PSERC

U.S. Energy Infrastructure Investment: Large-Scale Integrated Smart Grid Solutions with High Penetration of Renewable Resources, Dispersed Generation, and Customer Participation

White Paper

Power Systems Engineering Research Center

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Power Systems Engineering Research Center

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Our core purpose:

- Empowering minds to engineer the future electric energy system

What's important to us:

- Pursuing, discovering and transferring knowledge
- Producing highly qualified and trained engineers
- Collaborating in all we do

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Power Systems Engineering Research Center

Letter from the Director

March 2009

The 21st century will witness unprecedented growth of electricity as the dominant energy carrier. Such reliance on electricity requires resolution of numerous challenges related to the existing electricity grid. Much attention is being given to smart grid development in the U.S. and around the world. In the future, the name “smart grid” may be associated with a period in time in which the evolution of grid technologies moved quickly toward their convergence with communications, sensor, and information technologies. The goals of this evolutionary change include harmonizing old with new energy production technologies, enabling bidirectional energy exchange between service providers and customers, and facilitating system integration across the electricity enterprise.

This white paper’s purpose is to advance progress toward a future grid that is even more reliable, safe, efficient, secure, resilient, flexible and economic than the present grid. PSERC has taken a step back from current discussions of particular smart grid technologies, functionality, and standards to try to answer commonly heard questions about the vision of a smart grid and how to make it a reality. We suggest what the next steps could be for research, development, demonstration, and deployment activities that will help in achieving successful implementation of an envisioned smart grid.

We hope that this white paper will contribute to solving the challenges in the evolution of the legacy electric energy system to meet changing national priorities while improving service to customers and society at-large using leading-edge concepts, architectures, technologies and analytical tools.

Sincerely,

Vijay Vittal
Director

Acknowledgements and Disclaimer

This white paper is intended to promote discussion on the vision of a smart grid and the tasks needed for its timely implementation. The white paper was prepared by the Power Systems Engineering Research Center (PSERC) in an industry-university collaborative effort. Its contents do not necessarily reflect the views of any of the organizations who are PSERC members, including those organizations of the major contributors to the white paper.

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U.S. Energy Infrastructure Investment: Large-Scale Integrated Smart Grid Solutions with Increased Penetration of Renewable Resources, Dispersed Generation, and Customer Participation

The evolutionary path of the U.S. electricity grid is at an historical crossroad. Decisions are going to be made about the direction of grid development so that it can meet extraordinary economic challenges, critical needs for energy security, and essential requirements for a sustainable way of life. This is a defining moment in terms of our nation's commitment to providing an electric energy system, including the bulk transmission network, that meets societal needs of the 21st century and beyond. A major evolutionary step in the grid's design, planning, and operation is needed using new design concepts and innovative technologies that can be integrated into a modern infrastructure. The American Recovery and Reinvestment Act of 2009 provides opportunities to achieve these far-reaching objectives.

This white paper was created by the Power System Engineering Research Center (PSERC), a national consortium of universities, government, and industry. Drawing on the differing perspectives of members of that collaborative provides insights into how to integrate theoretical concepts with practical considerations. The paper describes a vision and needed steps for reaching a national objective of having a smart grid infrastructure. Demonstrations of a smart grid are needed to identify possible improvements and to show effectiveness from the generation system, to the bulk transmission and distribution networks, and finally to the customer premises. The vision described in this white paper can make a significant contribution to the U.S. DOE's efforts to lead the nation in developing and deploying a smart grid solution that will efficiently support a low-carbon energy infrastructure portfolio.

This paper's focus is on technological considerations in developing smart grid solutions. However, to maximize the benefits of a smart grid, demonstrations should allow for rigorous assessment of customer participation challenges, too. In addition, public policy scenarios should be considered when they affect decisions on smart grid implementation.

