The Big Picture

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Smart Research for Large-Scale Integrated Smart Grid Solutions

THE EVOLUTIONARY PATH OF THE U.S. ELECTRICITY GRID IS AT A HISTORICAL crossroads. Decisions must soon 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 a bulk transmission network, that can meet the societal needs of the 21st century and beyond. A major evolutionary step in the grid's design, planning, and operation is needed, one that adopts new design concepts and innovative technologies that can be integrated into a modern infrastructure. The American Recovery and Reinvestment Act of 2009 (ARRA) provided a number of opportunities to achieve these far-reaching objectives.

This article describes a vision of—and the steps needed to reach—the national objective of having a smart grid infrastructure. Our focus is on new concepts and related technological considerations in developing smart grid solutions that will meet the seven objectives of the smart grid, as identified by the U.S. Department of Energy (DOE):

1) enabling informed participation by customers
2) accommodating all generation and storage options
3) enabling new products, services, and markets
4) providing the level of power quality required to meet the full 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.

To achieve these goals, smart research and development efforts must harmonize four principal aspects of the future grid:

- ✔ **Expansion of the electricity grid infrastructure:** This includes building new infrastructure to replace aging infrastructure while expanding grid capacity, improving the operation and efficiency of the existing infrastructure, and 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 (e.g., from 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).

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To satisfy these objectives, there needs to be a novel mapping of smart grid applications to the proposed infrastructure.

- ✔ **Introduction of information technology, communications infrastructure, and modern sensors at large scales for both online 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, cybersecurity technologies, 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 bring technological advances in monitoring, data-to-information conversion and visualization technologies, and advanced control and protection schemes. These advances will serve to integrate renewable resources and distributed generation, support customer choices, facilitate risk-based asset management and control strategies, and improve efficiency and protection of the grid.
- ✔ **Enactment of a new regulatory environment for operating the smart grid that provides the correct economic signals for all participants and all market products:** The basic economic principle for the smart grid should be that all participants should pay for the services they use and be paid for the services they provide. Traditionally, the regulatory environment treated the levels of demand for energy on the grid as exogenous sinks. Regulation was directed to the suppliers of energy and ancillary services, and customers expected to have reliable sources of energy available wherever and whenever they wanted. The main change for the smart grid will be to recognize that customers can also supply services to the grid and modify the timing of their demand for energy in response to incentives. Allowing new demand response products to participate in capacity markets is only the first step in developing new demand response capabilities for the smart grid.

Next we discuss a systematic approach 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.

Defining a Vision for the Operations of Integrated Systems

To satisfy these objectives, there needs to be a novel mapping of smart grid applications to the proposed infrastructure. Figure 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 goals of the smart grid. 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.

The integration of smart grid solutions requires a versatile communications infrastructure that is much more flexible than the existing one. Figure 2 illustrates a communication system that will provide the needed integration. The communication requirements of the smart grid are much more demanding than those 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 require communication support for distributed databases and processing facilities. The communication infrastructure also has to enable the special protection schemes critical to reliable

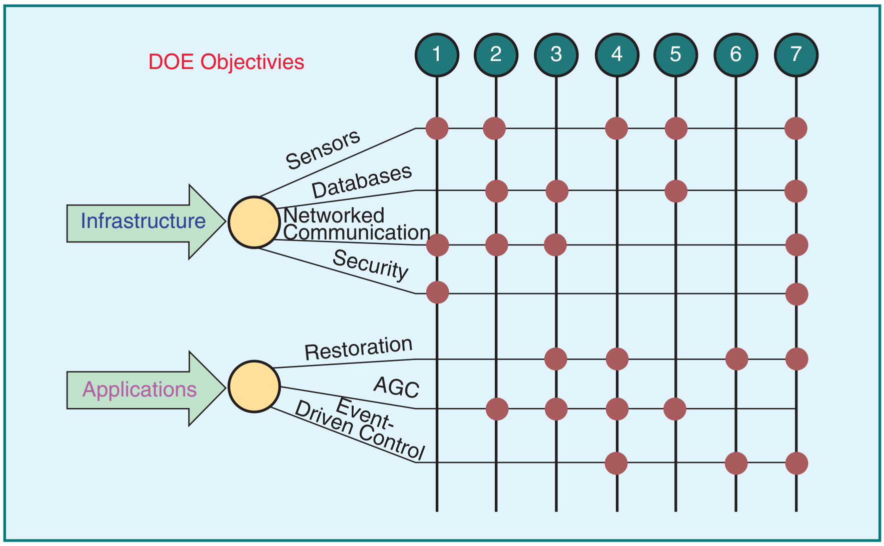

figure 1. Mapping solutions to objectives.

