SIPS), are already in use.

However, these one-of-a-kind special control and protection approaches are very expensive. What is needed is a streamlined process for the design, installation, operation, and maintenance of such control/protection schemes. The conceptual framework for this needs to be developed. New technologies have made it possible to move from largely local control and protection to system-wide control and protection of the grid. The new framework has to be **hierarchical** so that the whole system can be covered and, at the same time, **coordinated** across the power system geographically and across the various transmission and distribution voltage levels.

In Thrust Area 2, the objective is to develop the principle of **hierarchical coordinated control and protection** of the smart power grid. In achieving this objective, a major goal is to incorporate more renewable generation resources while increasing reliability and efficiency. The thrust area tasks are structured to comprehensively look at this subject from the development of the theory to the engineering design and then to the testing of hierarchical coordinated control and protection.

The first Thrust Area 2 task examines the requirements for the communication and computation architecture for hierarchical coordinated control and protection. Unlike many other operational functions, control and protection have stringent requirements for latency of measurement and control signals.

The second task investigates the hierarchical coordinated control of transient stability that could be significantly affected by high penetrations of wind and solar generation that will require energy storage devices for system-wide control. The coordination associated with off-line, on-line, and real-time time frames becomes more crucial with such system-wide controls.

The third and final task in this thrust area focuses on hierarchical coordinated protection. A different approach to protection design is proposed where local protection is coordinated with logic at regional levels and higher. At these fast speeds, control and protection are conceptually difficult to separate since protection can be viewed as digital control. However, the long tradition of protection engineering and the increasing use of SPS provide methodologies that can be used in developing new analog controls.

2.3 Thrust Area 3: Renewable Energy Integration and the Impact of Carbon Regulation on the Electric Grid

The integration of renewable energy resources into the power grid is driven largely by environmental regulation aimed at promoting sustainable energy resources and reducing carbon emissions resulting from energy use. Price and quantity controls of carbon emissions through taxation or cap-and-trade policies, along with renewable portfolio standards, are the primary drivers for (1) massive penetration of renewable resources (such as wind and solar power) into the mix of electricity resources and (2) the electrification of transportation. However, the economics and the environmental regulations underlying such resources, as well as the operating characteristic of these resources which are strongly influenced by weather patterns, has a profound impact on the planning and operation of the power grid.

There are two characteristics of the power supply from renewable energy resources which present significant obstacles to their large-scale integration into the power grid. Renewable energy production is uncertain and cannot be forecasted accurately. Furthermore, it is highly variable over time so that even if perfect forecasts were possible, integrating massive amounts of such resources into the power grid presents significant challenges in terms of the operational dispatch, reserves, and ramping requirements. These problems are particularly acute with respect to wind power whose availability is often adversely correlated with demand.

The unpredictability of wind power supply that may change rapidly due to cold fronts and wind shifts can cause large deviations from hour-ahead dispatch schedules. Starting up appropriate conventional units to compensate for a sudden shortage in wind power supply may take hours, necessitating curtailments of customer load. Furthermore, the need for emergency startups leads to increased emissions, and increased maintenance costs due to added use of the generating units for emergency startup. Such emergency startups also disrupt market operations and increase dispatch costs due to the minimum load constraints of these units. An unanticipated increase in wind power generation is also problematic because it may require shutting down generating units due to minimum load constraints and over-generation.

The minute-by-minute and intra-hour variability of wind power generation exacerbates the need for spinning reserve, non-spinning reserve, and regulation in order to mitigate potentially adverse impact on system reliability because of the inability to perfectly forecast wind. Since wind tends to vary rapidly and in great magnitude, it becomes necessary to invest in and dispatch fast-starting generators with sufficient ramping capabilities. Those units are typically more expensive to operate. The California Independent System Operator (CAISO) has estimated that meeting a 20% renewable energy integration target will require generating units that can ramp twice as fast as existing units in order to keep up with the abrupt changes in wind power supply [3]. The ramping challenge due to intraday variability of renewable resources, and the scheduling challenge due to unpredictability, are depicted in the two figures (Figures 1(a) and 1(b)) below. The figures were published by CAISO.