The seven objectives of the smart grid, as identified by the U.S. DOE, are:

1. Enabling informed participation by customers
2. Accommodating all generation and storage options
3. Enabling new products, services, and markets
4. Providing the power quality for the range of needs in the 21st century economy
5. Optimizing asset utilization and operating efficiently
6. Addressing disturbances through automated prevention, containment, and restoration
7. Operating resiliently against all hazards.

Meeting these functional needs of a smart grid will require consideration not only of the end-state when a smart grid vision is realized, but the evolutionary period to that state during which the legacy infrastructure will be used side-by-side with new technologies.

A smart grid research and development effort has to harmonize three principal aspects of the future grid:

- ***Expansion of the electricity grid infrastructure.*** This aspect includes (1) building new infrastructure to replace aging infrastructure while expanding grid capacity, (2) improving the operation and efficiency of the existing infrastructure, and (3) developing novel concepts, technologies and applications. The smart grid will integrate renewable generation and distributed energy sources. It will also enable creative options for customers to participate in system operations by offering their loads and storage capability (such as by using plug-in hybrid electric vehicles) as resources. Customers also want options for making their own usage more energy and cost efficient (such as through building energy management systems.
- ***Introduction of information technology, communications infrastructure, and modern sensors at large-scales for both on-line and back-office services to facilitate the operation and management of assets.*** Smart grid innovations will expand the use of computers and communications. They will also add new sensor technologies, database management systems, data processing capabilities, computer networking facilities, means of cyber security, and visualization tools for asset operators and managers.
- ***Incorporation of new monitoring, control, and protection applications that are integrated and operate seamlessly.*** The smart grid will have technological advances in monitoring, data-to-information conversion and visualization technologies, and advanced control and protection schemes. These advances will be for integrating renewable resources and distributed generation, for supporting customer choices, for facilitating risk-based asset management and control strategies, and for improving efficiency and protection of the grid.

The smart grid demonstrations completed so far have not been sufficiently comprehensive, integrative, and at a scale sufficient to provide the insights needed for large-scale smart grid deployment. Most demonstration projects have been limited to advanced metering infrastructure (AMI) that includes smart meters. Demonstrations have used communications technologies such as broadband over power line (BPL) and wireless communications, and have tested customer technologies for demand-side management (DSM).

Such demonstrations have provided insights on portions of a comprehensive smart grid solution. Most AMI and DSM applications were limited either by the technology (e.g., no two-way communication between the customer and the utility) or by the scope (e.g., limited options for controlling loads or no testing of time-of-use pricing). What is needed now is a clear vision of a system-wide smart grid. With that vision, it will be possible to conduct the necessary research, development and demonstration of integrated solutions that meet the overarching objective of enhancing performance of the entire system ranging from the generation source, to the grid, and finally to the customer.

Admittedly the state of knowledge needs to grow on the use of smart grid technologies at the bulk transmission level. For example, a significant effort in deploying technology for synchronized phasor measurements is under way through the North American Synchrophasor Initiative; however, the benefits and ramifications of this technology are yet to be fully explored.

There is a critical need for research, development, and demonstration of large-scale solutions that will revolutionize the design, planning, and operation of the electric energy network. A large-scale demonstration can be used to comprehensively assess and evaluate the feasibility and merit of applying smart grid technologies on the bulk transmission system, distribution system, and customer premises. Thus, there is a need to broaden the focus of the smart grid demonstrations beyond the existing distribution and customer-oriented projects. A holistic perspective is needed using a system vision of a smart grid that includes bulk transmission.

In this white paper, a systematic approach is suggested to identifying the challenges of integrating a mix of energy generation, storage, and customer resources; and to developing an integrated operations framework across the electric energy enterprise. This framework can be used (1) to meet established and updated reliability criteria, (2) to facilitate market mechanisms, and (3) to ensure efficiency and economy. The approach incorporates the smart grid functions selected by the U.S. DOE. It addresses the President's goal of facilitating a green economy and making the U.S. more self-sufficient in meeting its energy needs.

There are four crucial steps in advancing a smart grid:

- Define a vision of an integrated solution
- Conceptualize the overall smart grid architecture
- Conduct research and development to create an integrated solution
- Move forward with stakeholder collaboration and large-scale demonstrations.