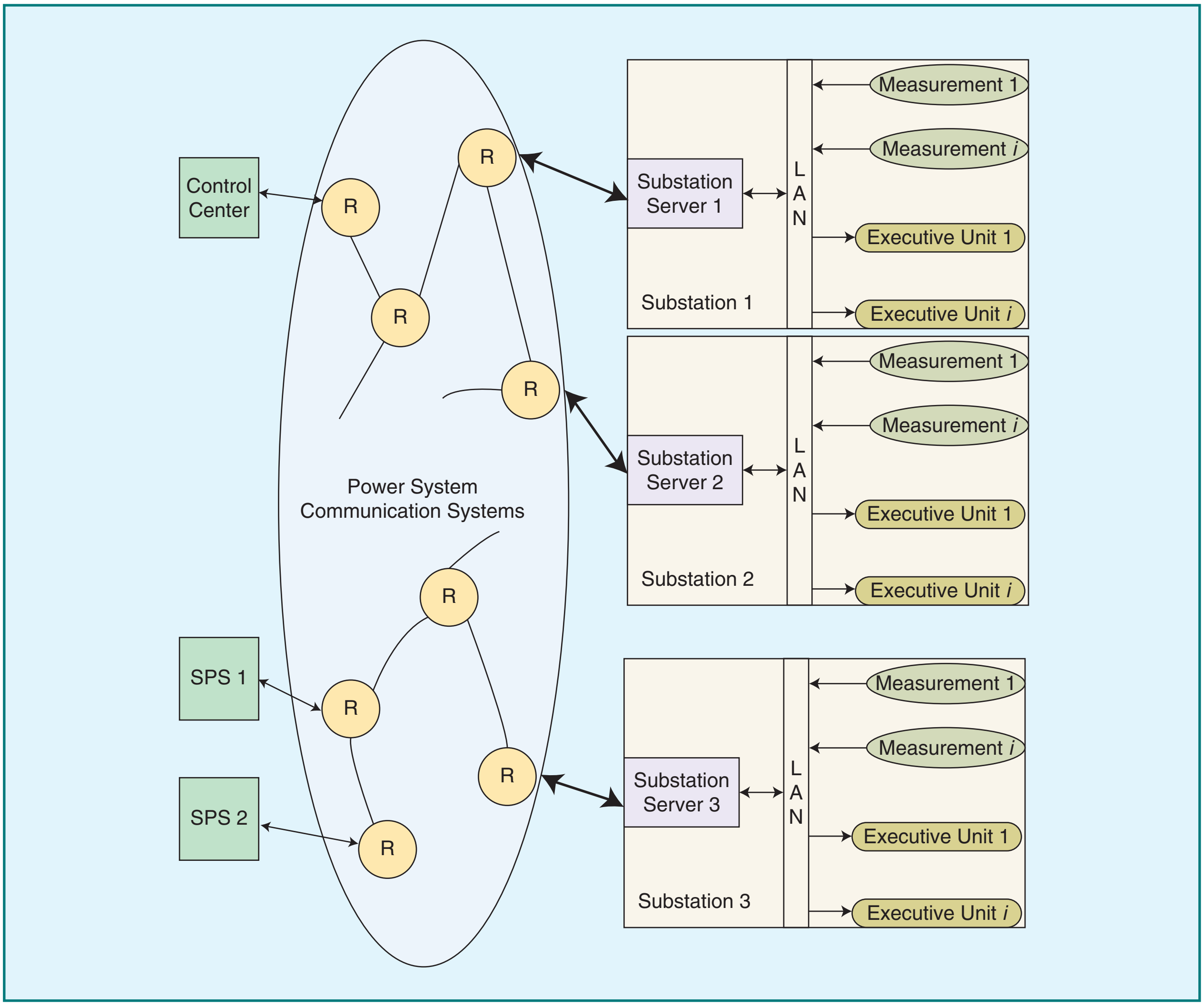

figure 2. Communication among system elements.

system operation and control. Recent developments of modern communication architectures, such as the North American SynchroPhasor Initiative network, are a step forward, but more work is needed to fully understand the communication requirements of new applications in a smart grid.

Conceptualizing the Smart Grid Architecture

A conceptual architecture for the smart grid is depicted in Figure 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 cybersecure energy management systems (EMSs) with a high-fidelity supervisory control and data acquisition (SCADA) front end. A notable change from the previous architectures is the two-way communication between customers or service aggregators with all electricity market stakeholders: distribution, transmission, and the market operator. This is shown in Figure 3, as a link through the information network. To reduce complexity, the market operator connection is not shown in Figure 3.

The information network of the future will merge the capabilities of traditional EMSs and SCADA with the next generation of substation automation solutions. It will enable multiscale networked sensing and processing, allow timely information exchange across the grid, and 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.

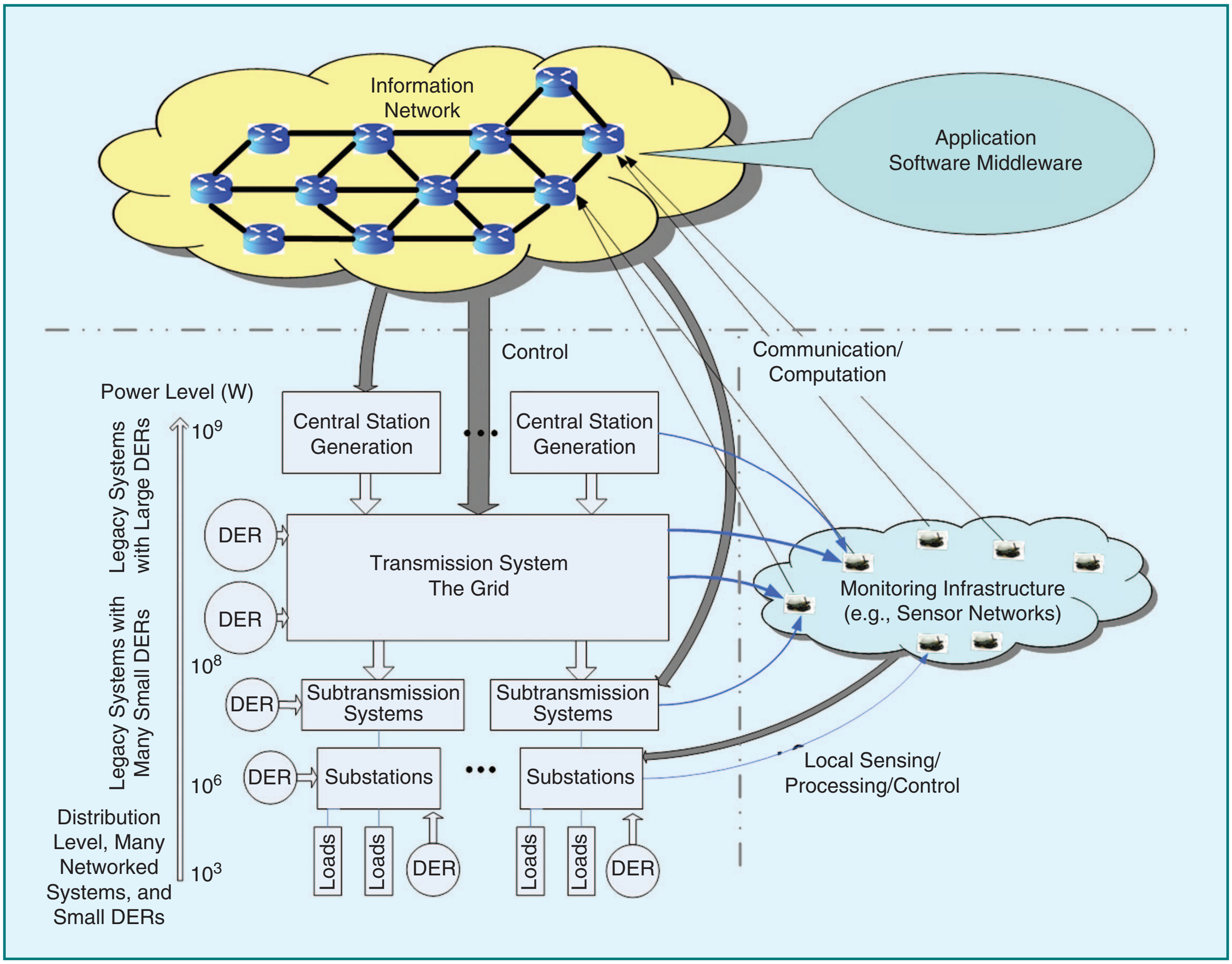

figure 3. Architecture for a proposed integrated smart grid system.