Regardless of the challenges of large-scale wind power integration, after 30 years of rapid technological development, and owing to current economic, political and environmental circumstances, wind power is poised to become a mainstream energy source capable of supplying bulk quantities of power to the electricity grid. Environmental regulations aimed at reducing carbon emissions are setting aggressive targets that will require high levels of renewable penetration. For instance, Assembly Bill 32 in California has set goals of cutting back greenhouse gas emissions to 1990 levels by 2012 and the renewable portfolio standard mandates 33% integration of renewable energy in California by 2020. As wind penetration increases, the aforementioned challenges may impact system reliability, dispatch efficiency, cost of operation, and may even undermine the environmental goals that renewable portfolio standards aim to achieve, unless the adverse impact of such penetration can be mitigated through the harnessing of demand flexibility and deployment of storage.

Studies have placed an estimate of wind integration costs of up to \$7/MWh for integration levels between 2.4% to 20% [4]. On the other hand, significant amounts of wind power are spilled by system operators in Denmark, Texas, and California. This can happen for reliability reasons during load pickup, in order to avoid oversupply due to unexpected increases in renewable supply, or at night time when other generating units need to maintain a minimum output level.

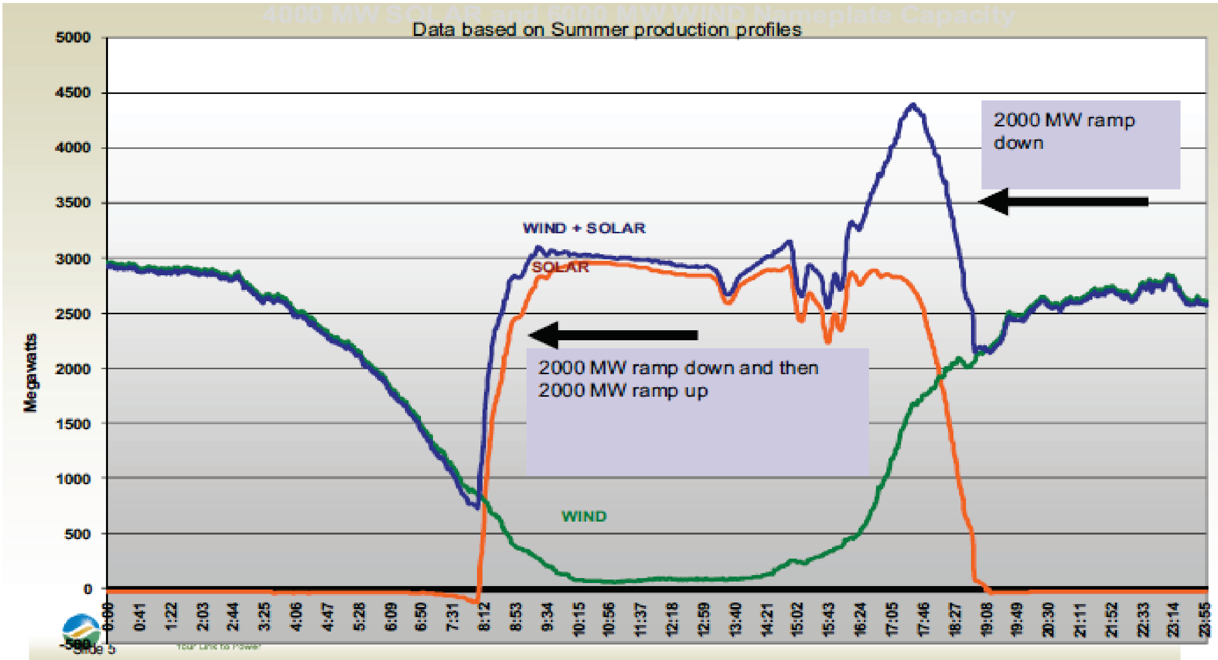

Figure 1(a) Example of ramping challenges at 20% Renewable Portfolio Standard

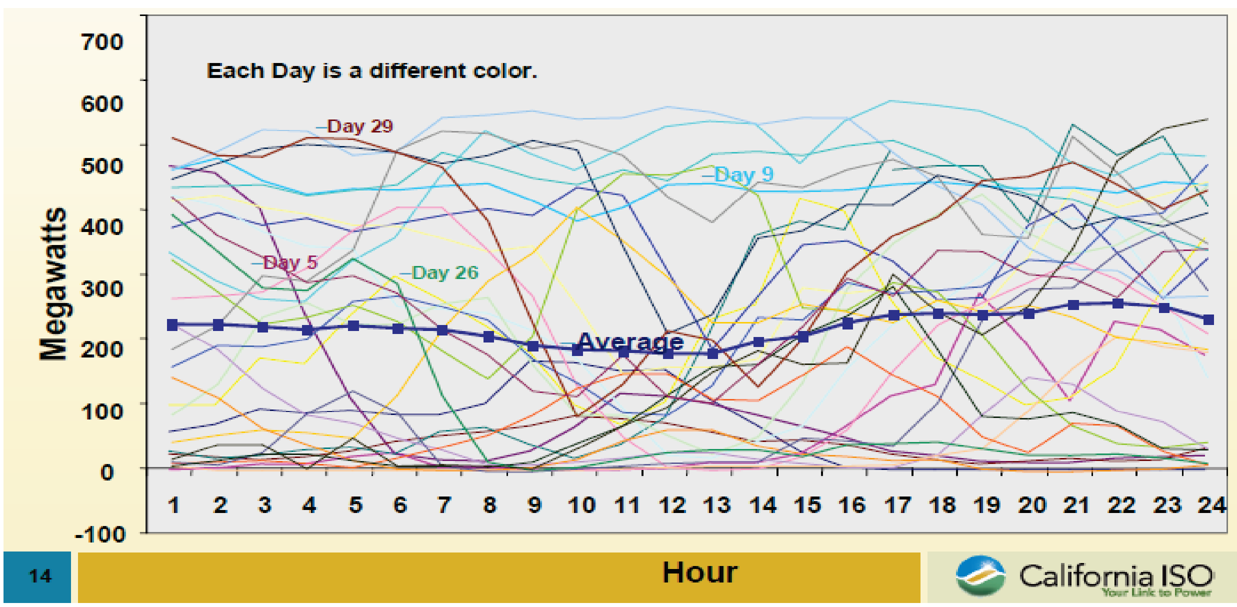

Figure 1(b) Techachapi Wind Generation in April 2005

The proposed research in Thrust Area 3 aims at understanding and quantifying the impact that massive integration of wind power will have on the power system in terms of efficiency, operational reliability, economic consequences, and environmental outcomes. It also focuses on the design and evaluation of technological and market-based approaches to mitigation of any adverse impacts of such integration. The analysis will be based on simulation models designed to explore and evaluate technological and market solutions that can facilitate the integration of renewable resources. Specifically, the analyses will explore