These steps are described in the next four sections.

I. Define a Vision for Integrated Systems Operations

The proposed vision for integrated systems operation must satisfy the objectives of the smart grid, such as those identified by the U.S. DOE. To satisfy the objectives, there needs to be a novel mapping of smart grid application to the proposed infrastructure. Fig. 1 illustrates how infrastructure and application solutions may be mapped to objectives. The vision needs to establish categories of new applications that are more effective than the existing ones in achieving the smart grid goals. This white paper places an emphasis on research and development needs to define, create, and test new applications that integrate the operations across the entire grid enterprise including generation, transmission, distribution, and end-use customers. The core of the new applications is integration of massive sources of data measured from the grid, and extraction of information that can serve the needs of the stakeholders: market operators, generator owners, wires companies, and, most of all, customers.

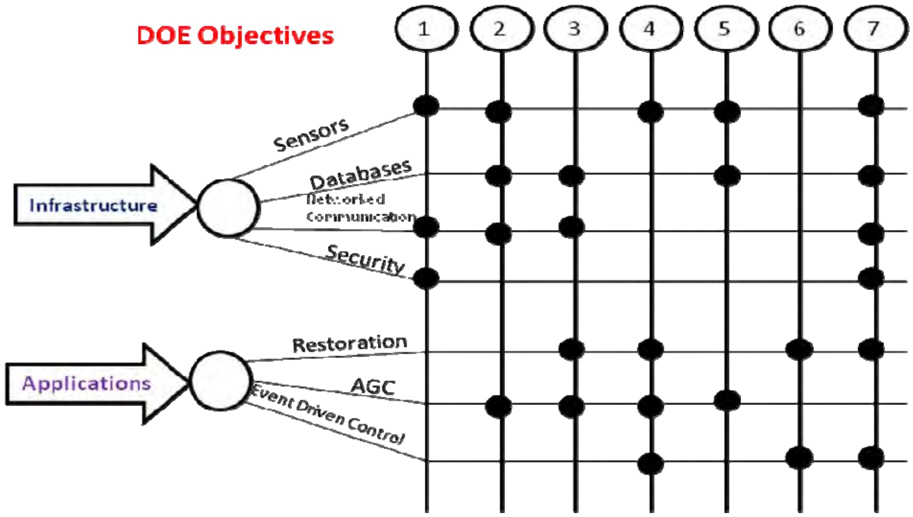

Fig.1: Mapping Solutions to Objectives

Integration of smart grid solutions requires a versatile communication infrastructure that is much more flexible than the existing one. Fig. 2 illustrates a communication system that will provide the needed integration. The communication requirements of the smart grid are much more demanding than of the legacy grid. The real-time requirements for exchange of data and information require low latency and redundancy in communication paths. The back-office data processing and storage requires communication support for distributed databases and processing facilities. The communication infrastructure also has to enable the special protection schemes critical to reliable system operation and control. Recent developments of modern communication architectures, such as the North American Synchrophasor Initiative net, are a step forward, but more work is needed to fully understand the communication requirements of new applications in a smart grid.