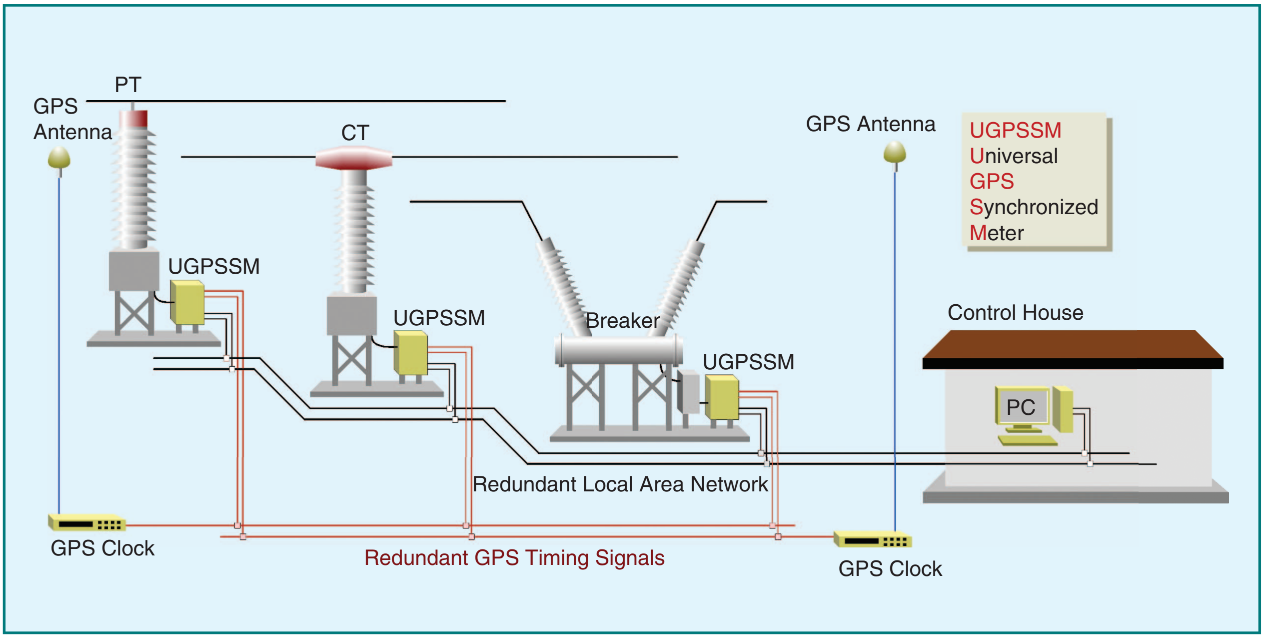

figure 4. Future substation physical diagram.

The key to the success of the smart grid infrastructure is an underlying system of data acquisition, data validation, and data processing that will provide accurate and reliable data as well as extracted information to all the applications implied in Figure 3. Two concepts, namely data validation and data processing, are elaborated next.

A more detailed view of a system at the substation level that will assure more reliable data is provided in Figure 4. The proposed system for data acquisition and processing is based on substation automation technologies that are feasible today and assures full validation and redundancy of data. In Figure 4, the redundant substation local-area network that connects all substation measurement and power devices to the substation control center (SCC) via a digital network is deployed. In addition, the presence of a merging unit (a universal GPS-synchronized meter, or UGPSSM) on each high-power device is assumed. The UGPSSM performs digitization and time synchronization of measurements and communicates the time-tagged information to the SCC. Finally, the SCC communicates with the power system's wide-area network (WAN) via a single communication channel. This lets the SCC communicate with external power system entities, such as a utility control center or other smart substations, to provide data necessary for smart grid wide-area functions.

In terms of device connectivity, Figure 5 shows the architecture of the system depicted in Figure 4. This architecture has evolved over many decades, and technology exists today to fully implement this architecture. The data acquired by merging units are available on a process bus where other equipment can be connected and can process the data for a variety of applications, including state estimation (SE) and data validation, protection, power quality analysis, and phasor data computation. The intelligent electronic devices (IEDs) connected to the process bus can post the processed data on the substation bus. The data at the substation bus can be accessed by other devices for additional applications and to communicate this data to other entities, such as the control center and the enterprise. In terms of future design requirements Figure 5 illustrates typical data types and data rates. As smart grid technologies are further developed, data rates will increase.

Validating the data with techniques such as SE is becoming essential. At present, SE methods provide a practical