- the potential of harnessing the inherent flexibility of certain load types, such as heating and cooling and PHEV charging
- the deployment of distributed and system level storage devices to mitigate the variability
- uncertainty of renewable resources.

The distinct thrust area tasks complement each other in terms of their scope and methodological approaches to addressing the issues raised above.

2.4 Thrust Area 4: Workforce Development

The electric power system is transforming into a clean and sustainable energy smart grid. The features that are expected to distinguish the future grid from the past grid are:

- heavy penetration of variable energy sources
- central and distributed energy storage
- massive deployment of distributed communication and computational technologies allowing smarter utilization of resources and consumer participation.

As a result of this evolution of the grid with emphasis on markets and integration of variable sources of energy, there will be higher uncertainty in the planning and operation of these systems.

The objective of this thrust area is development of educational tools to meet the needs of the current and future engineers who will be managing these complex cyber-physical systems as well as innovating to bring further transformations. The workforce development is important for several reasons. First, there is a projected workforce shortage [5] in this area. Second, this workforce will need to be educated with a different set of skills and tools than has been done in the past [6]. It is this workforce that will produce innovative ideas and transformative changes needed to orchestrate a clean and sustainable energy smart grid. *The relevant education of this workforce is thus critical to the success of the future grid.*

In proposing the tasks in Thrust Area 4, the intended audience, as well as their needs, has been considered. It is understood that the education system will need to cater to a diverse audience and to their educational needs to plug the gaps in their current education. To cover a wide spectrum of needs, breadth and depth have been considered. Some educational materials will be focused on providing the breadth, and others on depth in needed areas.