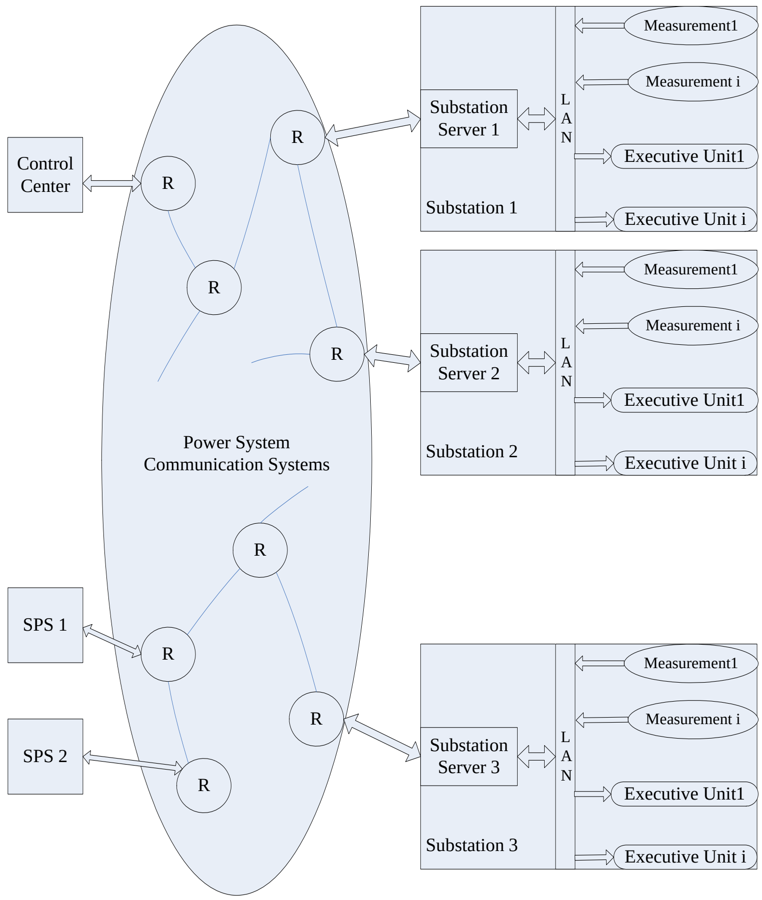

Fig. 2: Communication among System Elements

II. Conceptualize the Overall Smart Grid Architecture

A conceptual architecture of the smart grid is depicted in Fig.3. The proposed architecture advocates a synergy of computing and physical resources, and envisions a trustworthy middleware providing services to grid applications through message passing and transactions. The architecture also accounts for a power system infrastructure operating on multiple spatial and temporal scales. That infrastructure must support growing penetration of distributed energy resources. There will also be thousands of sensors and actuators that will be connected to the grid and to its supporting information network. Energy generation, transmission, and distribution will be controlled by a new generation of cyber-enabled and cyber-secure energy management systems (EMS) with a high fidelity supervisory control and data acquisition (SCADA) front end.