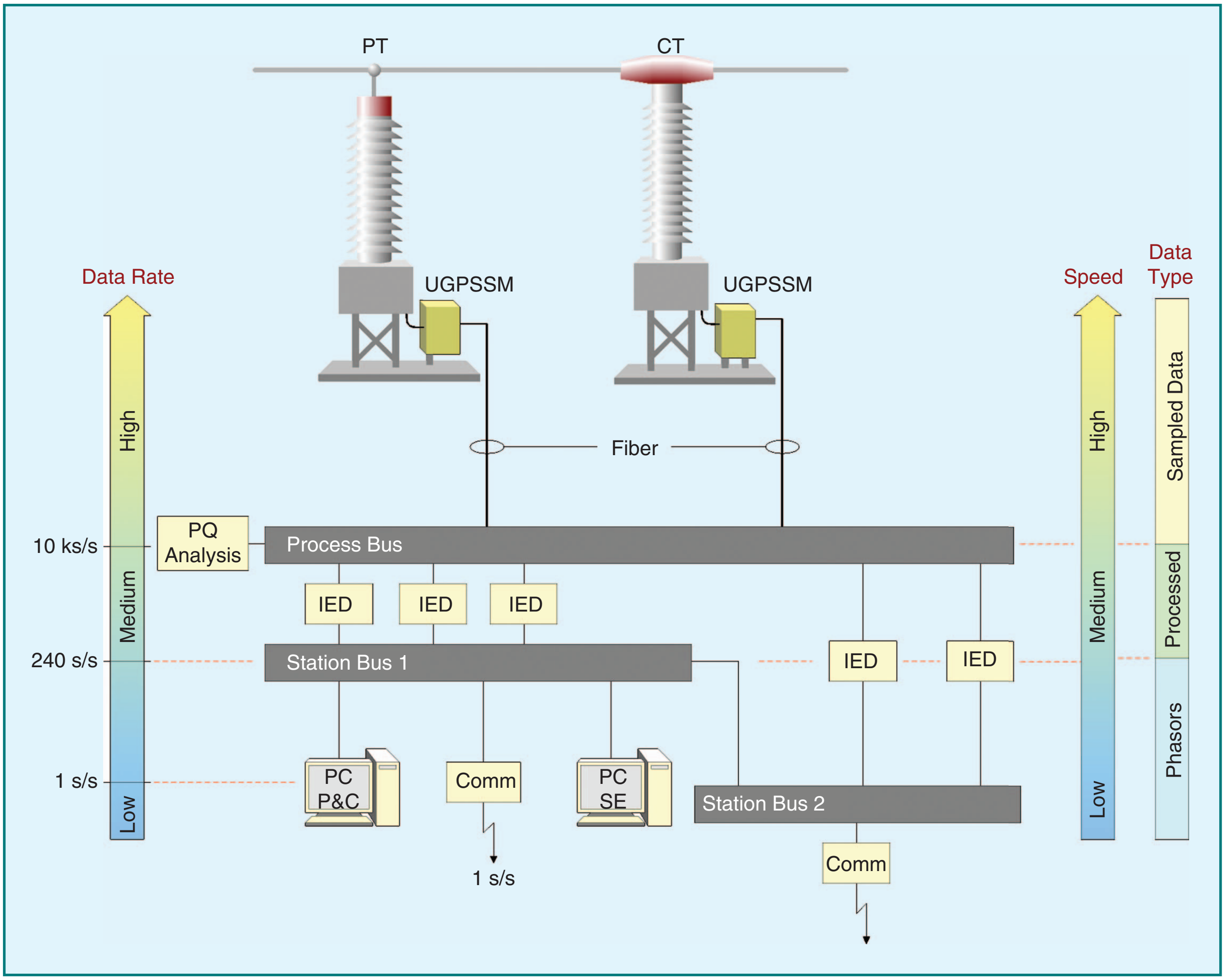

figure 5. Substation architecture with data rates and data types.

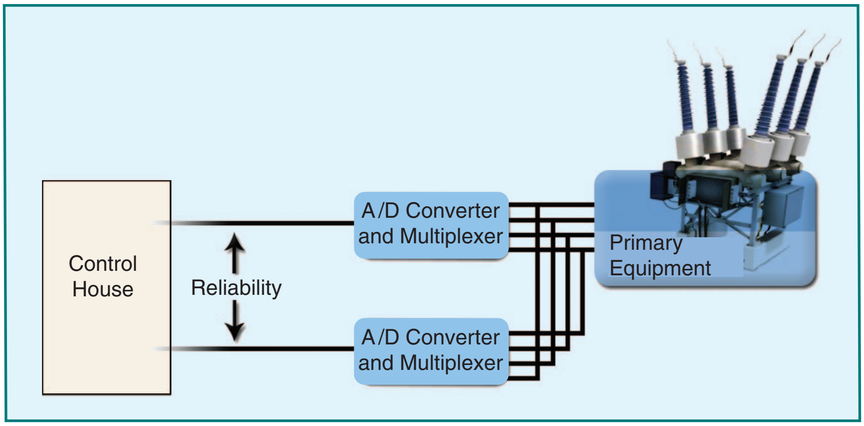

figure 6. Integrating field data by multiplexing multiple measurements on a single fiber.

to be brought to the control house, as shown in Figure 6.

The next level of processing involves extracting necessary information and feeding it to applications at different levels of the processing hierarchy: IEDs, substations, control centers, and market operators. To illustrate the concept, we will discuss automated analysis of faults and disturbances. Figure 7 shows different levels of automated software-based analysis that is information intensive and aims to convert data into information that provides further details about the causes of faults and disturbances.

technique for validating data. The architecture described above deals effectively with several well-known limitations of centralized SE and preemptively addresses many future goals of power system operations.

The scalability of the smart grid infrastructure is of paramount importance, since the amount of data captured in the smart grid will be huge. The proposed scheme can be implemented independently of the size of the grid because it is a distributed system. This is a major advantage for large regional transmission organizations as compared with competing centralized schemes. Currently, the amount of data to be transmitted between the substation and the control center and its frequency of transmission are fixed, but the proposed scheme can make this completely flexible, with the data amount and frequency adjusted to the particular control center application, which can also be made to run more or less often depending on the state of the system. The proposed scheme enables wide-area protection and wide-area control, which will be designed and implemented much more easily than they can be today.

The availability of large amount of data leads to the need for highly efficient and flexible data processing that will allow the integration of data from various IEDs, the extraction of information needed by various applications, and (eventually) the identification of the knowledge required for executing actions. In the future, data integration will start from the field, where sensor data will be multiplexed on single fibers

As an example, the system-wide analysis includes fault analysis and fault location (FAFL). The substation-level analysis includes digital fault recorder analysis (DFRA), circuit breaker monitor analysis (CBMA), power quality monitor analysis (PQMA) and digital protection relay analysis (DPRA). The monitoring and tracking analysis includes verification of substation database (VSDB), two-stage SE (TSSE), substation switching sequence verification (SSSV), and integration of substation database (ISDB). In this example, substation-level analysis provides information to serve control center applications such as fault location, topology processing for SE, and alarm processing. This analysis, together with power system component models, can provide the system with a wide-level disturbance monitoring and analysis solution that is unavailable today.