The intent is to offer a set of courses and develop materials for well-rounded education that has as broad an impact as possible by allowing access to these educational opportunities as conveniently as possible using modern educational technologies. The portability of the educational material will be an important feature.

2.5 Thrust Area 5: Computational Challenges and Analysis Under Increasingly Dynamic and Uncertain Electric Power System Conditions

Computational methods and information systems have been at the center of secure and economic planning and operation of electric power systems for several decades. Today, transformational forces, such as renewable energy, distributed resources, energy storage and massive sensing, pose numerous and much more difficult computational challenges than experienced in the past. The addition of sustainability objectives to the traditional goals of grid economy and reliability has resulted in growing uncertainty and complexity, and is likely to make obsolete a significant portion of the current computational methods and information systems.

The new decision-making tools needed in operations and planning must be based on computational methods that account for uncertain conditions and are capable of handling much more complex problems. On the other hand, the availability of massive, more detailed, and new data from phasor measurement units (PMU's), advanced metering infrastructure (AMI), and intelligent electronic devices (IED's) provides great opportunities for improved grid planning and operations. Ways must be found to aggregate, organize, and keep this data secure so that it can be leveraged to upgrade, extend, and replace existing modeling, computation, and decision-making tools. Use of computational systems in the future grid is illustrated in Figure 2.

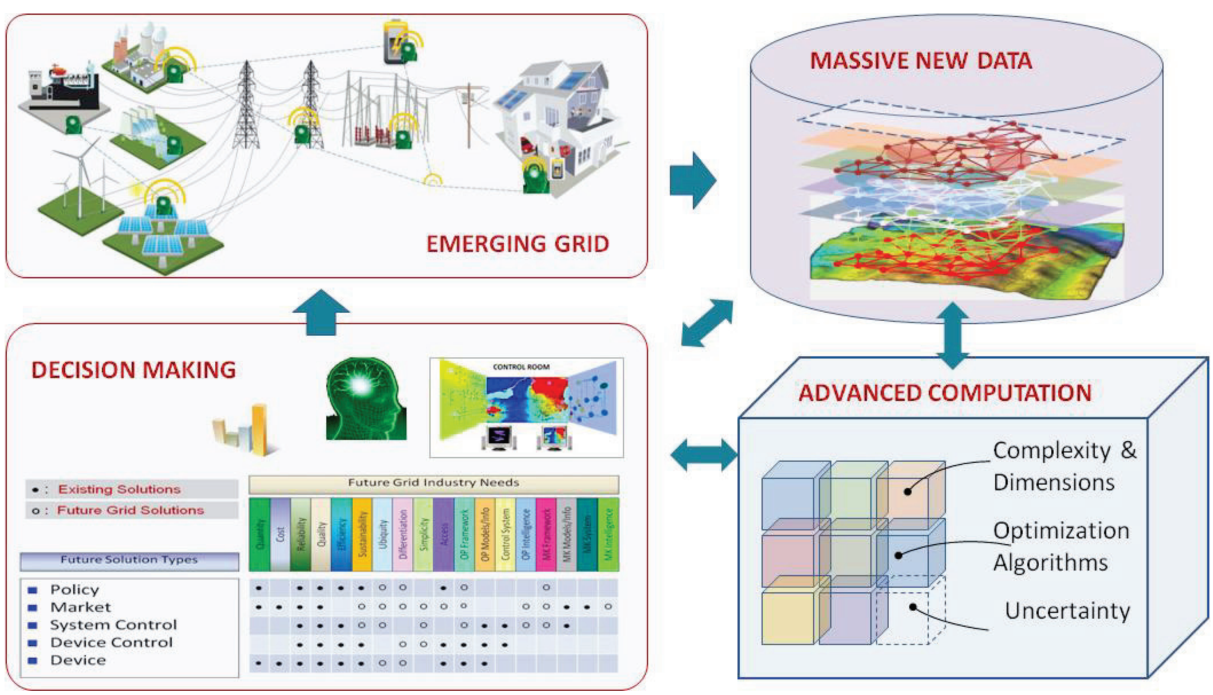

Figure 2 Computational Systems in the Future Grid

Two broad issues are considered in this thrust area: 1) new data, analytics, and information systems for critical decision making, and 2) new optimization methods that address uncertainty. The following tasks will address the key computational challenges and will provide research results to guide strategic technology development and policy:

1. *Decision-Making Framework for the Future Grid*. This task will develop and demonstrate a decision-making framework for the future grid that a) ensures that all the goals of the future grid can be met, b) covers all relevant spatial and temporal scales, c) addresses decision complexity, and d) identifies the gaps and technological needs for the industry transition.
2. *Computational Issues of Optimization for Planning*. This task will develop improved computational methods for long-term resource planning under uncertainty with efforts to (a) further develop, implement and test a method to reduce the number of scenarios considered in stochastic programming when implemented with a rolling time horizon, and (b) solve multiple variations of a bi-level optimization problem with uncertainty.
3. *Hierarchical Probabilistic Coordination and Optimization of DERs and Smart Appliances*. This task proposes a three-level hierarchical stochastic optimization methodology in real time around the physical separation of power systems into feeders, substations, and power grid. It addresses technology aspects and quantifies expected benefits.
4. *Real-Time PMU-Based Tools for Monitoring Operational Reliability*. This task will develop real-time, PMU-based tools for helping operators with operational reliability issues: a) system loadability condition monitoring, b) transient stability analysis, and c) real-time line model and equivalent parameter updating.

2.6 Thrust Area 6: Engineering Resilient Cyber-Physical Systems

While there are a number of different definitions for resiliency, probably the one most germane to electric grids is the "*ability of a system to gradually degrade under increasing system stress, and then to return to its pre-disturbance condition when the disturbance is removed*." A resilient power grid should not experience a sudden, catastrophic system collapse, but rather should be able to adapt to "keep all the lights on" under small to moderate system disturbances, and to keep at least some level of system service even in the event of severe system disturbances. This thrust area has research in three tasks to engineer more resilient cyber-physical systems.

The first task is to investigate how the cyber-physical infrastructure needs to be engineered to deal with low frequency, but high consequence events. An example of such an event could be a severe geomagnetic storm. In fact, according to a 2009 National Academy report, a repeat of the storm that occurred in May 1921 could result in hundreds of high voltage transformers being damaged. The research in this task will focus on the development of power system analysis algorithms and tools to help manage such a crisis in the power flow and transient stability time frames. Results will be demonstrated using models of the major North American electric interconnections.

The second task focuses on engineering resiliency with respect to prevention of cascading failure. The traditional way to inhibit cascading failure is to enforce the n-1 criterion. Nevertheless, some cascades will start and propagate. The amount of cascade propagation after an initial failure is one measure of system resilience. Previous work has resulted in new approaches to statistically quantify the amount of propagation from observed or simulated blackout data. The research objective with this task is to develop practical applications of these new approaches so that cascading failure risk can be quantified and mitigated.

The final task is to study how increased system monitoring and control can be used to improve power grid resiliency from an operations point of view. With increased penetration of renewable resources and the increased uncertainty due to these resources, the power grid of the future may be significantly less controllable on the generation side. Yet this loss of control on the generation side is compensated by (potentially) more controllable load, distribution and transmission. However, in order for the control to be more manageable and effective because of the increased uncertainty, it is imperative to utilize the next set of measurements in the hierarchy which consist of more localized measurements to actually perform the control. Once this is done, the wide area measurements would again be used to evaluate the effectiveness of the control and determine if more local adjustments are required.

3 Challenges and Opportunities in Meeting the Envisioned Objectives

Researchers in each of the six thrust areas have outlined a broad set of challenges that need to be addressed to design the future grid. These challenges are discussed in separate white papers [7-11]. In their work, researchers are focusing on specific aspects of the challenges they have identified. This section of the white paper provides a synthesis of the technology challenges identified in each thrust area in the broadest sense and outlines the steps needed to meet these objectives.

A critical consideration in meeting the technology challenges is the substantial capital investment in the legacy power grid. Any new implementation of solutions associated with the identified technology challenges will require a seamless transition in the legacy grid.