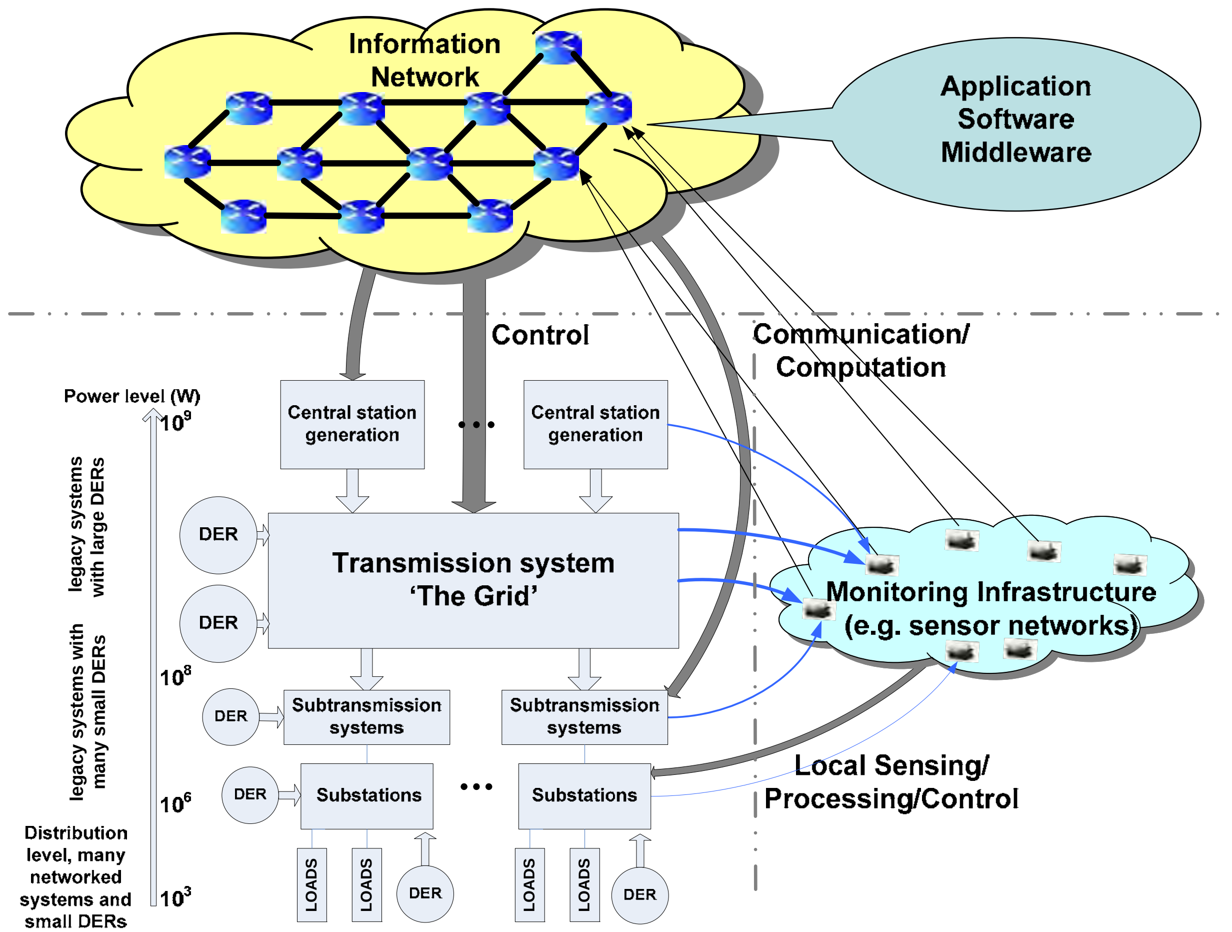

Fig. 3: Architecture for Proposed Integrated Smart Grid System

The information network will merge the capabilities of traditional EMS and SCADA with the next generation of substation automation solutions. It will (1) enable multi-scale networked sensing and processing, (2) allow timely information exchange across the grid, and (3) facilitate the closing of a large number of control loops in real-time. This will ensure the responsiveness of the command and control infrastructure in achieving overall system reliability and performance objectives.

III. Conduct Research and Development to Create an Integrated Smart Grid Solution

Much attention is being paid to customer-level smart grid devices in current smart grid discussions. There also needs to be planning for the implementation of a smart grid at the bulk transmission level. This planning must address challenges to achieve high penetration of renewable energy resources at different voltage and power levels in an environment where operating margins are declining due to load growth and retirement of legacy generation resources. The following tasks are needed to create an integrated smart grid bulk transmission solution that ensures the seamless accommodation of green resources and guarantees that operating criteria will be satisfied even under extreme system loading conditions.

1. Develop and establish forward-looking, updated operations criteria including methods, tools, and operational structure of the interconnection

Regional entities of the North American Electric Reliability Corp. (NERC) establish reliability criteria that are necessary to implement, to augment, or to comply with reliability standards. In broad terms, the regional criteria describe how planning and operations need to be done to ensure grid reliability. Thus, the criteria can include, for example, operating practices and protocols, tools, methods, and organizational processes. A critical element of an integrated solution approach will be developing appropriate system operations criteria that account for variable power output from renewable resources. New risk-based operations criteria will also be needed to balance economic and reliability goals while accounting for the increased uncertainty in the system.

The updated operations criteria will need to include control area and balancing area designs that account for increased penetration of renewables. The criteria must provide interoperability standards and criteria that enable flexible deployment of new and old generation sources. The criteria must ensure that the grid continues to be resilient under increased uncertainty about system conditions and resource availability.