An important observation for the applications shown in Figure 7 is the step that facilitates data integration and information exchange from multiple types of IEDs to serve the automated analysis applications that start with individual IED types. Figure 8 illustrates the substation-level data processing needed to implement such data integration and information extraction concepts.

Conducting R&D 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 the challenges that must be overcome in order to achieve a 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 the retirement of legacy generation resources. The following tasks are needed

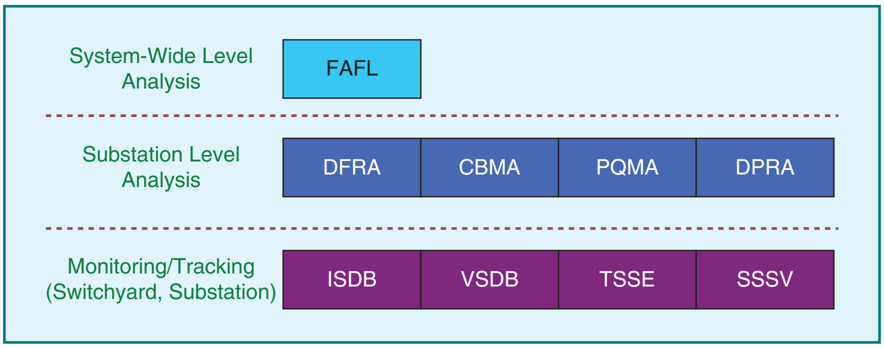

figure 7. Software architecture for fault and disturbance analysis.

The scalability of the smart grid infrastructure is of paramount importance, since the amount of data captured in the smart grid will be huge.

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.

Develop and Establish Forward-Looking, Updated Operations Criteria

Regional entities of the North American Electric Reliability Corporation (NERC) establish the reliability criteria necessary to implement, augment, or comply with reliability standards. In broad terms, the regional criteria describe how planning and operations need to be done to ensure grid reliability. The criteria can therefore include, for example, operating practices and protocols, tools, methods, and organizational processes. A critical element of an integrated solution for the smart grid 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 an increased penetration of renewables. The criteria must provide interoperability standards and criteria that enable the flexible deployment of new and old generation sources. The criteria must ensure that the grid continues to be resilient in the face of 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 allow for the examination of legacy and new criteria and be able to quantify the impact of proposed criteria on power system economics and reliability, particularly under extreme events.

R&D should be conducted in a number of areas. These include:

1) **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, is needed. Phasor measurement units (PMUs) and other GPS-enabled IEDs will play a critical role in the smart grid solution being envisioned. Methods will also be needed for intrasubstation data collection and storage. As an example, Figure 9 illustrates the future use of PMUs in conjunction with data-mining tools such as decision trees to conduct online dynamic security assessment for a range of phenomena, including transient stability, small-signal stability, and voltage stability.
2) **Communications:** A high-bandwidth network capable of intrasubstation, intersubstation, 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.
3) **Integration of information technology:** The envisioned information technology infrastructure will include distributed databases that require local and distributed management capable of addressing both real-time and off-line requirements. The architecture relies on local processing capabilities to perform data integration and information extraction. Cybersecurity and data integrity issues will need to be addressed to ensure that operational criteria are met.
4) **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.

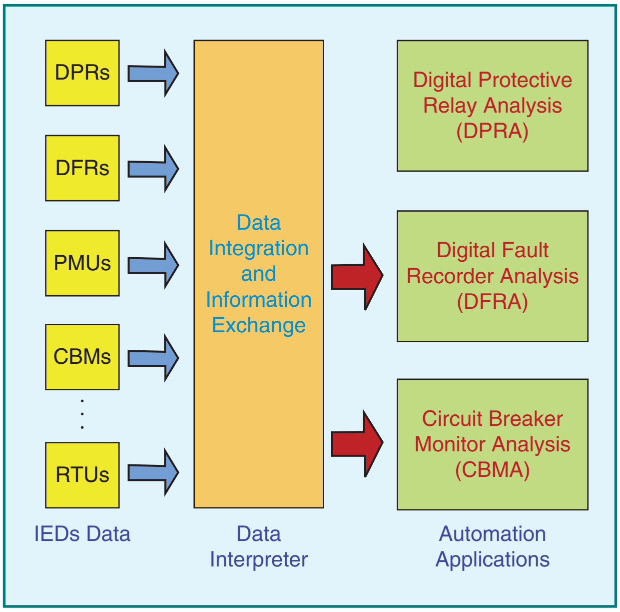

figure 8. Substation-level data integration and information exchange.