3.1 Thrust Area 1: Electric Energy Challenges of the Future

Several key technology challenges are associated with this thrust area. They include:

1. Eventuality of a national transmission overlay to support increased penetration of renewables and the utilization of a mix of energy resources
    a. Technology to use AC versus DC
    b. If AC, consideration of ultra high voltage levels, six phase and related polyphase transmission
    c. If DC, consideration of multiterminal DC and meshed DC transmission
    d. Need for a DC circuit breaker
    e. Implications of the use of high temperature, low sag conductors
    f. Utilization of compact transmission designs to optimize hard to find right of way
2. Critical need for high levels of energy storage at the bulk power level
    a. Need for high energy density storage other than pumped hydro in the Gigawatt-days range
    b. Economically viable energy storage
    c. Determination of the level of renewable resource penetration and associated variability that would render the cost to benefit ratio of energy storage to favorable ranges
3. Robust and dynamic reserve requirements
    a. Determination of an optimal reserve requirement
    b. Examination of reliability criteria associated with reserve requirements
    c. Probabilistic risk assessment of reserve requirements
4. Wide area control
    a. Designing robust, coordinated, and reliable wide area controls
    b. Tailoring wide area controls to dedicated applications
    c. Locating wide area controls
    d. Coordination of wide area controls
    e. Real time adaptation of wide area controls

3.2 Thrust Area 2: Control and Protection Paradigms of the Future

The main technical challenges outlined by this thrust area deal with the concepts related to the development of a hierarchical framework to design and coordinate control and protection schemes for the future grid. They include:

1. Communication and computational architecture requirements for hierarchical coordinated control and protection
    a. Requirements on communication latency and quality of service
    b. Robust communication networks with associated software development
    c. Design and development of databases to handle massive volumes of data
    d. Communication requirements within control areas and associated constraints on latency, bandwidth, protocols and communications technology
    e. Needed enhancements for simulation and design applications to support control and protection applications
    f. Simulations tools to analyze interdependent cyber-physical systems to examine required performance aspects
    g. Cyber security requirements
2. Hierarchical decomposition of protection systems
    a. Predictive protection
    b. Inherently adaptive protection
    c. Corrective protection
    d. New architectures for coordinated hierarchical protection systems

3.3 Thrust Area 3: Renewable Energy Integration and the Impact of Carbon Regulation on the Electric Grid

This thrust area includes several technology challenges that deal with the development of optimization and simulation tools that explicitly account for uncertainty in planning and operation of the future grid with increased penetration of renewable resources. The technology challenges associated with this thrust area include:

1. Exploiting demand side flexibility as a hedge against renewable resource supply uncertainty instead of using conventional generation resources
    a. Is this paradigm shift viable?
    b. Optimal strategies needed to operate the system reliably
    c. Business models needed to aggregate load flexibility
    d. Centralized versus decentralized approach comparison
2. Utilizing non-disruptive distributed load control to mitigate renewable resource variability
    a. Developing high fidelity models for thermostatically-controlled loads
    b. Evaluating the ability of such loads to provide the desired benefit
    c. How well would load control work in comparison to the same control achieved by generators?
    d. What are infrastructure needs for implementing this approach?

3. Market design to utilize dispatchable loads to meet renewable portfolio standards and emission reduction targets
    a. Can variability of renewable resources be accurately characterized stochastically?
    b. Can future needs for frequency regulation and generation/load following be accurately estimated under different renewable resource penetration levels and emission targets?
    c. Can dispatchable loads be aggregated in order to examine engineering/economic feasibility?
4. Need for stochastic optimization tools for planning and operation
    a. Adequate representation of system complexity
    b. Representation of production costing and reliability assessment
    c. Consideration of correlated behavior of loads and supply resources
    d. Validity of analysis over a time horizon
    e. Guaranteeing computational tractability

3.4 Thrust Area 4: Workforce Development

This thrust area has identified key aspects of workforce development and identified the following challenges to nurture and train the workforce needed to design and operate the future grid:

1. Steps to tackle the projected workforce shortage
    a. Need to address workforce needs across the spectrum – skilled workers, engineers and managers
    b. Play to our strengths of meeting needs at the BS, MS and PhD levels
    c. U.S. power engineering academic workforce is also graying.
2. Curriculum redesign to meet the needs of the future grid
    a. Need solid grounding in basic power engineering fundamentals
    b. Evolve curriculum to address needs in complementary disciplinary areas (shown in Fig. 3) which are essential in engineering the grid of the future
3. Leverage PSERC's broad spectrum of expertise to develop relevant and appropriate material to meet the interdisciplinary needs of education to engineer the future grid
    a. E-learning techniques
    b. Online course material
    c. Textbooks
4. In addition to updating university curriculum, critical need to provide life-long learning experiences to the practicing engineer
    a. Self-paced online material
    b. Short courses
    c. Textbooks