Models, operational structure, and analysis tools for studying requirements for interoperability standards will be needed. These tools must have the capability to allow examination of legacy and new criteria, and to quantify the impact of proposed criteria on power systems economics and reliability, particularly under extreme events.

Research and development should be conducted in a number of areas.

a) *Measurements and sensors*: Development of high bandwidth, high accuracy current and voltage transformers, and other types of sensors, such as sensors that monitor mechanical variables of the transmission infrastructure. Phasor measurement units and other GPS-enabled intelligent electronic devices will play a critical role in the envisioned smart grid solution. Methods will also be needed for intra-substation data collection and storage.

b) *Communications*: A high bandwidth network capable of intra-substation, inter-substation, and control center communication will be required to facilitate large-scale data collection, local processing, and distilled information transfer. A key feature of this architecture will be communications management via advanced middleware.

c) *Integration of information technology*: The envisioned information technology infrastructure will also include distributed databases that require local and distributed management addressing real-time and off-line requirements. The architecture relies on local processing capabilities to perform data integration and information extraction. Cyber security and data integrity issues will need to be addressed to ensure that operational criteria are met.

d) *Monitoring and supervisory control*: The proposed smart grid solution needs to provide advanced visualization and situation awareness, intelligent alarming and alarms management, the ability to quantify reliability and market performance as operation aids, and supervisory control aids during alert and emergency conditions.

e) *Intelligent recovery and restoration*: With the need to monitor and control a system on diverse spatial and temporal scales, a high degree of coordination, and automation is imperative when restoring a system following major outages. This will require development of special monitoring methods and on-line analytical tools not currently in use, and will also involve the development of operator aids to translate restoration procedures into actions.

f) *Wide area control and protection*: New requirements for control and protection will result from the wide diversity of the distributed energy resources interconnected to the grid at a range of voltage levels. To manage and enhance the speed and effectiveness of such functions, innovations will be needed in synchrophasor-based monitoring, relaying and control, fast utilization of FACTS devices for system-wide changing conditions, suppression of inter-area oscillations, system integrity protection schemes, and adaptive islanding as a last resort.

g) *On-line grid control and management tools*: The increasing complexity and size of the electric energy system will also necessitate new developments in (1) fast state estimation that will replace SCADA data for operator displays, (2) intelligent integrated (static, dynamic, voltage) contingency analysis, (3) OPF-based control decisions during reliability or market deterioration, (4) direct state measurements that replace state estimation, (5) fast simulation techniques for real time contingency applications, and (6) system representation and modeling for operations (real time) and planning (off-line) applications.

2. Analyze the likely interactions of renewable resources and storage with the bulk transmission system

The increased penetration of renewable resources will necessitate the need for large-scale energy storage at the bulk transmission level. It will be complex to conduct a rigorous investigation of the interactions between renewable resources and large-scale storage in the bulk transmission system. The investigation will need to account for the variability of power and energy output from renewable resources, and incorporate interactions among diverse renewable resources (e.g., wind, solar, and biomass). The effect of renewable resources and storage on power system operation should be examined, such as balancing authority functions, automatic generation control, and market operation.

These analyses have not been carried out for large-scale integration of renewables. Novel analytical approaches and tools will have to be developed.

3. ***Assess the effects of high penetration of low-carbon solutions along with implementation of possible policy scenarios (such as cap and trade) on investment and operations, and on economic profitability and risk under today's market designs to determine whether those designs need to be changed in the future***

To facilitate the penetration of renewable resources, an integrated approach that accounts for both system operations and the underlying market mechanisms is essential. This integrated analysis under plausible future scenarios should account for renewable resources, demand resource programs enabled by a smart grid, massive energy storage, a transmission grid backbone of HVDC and HVAC technologies, and central station generation (including legacy generation, and new nuclear, clean coal, and other relevant generation technologies).