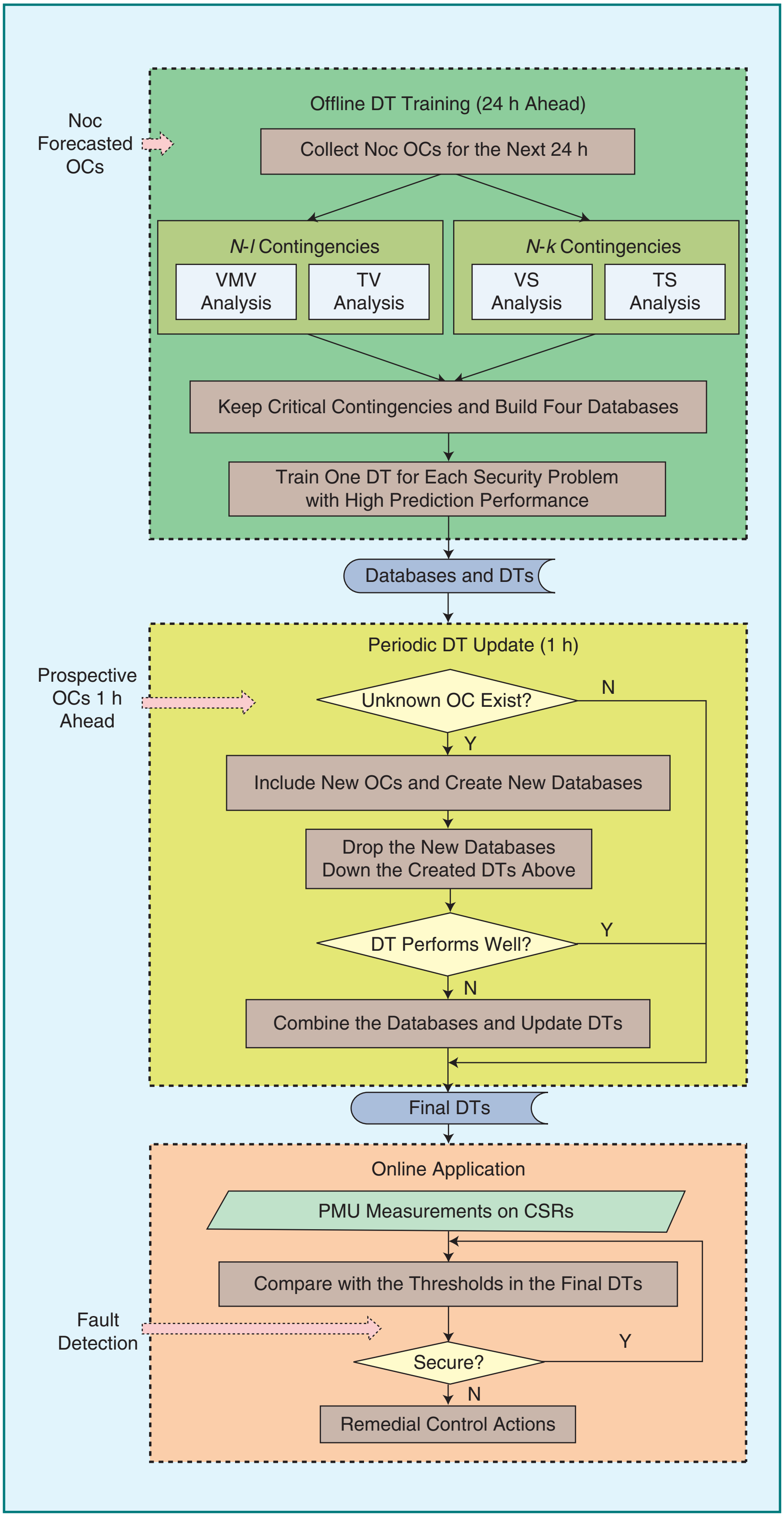

figure 9. Applications of PMU measurements in an online security assessment envisioned as part of the proposed smart grid solution.

An example of future research in this area is the concept of "economic alarms." Figure 10 shows an integration of alarms associated with faults and disturbances in a physical network with electricity market functions. Such integration would allow automated knowledge extraction that could provide market operators with an understanding of the impact of power system events on economic dispatch and local marginal prices (LMPs). This would create economic alarms indicating that either the electricity market was in an emergency state due to the violation of market parameters or that power system connectivity was disturbed and required immediate restorative action.

5) **Intelligent recovery and restoration:** Given the need to monitor and control a system existing on diverse spatial and temporal scales, a high degree of coordination and automation is imperative for system restoration following major outages. This will require the development of special monitoring methods and online analytical tools not currently in use and will also involve the development of operator aids to translate restoration procedures into actions. Figure 11 depicts a proposed automatic restoration scheme that includes an integrated restoration plan for generation, transmission, and distribution in conjunction with a detailed constraint-checking approach to guarantee that the system meets reliability requirements as it is restored.

6) **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 flexible alternative current transmission systems (FACTS) devices for changing system-wide conditions; suppression of interarea oscillations; system integrity protection schemes; and, as a last resort, adaptive islanding.

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

Analyze the Interactions of Renewables and Storage with Transmission

The increased penetration of renewable resources will necessitate the need for large-scale energy storage at the bulk