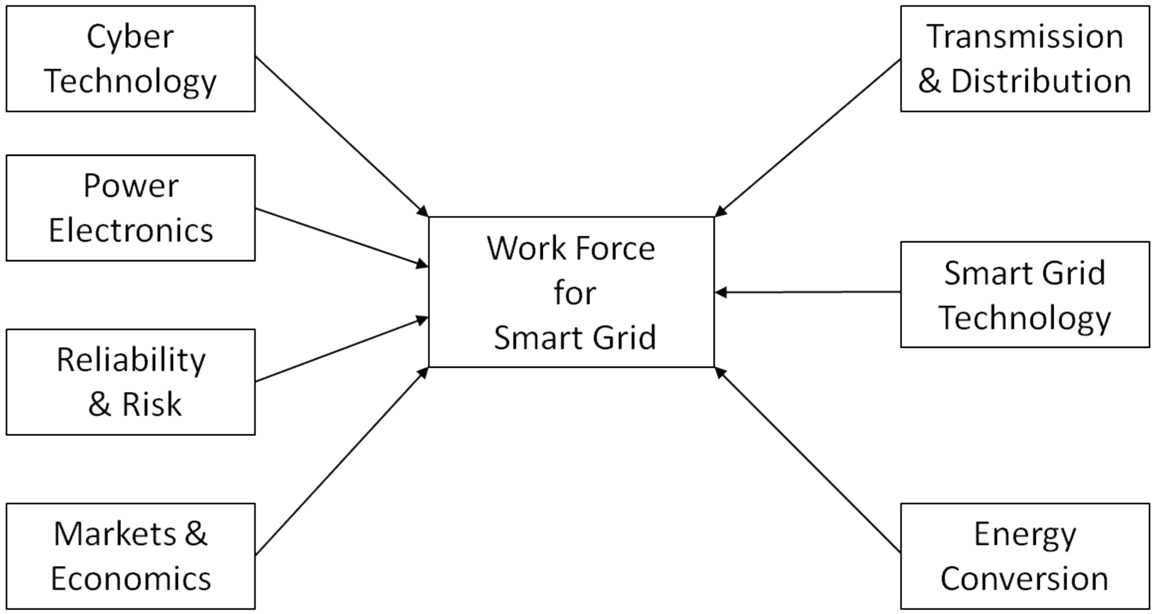

Figure 3 Complementary Disciplinary Areas

3.5 Thrust Area 5: Computational Challenges and Analysis under Increasingly Dynamic and Uncertain Electric Power System Conditions

The primary objective of this thrust area deals with examination and development of appropriate computational techniques to handle the increasing dynamic and uncertain operating conditions in the future electric grid arising due to the high penetration of renewable resources, and the ability to control demand resources. The technology challenges identified in this thrust area include:

1. A decision-making framework for the future grid
    a. Should be designed to meet the goals and objectives of the future grid
    b. Ability to address both spatial and temporal scales of the problem
    c. Ability to handle decision complexity
    d. Capability to fill the technology gaps in existing tools and provide for a seamless transition
    e. Flexibility to handle massive streams of data
    f. Consideration of demand as a resource
2. Computational issues associated with optimization and planning
    a. Incorporating uncertainty – Dual stage approach in stochastic programming models needs to be made more efficient taking into account a careful choice of the number of scenarios and the appropriate level of uncertainty representation
    b. Concomitant consideration of market implications of planning decisions results in significant computational complexity – a bi-level structure based approach needs to be designed keeping in mind the computational issues

3. Coordination and optimization of distributed energy resources and smart appliances
    a. Need for a hierarchical probabilistic approach
    b. Ability to level total load, utilize most efficient units and control greenhouse gas emission
    c. Minimize losses in distribution systems
    d. Capability to provide ancillary services
    e. Maximize reliability
4. Utilization of real time PMU measurements for monitoring operational reliability
    a. Leverage the large national investment in PMUs
    b. Develop efficient application tools for a range operational reliability problems – system loadability, online security analysis
    c. Accuracy of developed tools need to be established