4. Develop technologies and tools to facilitate customer participation

Customer response to communications (such as prices) from service providers plays an important role in the scheme envisaged for a smart grid that is integrating renewable sources. Technologies and tools that facilitate customer participation must be developed and incorporated in the smart grid vision. This research activity should consider:

- Demand side management
- Intelligent metering
- Use of plug-in hybrid and all electric vehicles
- Aggregation as a means of collective participation
- Load as a resource
- New designs for information sharing and transacting in an energy exchange system
- Factors that drive customer and business adoption of new technologies and ways of transacting
- Business models in the new energy enterprise.

IV. Move forward with stakeholder collaboration and large-scale demonstrations

The next step in the path to smart grid implementation is to conduct large-scale demonstrations using the vision of an integrated solution and architecture, and the applications from generation sources to end-uses. Large-scale demonstrations will facilitate continuing research and development, testing, and implementation of proposed solutions.

A number of key steps should be taken to ensure a successful large-scale demonstration.

1. *Engage stakeholders from the beginning in defining the scale, scope, and objectives to the end when results are evaluated and next steps are discussed.* A comprehensive smart grid solution will require substantial investment in transmission and distribution systems, will affect customers and energy service providers throughout a service territory, and will rely on manufacturers to supply needed hardware and software. The more

the stakeholder collaboration is from the beginning, the less the uncertainty there should be about the appropriate technologies, and the effects and acceptability of implementation of those technologies. In addition, it is useful to clarify smart grid design concepts based on discussions between academics and industry participants fully engaged in research and development as well as deployment of smart grid technologies.

2. *Link the scale, scope and objectives to the information needed to commit resources to building a smart grid.* If the demonstration does not fill gaps in the information needed, then there will still be questions at the end of the demonstration as to whether and how the smart grid should be built. Collaboration among stakeholders will be very important in identifying the information that needs to be gained from the demonstration.

3. *Define the metrics for evaluating the demonstration's results*. The evaluation metrics should be specified from the beginning to ensure that the necessary data are gathered during the course of the demonstration. Of course, the metrics should be related to the information gaps that the demonstration is seeking to fill. An evaluation analysis team should be formed as the demonstration is being planned so that their input can be considered in the design. This team should be multi-disciplinary (such as engineers, statisticians, consumer market researchers, and economists) to provide the multi-disciplinary information needed to decide whether and how to implement a smart grid solution.

4. *Coordinate the planning of the demonstration with other demonstration projects.* Large-scale demonstration projects take considerable resources and time. Efficiency and effectiveness of the demonstration will be well-served by coordinating with other demonstration projects that are being planned or that are in progress, and by reviewing results of completed demonstration projects. This coordination will be facilitated by the common demonstration project database that is being planned by the U.S. DOE.

5. *Use scientific study methodologies rather than just technology demonstrations when appropriate.* Just because a proposed solution works technically does not mean that it is the preferred solution. Results in a technology-based demonstration may not be useable in making inferences about how all customers (be they end-use customers, distributed generation customers, or other types of customers) will change their electric energy consumption or production decisions in response to a particular solution. There may also be customer adoption barriers that should be considered in developing or selling the solution to them. Using scientific approaches where appropriate, such as in trying to understand customer response, could provide results that can be generalized to an entire service territory. Good estimates of customer response are needed to evaluate smart grid solutions even at the bulk transmission level where planners need to know how transmission flows will be affected by customer response to smart grid solutions.

V. Conclusions

The four tasks described above are crucial to smart grid research and development, demonstration, and eventual deployment. As learning and innovation occurs during the course of a demonstration, changes may be needed in the architecture, the components, and how they are integrated operationally. The goal is to acquire the best information possible for the eventual decisions on whether and how an integrated smart grid solution should be implemented, so adjusting demonstrations as needed to provide that information could be very appropriate.

It is also important that demonstrations be designed and implemented to gain the knowledge needed for a system-wide deployment of a smart grid. The bulk transmission system should be included in the design.

There are a great number of unknowns in moving toward a national goal of a low-carbon economy. That uncertainty can be reduced by effectively designed large-scale demonstrations drawing on results of research and development work.