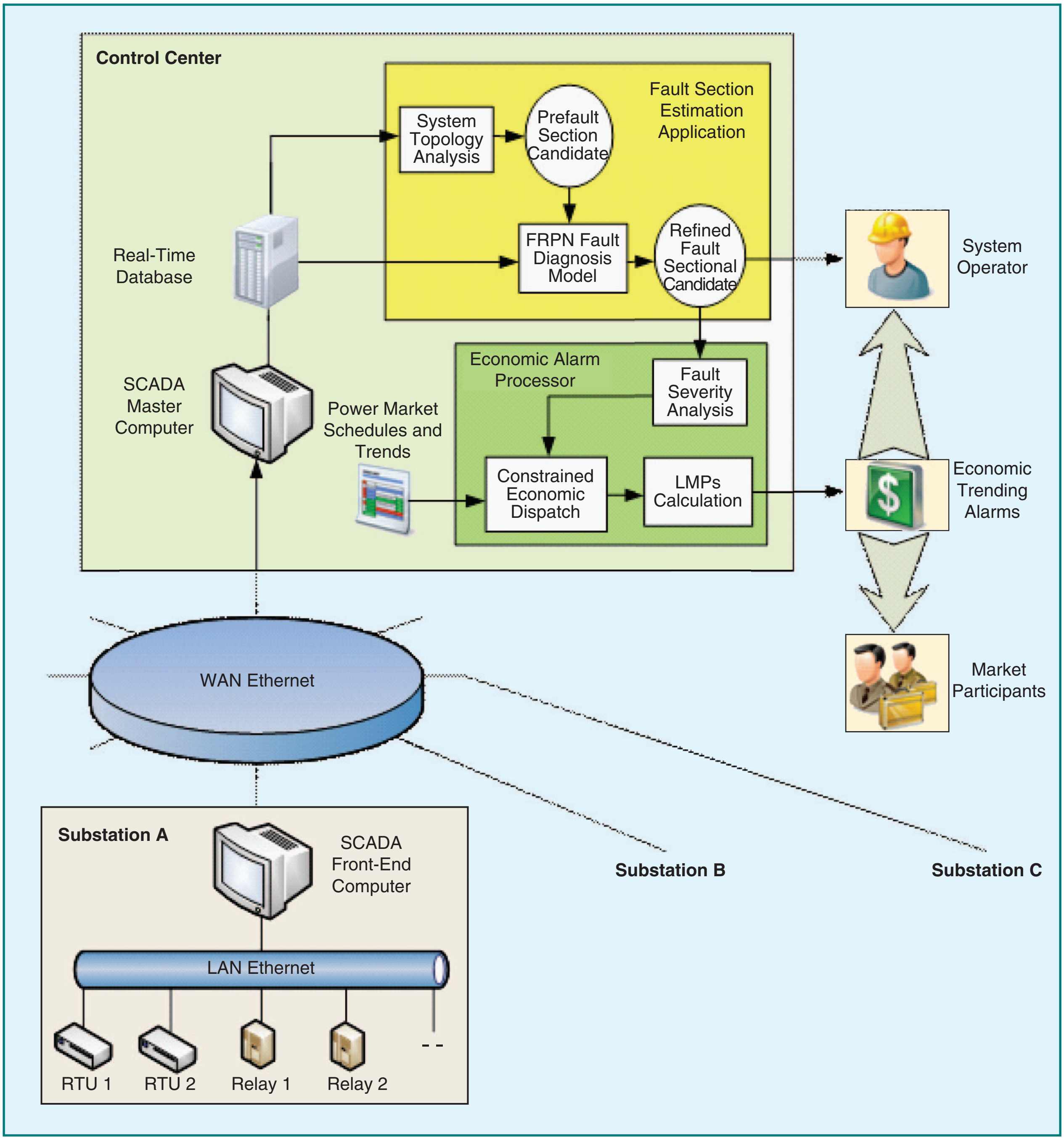

figure 10. Architecture of an intelligent economic alarm processor.

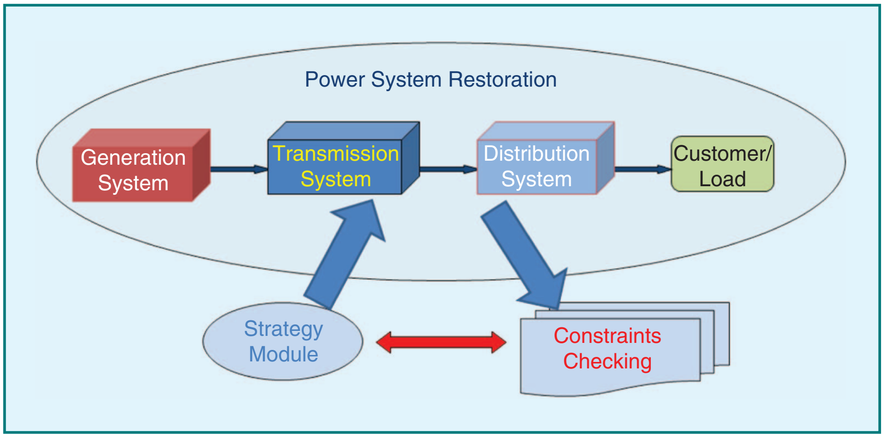

figure 11. Automated integrated restoration with constraint checking.

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, including balancing authority functions, automatic generation control, and market operation.

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

Assess Effects of High Penetration of Low-Carbon Solutions and Policy Scenarios

To facilitate the penetration of renewable resources, an integrated approach that accounts for both system operations and 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).

Develop Tools that 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 energy sources. Technologies and tools that facilitate customer participation must be developed and incorporated in the smart grid. With higher penetrations of variable generation from renewable sources, the need to install effective forms of storage capacity on the electric delivery system is critical. But installing dedicated storage capacity designed only to mitigate the variability of generation from a wind farm, for example, is expensive. Furthermore, demand-side storage resources, such as the discharging and charging of electric vehicles, can be used to mitigate variable generation and smooth daily load cycles as well as provide regulation and ramping services to support the reliability of supply. If the owners of electric vehicles are compensated correctly for providing these services, the overall cost of operating the vehicles will be reduced. Since the primary purpose of the batteries in electric vehicles is to provide a means of transportation, the substantial cost of a battery will then be shared between transportation and supporting the grid. As a result, electric vehicles will provide a relatively inexpensive source of controllable load and energy storage for the grid.

The impact of controllable loads can be expanded by including thermal storage, and in particular by the use of ice batteries to replace standard forms of air-conditioning. The potential benefit of this type of storage is that a substantial amount of the peak system load on hot summer afternoons can be moved to off-peak periods at night. Instead of using air conditioners when space cooling is needed, ice can be made when this is convenient for the network. Similar arguments can be made for space heating using oil, for example, to store heat. In this way, thermal storage can be used to mitigate variable generation and reduce the total amount of installed generating capacity needed to maintain system adequacy. At the present time, however, the regulatory procedures for measuring and compensating these types of services are poorly developed. For example, demand-side products for reliability are typically paid on the basis of the reduction of use at peak periods instead of having customers always pay for what they actually do use.

The results in Figure 12 demonstrate how high penetrations of renewable sources of generation affect annual production costs on a test network. Each plot shows ten different load bins representing a load duration curve; the black line represents the wholesale payments made by customers in each bin. The operating and fuel costs (in blue) and the net revenue (the sum of green and yellow. The green part represents the contribution to the "fair share" if the total capital costs are allocated equally to the ten bins. The yellow is the contribution above this fair share.) show the allocation of the wholesale payments by suppliers. This net revenue covers part of the annual capital costs for generation and transmission. The remaining revenue needed to cover the annual capital costs is the "missing money" (red) that is paid indirectly to suppliers (e.g., in a capacity market). The costs below the black line are covered by the price paid for energy (US$/MWh), and the costs above the black line are covered by the price paid for installed generating capacity (US$/MW/year). Figure 12(a) shows the results with no wind generation, and Figure 12(b) shows the results with a high penetration of wind generation. The main conclusion that can be drawn is that adding wind generation tends to lower the average wholesale price of energy and increase the annual price of capacity. This increases the economic incentive to reduce the amount of installed capacity needed for system adequacy by reducing peak system loads and mitigating the effects of unexpected drops in wind speeds.