3.6 Thrust Area 6: Engineering Resilient Cyber-Physical Systems

With the potential transformation of the future grid into a cyber-physical system, Thrust Area 6 examines approaches to enhance the resiliency of such systems. The technological challenges that need to be addressed in this area include:

1. Building resiliency to high impact, low-frequency events
    a. Identifying events that could result in vulnerabilities to the system
    b. Designing and developing monitoring capability to sense such events
    c. Preventive or corrective control strategies to mitigate impact of such events
2. Operating and planning considerations for resiliency
    a. Mitigating the impact of cascading blackout given increased uncertainty
    b. Since such events are rare, need to develop a suitable statistical model
    c. Cannot rely on past reliability and resilience of the power system due to transformational changes
    d. Need to quantify resilience and develop appropriate metrics and demonstrate the advantages of using them
3. Approach to build resiliency in cyber-physical systems
    a. Ability to handle loss of cyber system components in critical applications
    b. Can redundancy be built in the physical system to handle disruptions in the cyber system?
    c. How can such redundancy be designed?
    d. Can the approach be generalized?
    e. What are suitable application scenarios?

4 Conclusion

The challenges in creating the future grid that enables sustainable energy systems are wide-ranging and diverse. The PSERC Future Grid Initiative has identified a set of technical challenges in six thrust areas to which solutions are being sought in collaboration with industry and government. Through a process that informs others about the research and education efforts, it is hoped that this research effort spawns other initiatives that pursue the solutions needed to create the grid that best meets national needs in the decades to come.

References

[1] L. Castanheira, G. Ault, M. Cardoso, J. McDonald, J. Gouveia, Z. Vale, "Coordination of transmission and distribution planning and operations to maximise efficiency in future power systems," *Proc. International Conf. on Future Power Systems,* Amsterdam, Netherlands, 2005, pp. 1 – 5.

[2] G. Heydt, "The next generation of power distribution systems," *IEEE Transactions on Smart Grid,* accepted for publication, September 2010, pp. 1 – 10.

[3] C. Loutan, and D. Hawkins, "Integration of Renewable Resources", California Independent System Operator, CA, Nov. 2007; U.S. DoE Energy Efficiency and Renewable Energy "20% Wind Energy by 2030.Increasing Wind Energy's Contribution to U.S. Electricity Supply", May 2008. Avalable online at : http://www.20percentwind.org/20p.aspx

[4] T. Ackermann, "Wind Power in Power Systems". Chichester: John Wiley and Sons, 2005; F. van Hulle, "Large Scale Integration of Wind Energy in the European Power Supply: Analysis, Recommendations and Issues", European Wind Energy Association, Brussels, 2005.

[5] Preparing the US Foundation for Future Electric Energy Systems: A Strong Power and Energy Engineering Workforce, www.pserc.org/.../workforce/US_Power_and_Energy_Collaborative_Action_Plan_April_2009.pdf

[6] Gerald T. Heydt, et al, Professional Resources to Implement the Smart Grid, NAPS 2009.

[7] Thrust Area 1: Electric Energy Challenges of the Future (http://www.pserc.org/documents/publications/papers/fgwhitepapers/Heydt_PSERC_Future_Grid_TA1_May_2012.pdf)

[8] Thrust Area 3: Renewable Energy Integration and the Impact of Carbon Regulation on the Electric Grid (http://www.pserc.org/documents/publications/papers/fgwhitepapers/Oren_PSERC_Future_Grid_TA3_May_2012.pdf)

[9] Thrust Area 4: Workforce Development - Meeting the Educational Challenge of the Smart Sustainable Grid (http://www.pserc.org/documents/publications/papers/fgwhitepapers/Singh_PSERC_Future_Grid_TA4_May_2012.pdf)

[10] Thrust Area 5: Computational Challenges and Analysis under Increasingly Dynamic and Uncertain Electric Power System Conditions (http://www.pserc.org/documents/publications/papers/fgwhitepapers/Grijalva_PSERC_Future_Grid_TA5_May_2012.pdf)

[11] Thrust Area 6: Engineering Resilient Cyber-Physical Systems (http://www.pserc.org/documents/publications/papers/fgwhitepapers/Overbye_PSERC_Future_Grid_TA6_May_2012.pdf)