The main limitation of current regulatory practices is that the rate structures paid by most retail customers do not charge real-time prices for energy and do not include explicit payments for capacity. Although there has been a recent effort to install more advanced meters that can give real-time price signals to customers, this step is not sufficient. New efforts should be made by regulators to provide better incentives for customers to manage the timing of their demand more effectively. In addition, the same technologies that can move demand from peak to off-peak periods (e.g., thermal storage) can also be used to provide ramping services to mitigate the inherent variability of wind generation. Rate structures should be designed to recognize that all participants are potential users and providers of services. The traditional distinction between suppliers and buyers will no longer be appropriate for the smart grid. Although retail customers will be the primary users of energy, they may also provide ancillary services and, under certain conditions, energy. In addition, some traditional suppliers of energy may also be users of ancillary services such as ramping, and they should pay for these services. To reiterate the fundamental economic principal for the smart grid, all users of energy and ancillary services should pay for these services, and all providers of these services should be compensated.

Moving Forward: 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 users. Large-scale demonstrations will facilitate continuing R&D, testing, and implementation of proposed solutions. Examples of such large-scale demonstrations include recent investments in the ARRA demonstration projects.

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

1) **Engaging stakeholders, from the beginning of the demonstration (defining its 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 greater the stakeholder collaboration is from the beginning, the less uncertainty there should be about the appropriate technologies and the effects and acceptability of implementing those technologies. In addition, it is useful to clarify smart grid design concepts based on discussions between academics and industry participants fully engaged in R&D as well as deployment of smart grid technologies.
2) **Linking the scale, scope, and objectives of the demonstration to the information needed to commit resources to building a smart grid:** If the demonstration does not fill gaps in the information needed,

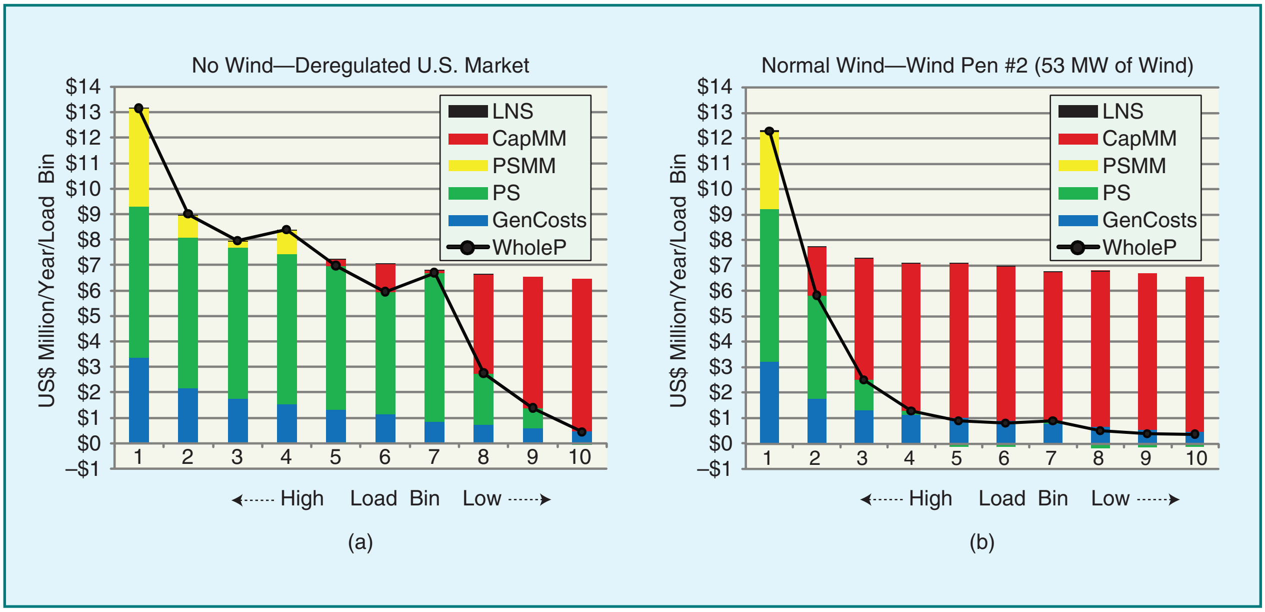

figure 12. The composition of production costs for networks (a) without and (b) with wind generation.

There are a great number of unknowns in moving toward the national goal of a low-carbon economy.

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) **Defining metrics for evaluating demonstration 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 its input can be considered in the design. This team should be multidisciplinary (it could include, for example, engineers, statisticians, consumer market researchers, and economists) so as to provide the multifaceted information needed to decide whether and how to implement a smart grid solution.
4) **Coordinating the planning of the demonstration with other demonstration projects:** The implementation of large-scale demonstration projects demands considerable resources and time. The efficiency and effectiveness of the demonstration will be well served by coordinating with other demonstration projects that are being planned or are in progress and reviewing the results of completed demonstration projects. This coordination will be facilitated by the common demonstration project database being planned by the DOE.
5) **Using scientific study methodologies rather than just technology demonstrations, as appropriate:** Just because a proposed solution works technically does not mean that it is the preferred solution. The results obtained from a technology-based demonstration may not be useful 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. Using scientific approaches where appropriate, e.g., when trying to understand customer response, could provide results generalizable 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.

Conclusions

This article represents an edited version of opinions expressed in an extensive white paper created by many individuals associated with the Power Systems Engineering Research Center (PSERC) of the National Science Foundation (NSF) and posted on PSERC's Web site, www.pserc.org. The four tasks described above are considered crucial to smart grid R&D, demonstration, and eventual deployment. As learning and innovation occur during the course of a demonstration, changes may be needed in the architecture, the components, and the way 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 is 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 the national goal of a low-carbon economy. That uncertainty can be reduced by effectively designed large-scale demonstrations drawing on the results of prior R&D efforts.

For Further Reading

PSERC White Paper. (2010). Future US energy infrastructure investment: Large-scale integrated smart grid solutions. [Online]. Available: http://www.pserc.org

PSERC. (2011). The 21st century substation design, Rep. T-37. [Online]. Available: http://www.pserc.org

PSERC. (2010). Substation of the future: A feasibility study, Rep. T-38. [Online]. Available: http://www.pserc.org

PSERC. (2011). Next generation of on-line dynamic security assessment, Rep. S-38. [Online]. Available: http://www.pserc.org

PSERC. (2012). Coupling wind generation with controllable load and storage: A time series application of the SuperOPF, Rep. M-22. [Online]. Available: http://www.pserc.org

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